U.S. Department of the Interior
Bureau of Land Management

Mineral Potential Report For the Royal Gorge Field Office

November 2018

Cover: Custer County obsidian landscape rock quarry. BLM photo.

MINERAL POTENTIAL REPORT
For the
ROYAL GORGE FIELD OFFICE

Prepared by:

U.S. Department of the Interior
Bureau of Land Management
Royal Gorge Field Office
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ACRONYMS AND ABBREVIATIONS

$	Dollars (U.S.)
AEC	Atomic Energy Commission
a.k.a.	Also known as
BLM	United States Bureau of Land Management
Btu	British thermal unit
ºC	Degrees Celsius
ºC/km	Degrees Celsius per kilometer
CBM	Colorado Bureau of Mines
CGS	Colorado Geological Survey
CMB	Colorado Mineral Belt
COGCC	Colorado Oil and Gas Conservation Commission
DOE	United States Department of Energy
DRMS	Colorado Division of Reclamation, Mining and Safety
EIA	United States Energy Information Administration
ºF	Degrees Fahrenheit
g/cm^3	Grams per cubic centimeter
g/t	Grams per metric ton
GIS	Geographic Information System
GPS	Global positioning system
HFU	Heat flow unit
HREE	Heavy Rare Earth Elements
kg	Kilogram
km	Kilometer
Leca	Lightweight expandable clay aggregate
LREE	Light Rare Earth Elements
mW/m^2	Milliwatt per square meter
Ma	Mega-annum (also used as: millions of years before present)
mm	Millimeter
MMst	Million short tons
MPR	Mineral Potential Report
MRDS	Mineral Resources Data System
MW	Megawatt
NGDB	National Geochemical Database
NPS	National Park Service
NURE	National Uranium Resource Evaluation
PGM	Platinum-Group Metals
ppm	Parts per million
REE	Rare Earth Element

RGFO	Royal Gorge Field Office
RMP	Resource Management Plan
SCM	Supplementary cementitious materials
ton	Short ton (2,000 pounds)
tonne	Metric ton (1,000 kilograms or 2,204.6 pounds)
U.S.	United States
USBM	United States Bureau of Mines
USFS	United States Forest Service
USGS	United States Geological Survey

1. INTRODUCTION

1.1 Purpose and Scope

The purpose of this mineral potential report (MPR) is to assess and document the wide array of mineral resources occurring within the boundaries of the Bureau of Land Management's (BLM's) Royal Gorge Field Office (RGFO). The MPR consists of this comprehensive written report along with a geographic information system (GIS) dataset that can be used for internal decision-making purposes within the RGFO and incorporated into the Eastern Colorado Resource Management Plan (RMP).

The MPR objective was to analyze mineral occurrence potential (excluding oil and gas and coalbed-methane resources, and carbon dioxide) in the vast RGFO area on a general scale in order to establish a baseline. From there, specific emphasis can then be placed on the mineral potential of Federal minerals under BLM management on a reasonable scale for further planning purposes. Understanding the current mineral occurrence potential (based on existing geologic conditions and past mining and extraction activities) as well as the future use potential is essential for effective management of the RGFO's mineral resources.

1.2 Lands Involved

The boundaries of the RGFO encompass a geographic area of more than 35,600,000 acres in the eastern half of Colorado, including all or portions of 38 counties (Figure 1-1). The RGFO manages an area that is roughly 320 miles long and 250 miles wide, and extends from the Continental Divide on the west to the Wyoming and Nebraska borders on the north, the Kansas border on the east, and the Oklahoma and New Mexico borders on the south. The RGFO area includes approximately 680,000 acres of BLM-administered surface estate and approximately 6.8 million acres of BLM-administered mineral estate (Figures 1-2 and 1-3). The RGFO mineral estate includes areas where Federal minerals underlie surface estates on lands that are not administered by the BLM, such as the following:

- U.S. Forest Service (USFS) lands (including portions of Arapahoe, Pike, Roosevelt, and San Isabel National Forests and Comanche and Pawnee National Grasslands);
- U.S. National Park Service (NPS) lands (including a portion of Rocky Mountain National Park and other locations such as Bent's Old Fort National Historic Site and Florissant Fossil Beds National Monument);
- Various U.S. Department of Defense installations (including Fort Carson and Piñon Canyon Military Reservations, Air Force Academy, Rocky Mountain Arsenal, and Pueblo Ordnance Depot); and
- A variety of State and private lands.

Split estates occur when the surface and mineral estates are severed, and each is under separate ownership. Active mining claims within the RGFO boundaries are shown on Figure 1-4.

1.3 MPR Methodology

This MPR follows the general format prescribed in BLM Manual 3060 (*Mineral Reports—Preparation and Review*) and provides an intermediate level of detail using the Mineral Potential Classification System found in BLM Manual 3031, *Energy and Mineral Resource Assessment*. The mineral resource occurrence ratings in this MPR are for all lands within the RGFO regardless of the surface ownership. This report is not intended to be a decision document and does not present specific recommendations on the management, protection, leasing, permitting, or extraction of mineral resources.

This report synthesizes information obtained from published geologic and mineral resource data for the RGFO area, including available scientific literature, databases, and maps and aerial photography acquired from sources such as the BLM; Colorado Geological Survey (CGS); Colorado Division of Reclamation, Mining and Safety (DRMS); Colorado Oil and Gas Conservation Commission (COGCC); Colorado State Land Board; NPS; USFS; United States Geological Survey (USGS); United States Bureau of Mines (USBM); Natural Resources Conservation Service; various professional and industry organizations (i.e., mining- and geology-related) and universities; and individual counties within the RGFO boundaries. These resources are cited throughout this MPR.

Mineral occurrence potential mapping presented in this MPR was done by senior-level professional geologists working with geographic information system (GIS) specialists to digitize areas of mineral occurrence based on a variety of resources:

- Published literature;
- Published geologic mapping and geologic spatial datasets (of varying scales);
- Historic mining district records and locations;
- Publicly available spatial and tabular databases (including USGS's Mineral Resources Data System [MRDS] and DRMS' Permitted Mines database); and
- Professional experience.

The maps and geodatabase included with this MPR were generated using Esri ArcGIS 10.4.1 and organized according to BLM's recommended GIS project directory structure. Map base layers such as administrative boundaries, land status, township and range grid, topographic hillshade, landmark locations, and transportation corridors were obtained from publicly available sources. Literature and source layers consulted or used to digitize occurrence potentials in GIS are cited in the specific descriptions of mineral commodities in sections 3.0 and 4.0 of this MPR. GIS processes used to generate occurrence potential feature classes are described in the feature class metadata.

Although the map layouts included with this MPR help the user visualize mineral occurrence potential at a regional scale, those wishing to use this MPR to inform planning or resource management decisions should view the spatial data directly using a GIS software application. However, it should be noted that the MPR was generally prepared at a scale of 1:500,000, using geologic units mapped at that scale for much of the delineation of occurrence potential regions or areas. Analysis at much finer scales (e.g., 1:24,000) may lead to conflicting information, such as designation of an area as one potential level, even though the rock type is not appropriate. In such instances, it is recommended that the reasoning and logic used to assign occurrence potential presented in the text be applied to the finer scale map. For example, if the 1:500,000 GIS layer shows an area as high potential for base metals due to deposits found in Precambrian rocks, but the 1:24,000 map shows parts of that area of interest are actually composed of loose alluvial material, it would be logical to discount any base-metal occurrence in the alluvial material, as it does not actually meet the geologic criteria that were the basis of the designation.

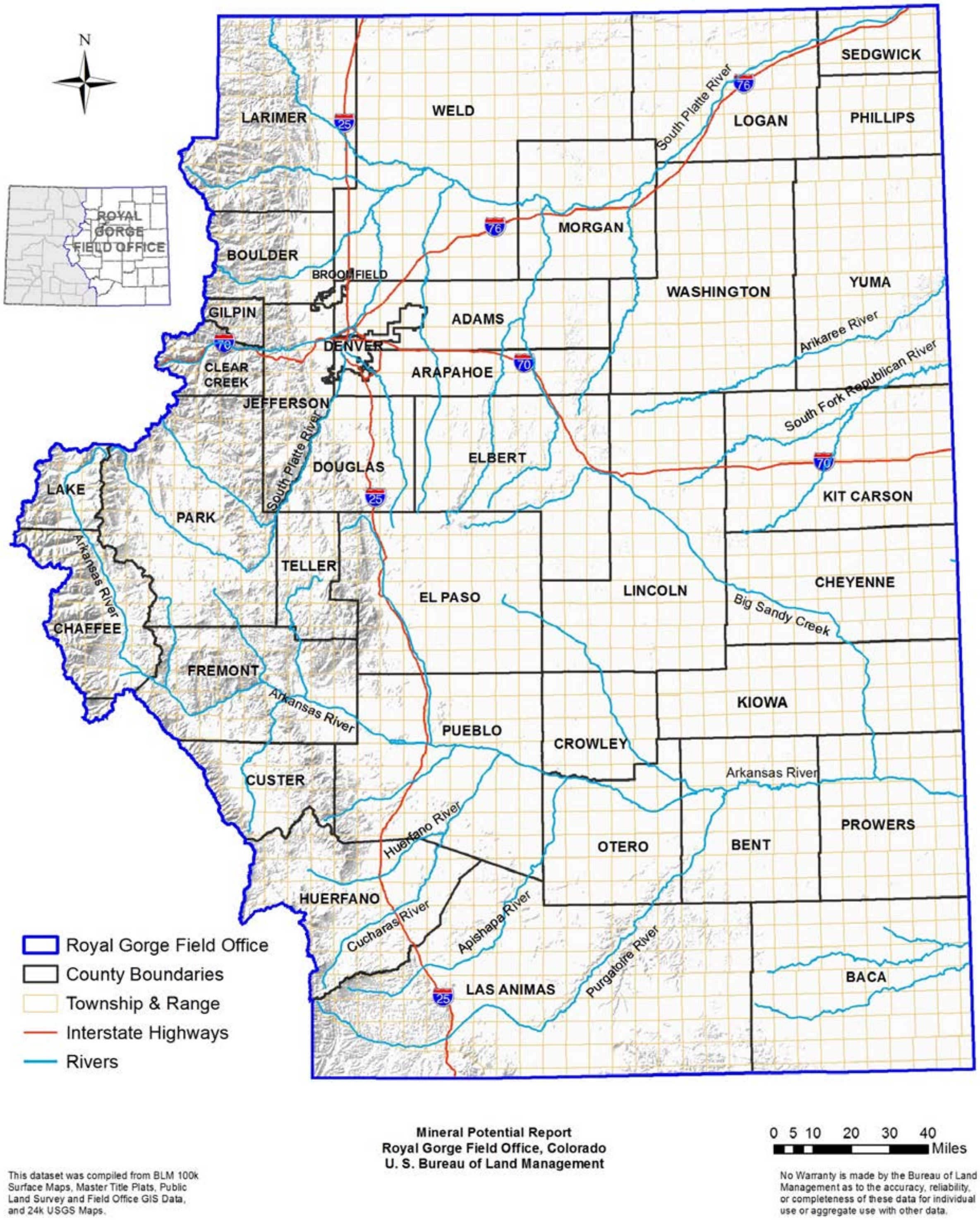


Figure 1-1. Planning area.

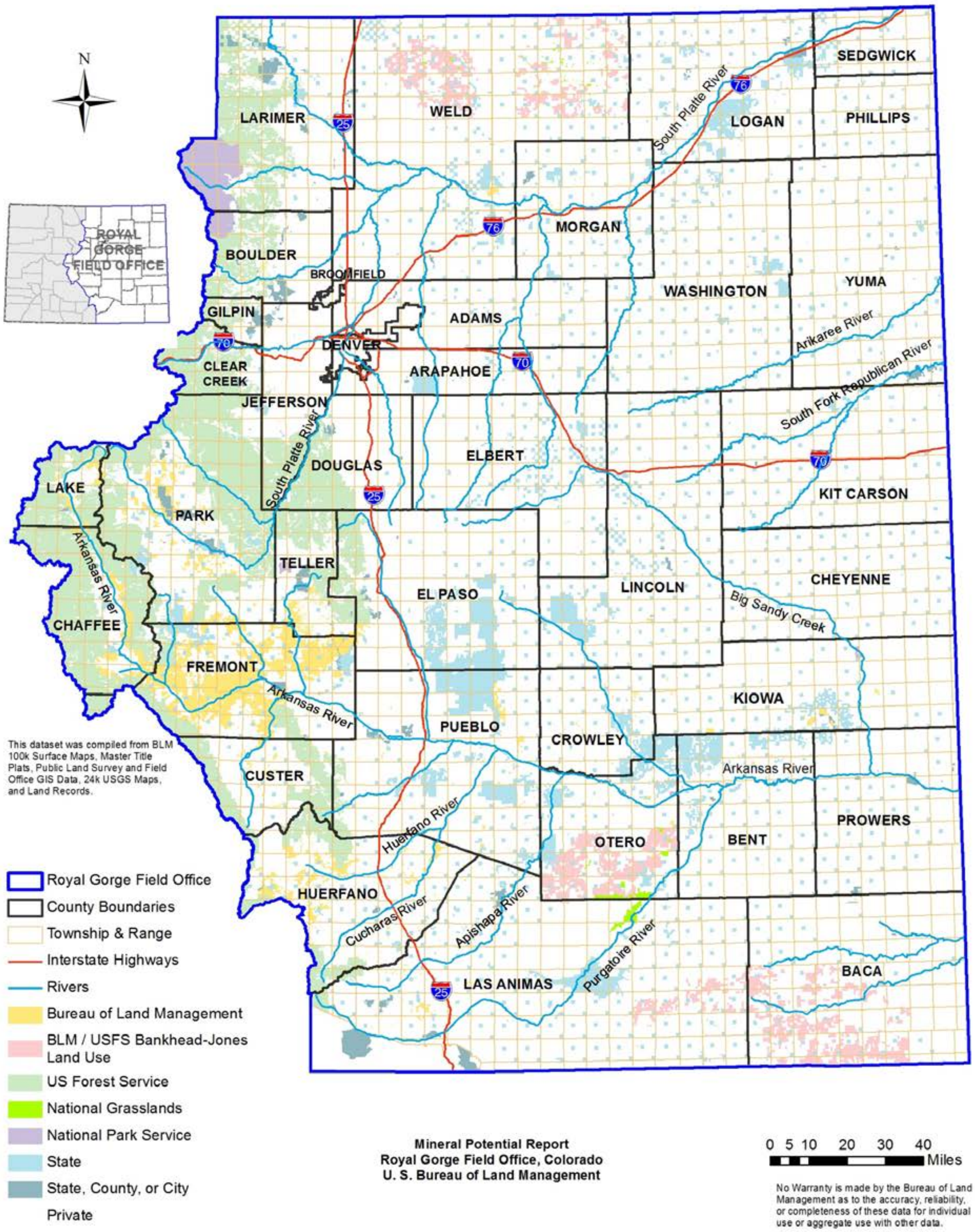


Figure 1-2. Land status—surface lands.

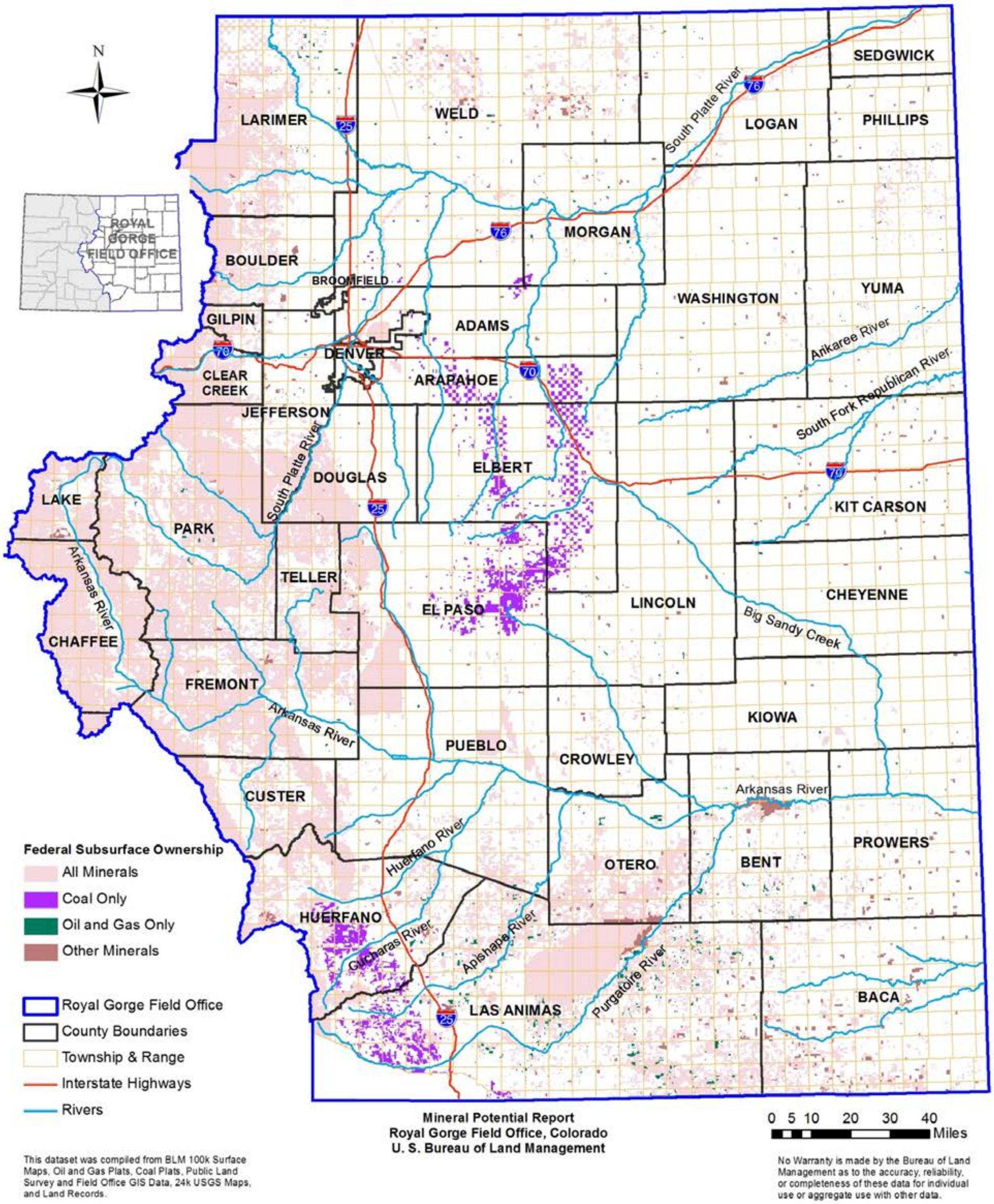


Figure 1-3. Land status—subsurface minerals.

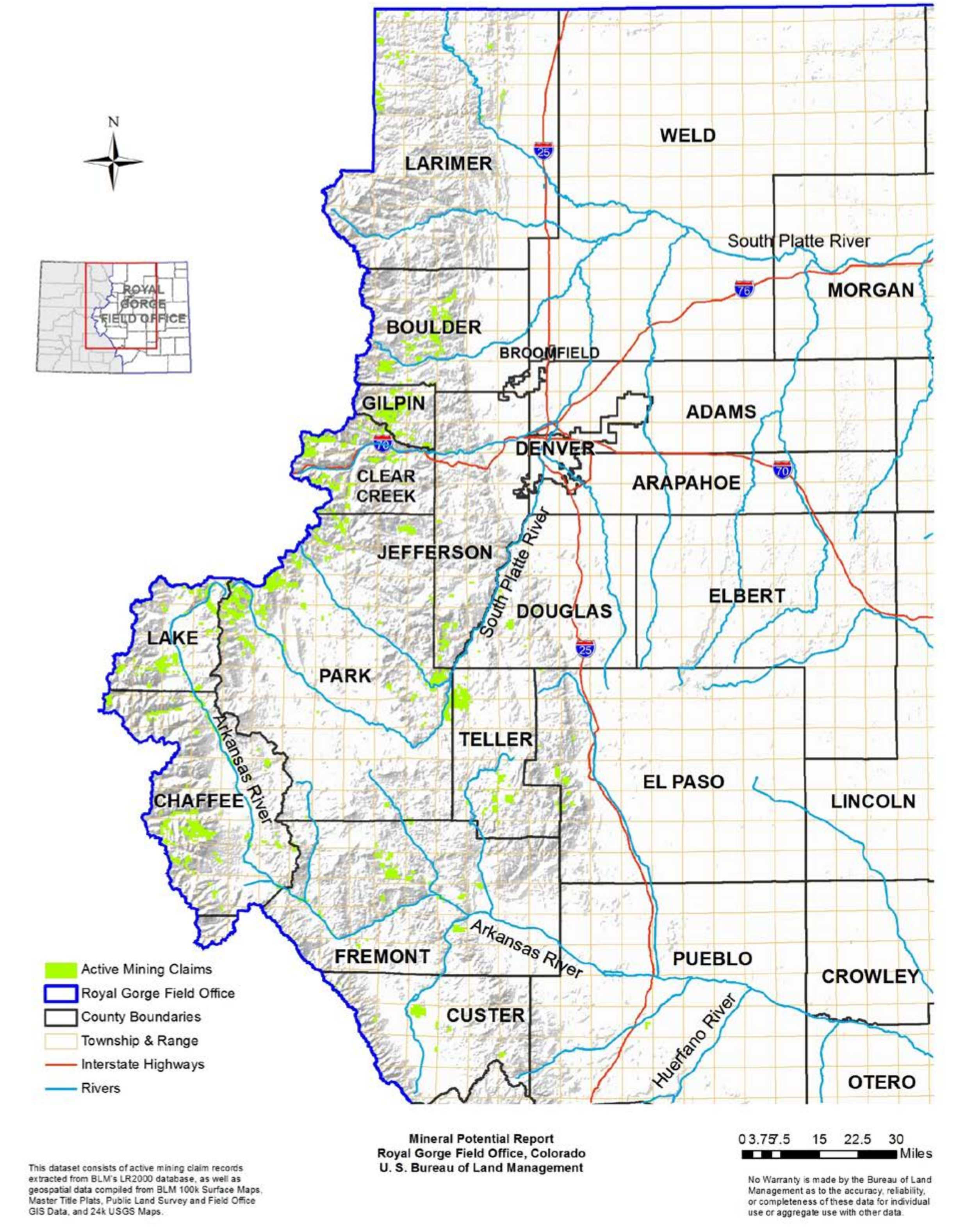


Figure 1-4. Active mining claims.

2. DESCRIPTION OF GEOLOGY

This section summarizes the regional geology and geological setting for the vast RGFO management area and includes detailed descriptions of the physiography, historical geology, structural geology, and rock units, along with a general discussion of geophysics/geochemistry. Relevant figures and maps are embedded in this section, and literature references can be found at the end of this MPR in section 6.0.

2.1 Physiography

The physiography or geomorphology of the RGFO is incredibly diverse.

Figure 2-1 displays the physiographic divisions, provinces and sections as defined in the enduring study by Fenneman (1946). This classification scheme was based not only on topography, but also on the underlying geology that in part controls the topography.

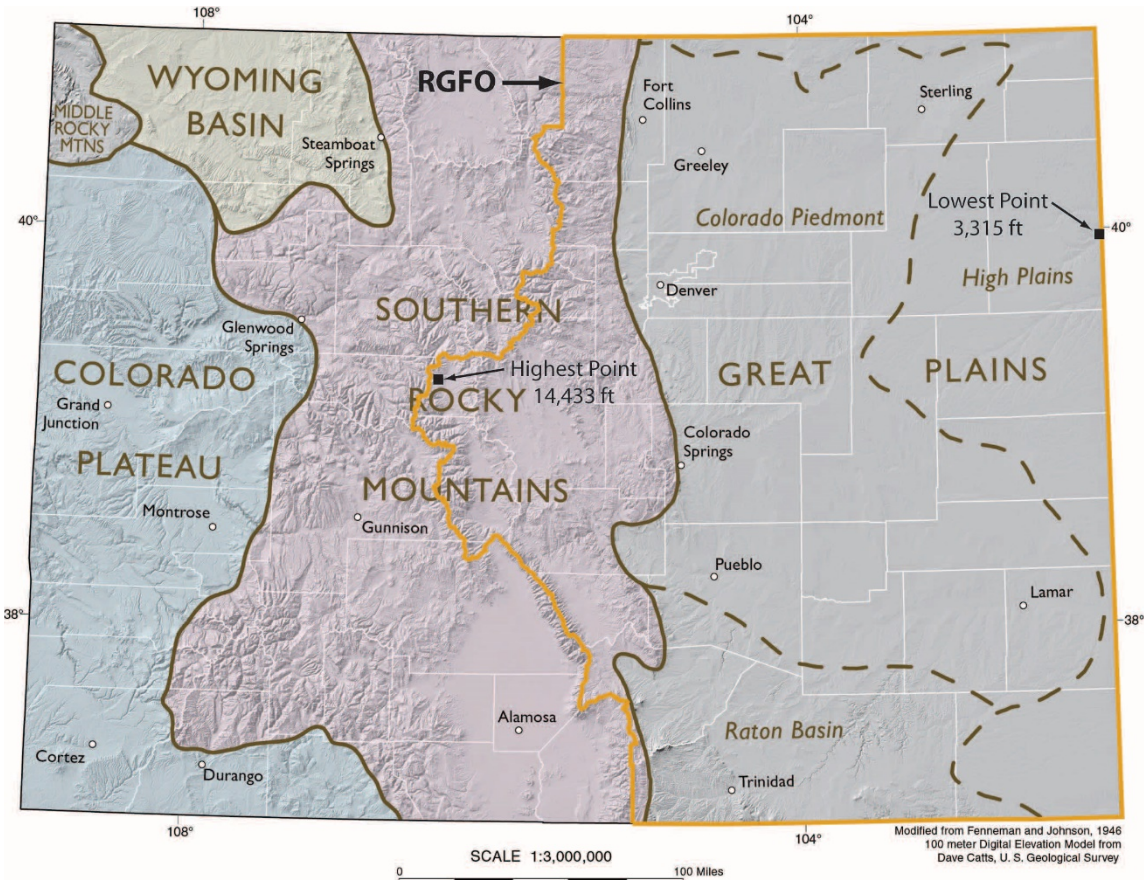


Figure 2-1. Physiographic provinces of Colorado (modified from Cappa and Wallace, 2007).

Two of Fenneman's major physiographic divisions are within the RGFO: the Rocky Mountain System and the Interior Plains. The mountainous western part of the RGFO lies within the Southern Rocky Mountains Province of the Rocky Mountain System, and the eastern part of the RGFO is in the Great Plains Province of the Interior Plains. Fenneman further subdivided the Great Plains Province into the Colorado Piedmont, the High Plains to the east and north, and the Raton Section to the south. The High Plains coincide with areas underlain by the Ogallala Formation, whereas in the Colorado Piedmont and Raton Section, river incision has cut downward through the Ogallala and exposed underlying older geologic formations.

The RGFO includes the lowest and highest points in Colorado (see Figure 2-1), and all the varied terrain in between. Major rivers such as the Arkansas, South Platte, North Platte, and Laramie Rivers have their headwaters high in the Southern Rocky Mountains Province in the western part of the RGFO. Large tributaries to these major rivers include the Purgatoire, Cucharas, Huerfano, Big Thompson, and Cache la Poudre Rivers; also with headwaters in the Southern Rocky Mountains Province (see Figure 1-1 for locations). Other smaller, but still important, rivers like the Arikaree, Smoky Hill, and North and South Forks of the Republican River have headwaters within the High Plains Section of the Great Plains Province. The lowest point in Colorado is where the Arikaree River exits Colorado and flows east into Kansas at an elevation of 3,315 feet.

Some of the few streams that flow into Colorado are found within the RGFO, including Crow Creek and its tributaries such as Porter Draw, Bull Canyon, and Little Simpson Creek. Crow Creek originates in the Laramie Mountains in Wyoming and flows east and southeast across the High Plains until just south of the Colorado-Wyoming border. From there to its confluence with the South Platte River downstream of the City of Greeley, the creek flows southward across part of the Colorado Piedmont.

All or parts of eight major mountain ranges lie within the RGFO. They include the highest point in Colorado (Mount Elbert at 14,433 feet) and many of the highest points in the contiguous United States. All or parts of the Culebra Range, Sangre de Cristo Mountains, Wet Mountains, Sawatch Range, Mosquito Range, Front Range, Mummy Range, and Laramie Mountains are found within the RGFO.

The Front Range is locally subdivided into several small sub-ranges like the Tarryall Mountains, Kenosha Mountains, Platte River Mountains, Rampart Range, Puma Hills, and Mummy Range. The Sangre de Cristo Range is also subdivided: the section from Poncha Pass to La Veta Pass is called the Northern Sangre de Cristo Range, the section from La Veta Pass to the New Mexico State line is the Culebra Range, and south of the State line it is called the Taos Range. Similarly, a subset of the Sawatch Range is known as the Collegiate Peaks or Collegiate Range.

South Park, the Upper Arkansas Valley, Wet Mountains Valley, and Laramie River Valley are large, high altitude, intermontane valleys within the RGFO. The RGFO also includes several tablelands or plateaus. Raton Mesa and Mesa de Maya are in the High Plains in the southern part of the RGFO; these prominent mesas are capped by young lava flows. Peetz Table is a subtle tableland in the High Plains near the northeastern corner of the RGFO.

One of the more interesting streams in the RGFO from a physiographic perspective is Lost Creek, located between the Tarryall and Kenosha Mountains on the northeastern side of South Park. Lost Creek has carved a deep, steep-walled canyon into granitic rocks and the rocks have locally failed, creating large deposits of rockfall debris that bury the creek in several places. The largest deposit of rockfall debris is over 150-feet thick, and the creek is buried by debris for a distance of nearly one-half mile. When the creek flows out of the downstream end of this debris pile, the creek has a new name: Goose Creek.

2.2 Historical Geology

2.2.1 Introduction

Geologic time is classified in various ways by different organizations. For this MPR, the CGS geologic time chart is used (Figure 2-2). Geologic time is divided by the CGS into two major eons, the Precambrian, and the Phanerozoic. The vast majority of geologic time, from when the earth's crust began to form (estimated to be around 4.5 billion years ago) to about 542 million years ago, is included in the Precambrian Eon. Apparently, carbon-based life forms evolved very slowly during the Precambrian, starting with bacteria around 3.8 to 3.5 billion years ago. Stromatolites thrived during the Precambrian, and by about 600 million years ago, complex multicelled life forms called the Ediacaran biota appear in the fossil record. The second and more recent eon is called the Phanerozoic, which is subdivided into three Eras: Paleozoic Era (~542 to 251 million years ago), Mesozoic Era (~251 to 65 million years ago), and Cenozoic Era (~65 million years ago to present). The Paleozoic Era comprises seven periods. From oldest to youngest, they are the Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian Periods.

By about 540 to 530 million years ago, very diverse and in some cases modern-like fauna rather abruptly appeared during the Cambrian explosion of life. Fishes, arthropods, amphibians, and reptiles all evolved during the Paleozoic. Life transitioned onto land during the Paleozoic, and by the Pennsylvanian Period, vast forests of primitive plants covered much of the terrestrial landscape. Some of these plants were preserved in anaerobic environments and eventually transformed to coal when buried in the subsurface.

The Paleozoic Era ended and the Mesozoic Era began with what may be the largest mass extinction in earth's history (Permian-Triassic extinction event). In addition to the Triassic Period, the Mesozoic includes the Jurassic and Cretaceous Periods. The Mesozoic is commonly referred to as the Age of Reptiles, because reptiles, especially dinosaurs, were the dominant terrestrial and marine vertebrates of the time. Besides starting with a mass extinction event, the Mesozoic also ended with a mass extinction, the Cretaceous-Paleogene extinction event.

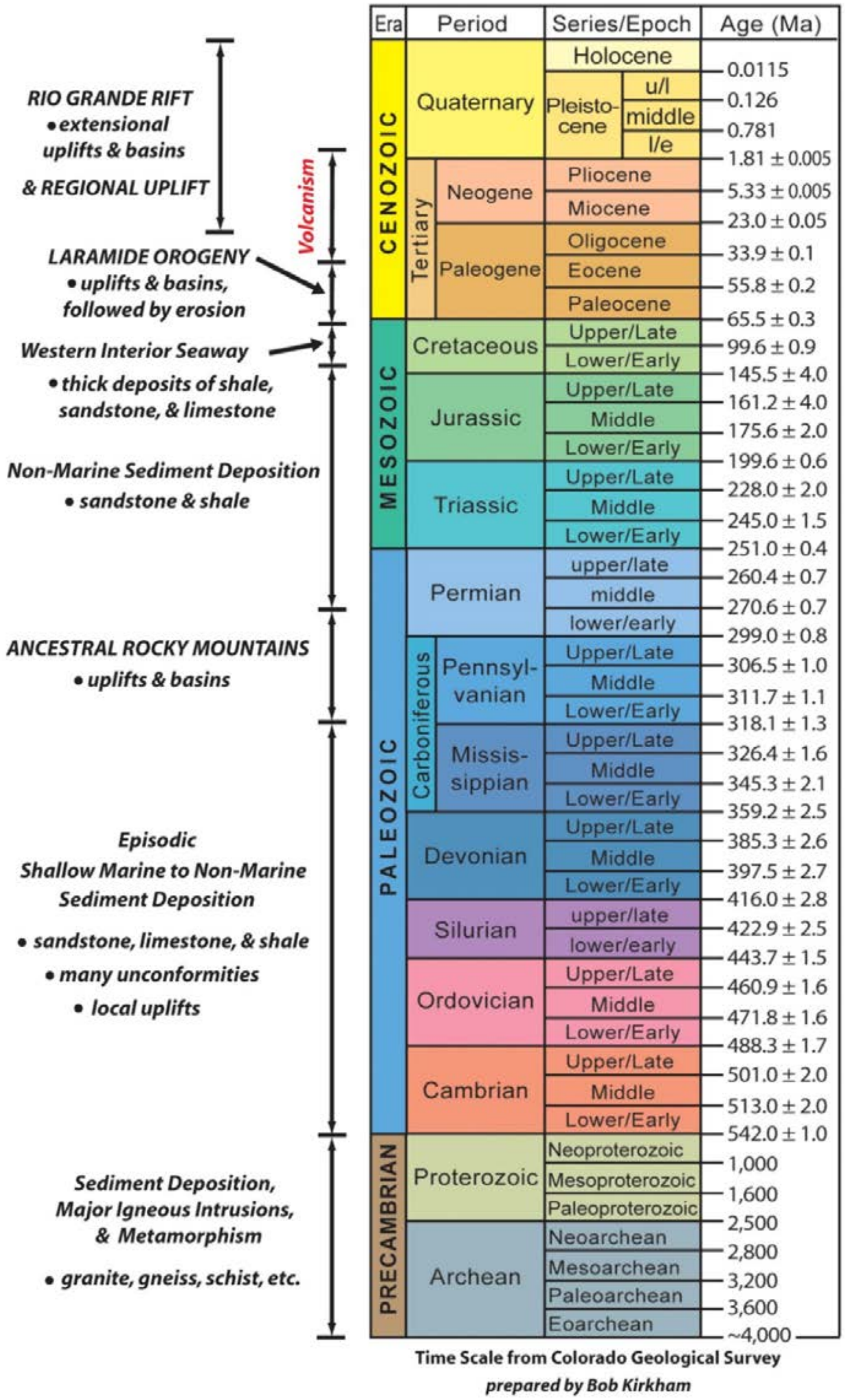


Figure 2-2. Geologic time chart by CGS. Major geologic events in the RGFO are listed on left side of the figure.

The Cenozoic Era is the third and youngest division of the Phanerozoic. It is often called the Age of Mammals, because mammals became abundant and greatly diversified after the Cretaceous-Paleogene extinction event, which marked the beginning of the Cenozoic. The Cenozoic is divided into the Tertiary and Quaternary Period, with the latter including the Pleistocene ice ages and the Holocene, the current interglacial period in which we live.

2.2.2 Precambrian Era

Even though the Precambrian comprises about 88 percent of geologic time, little is known about the geology of much of Precambrian time in the RGFO because the oldest known rocks in the area extend only to the Late Paleoproterozoic Era. Precambrian time is divided into the Archean (older) Eon and Proterozoic Eon. Only Proterozoic rocks are known to exist in the RGFO management region. Archean rocks crop out only in the northwestern corner of Colorado. Although Colorado contains some of the best and most widespread exposures of Proterozoic rocks in the United States, the extent of the exposed ancient rock is still relatively limited (Figure 2-3), which further complicates our understanding of Precambrian history.

The Precambrian continental crust underlies the entire RGFO region and forms what geologists call “basement rock” or simply “the basement.” It was assembled during the Paleoproterozoic to Mesoproterozoic eras. During this time, a series of continental-scale geologic interactions occurred along the margin of the ancient North American continent, which was called *Laurentia*. Laurentia was composed of Archean rocks that were accreted during a series of very ancient tectonic events.

In one popular model (e.g., Gonzales and Van Schmus, 2007; Whitmeyer and Karlstrom, 2007), the margin of Laurentia was situated approximately along the present-day Colorado-Wyoming border, with Laurentia lying to the north. During the Late Paleoproterozoic Era, large areas of new continental crust formed in volcanic-arc subduction zones along the margin of Laurentia. This new crust collided with and was added or sutured to Laurentia during at least one regional tectonic event. The resulting complex geology from this process is illustrated in Figure 2-4.

In another recent hypothesis (Hill and Bickford, 2001; Bickford and Hill, 2006), the margin of Laurentia is placed in central Colorado. The margin was affected by major rifting, magmatism, and sedimentation between during the Late Paleoproterozoic Era. A major difference with this model is that the Precambrian crust beneath the RGFO region was created during modification of Laurentia’s margin by recycling and alteration of existing crust during later tectonic and magmatic events, not by accretion or suturing of new volcanic-arc complexes.

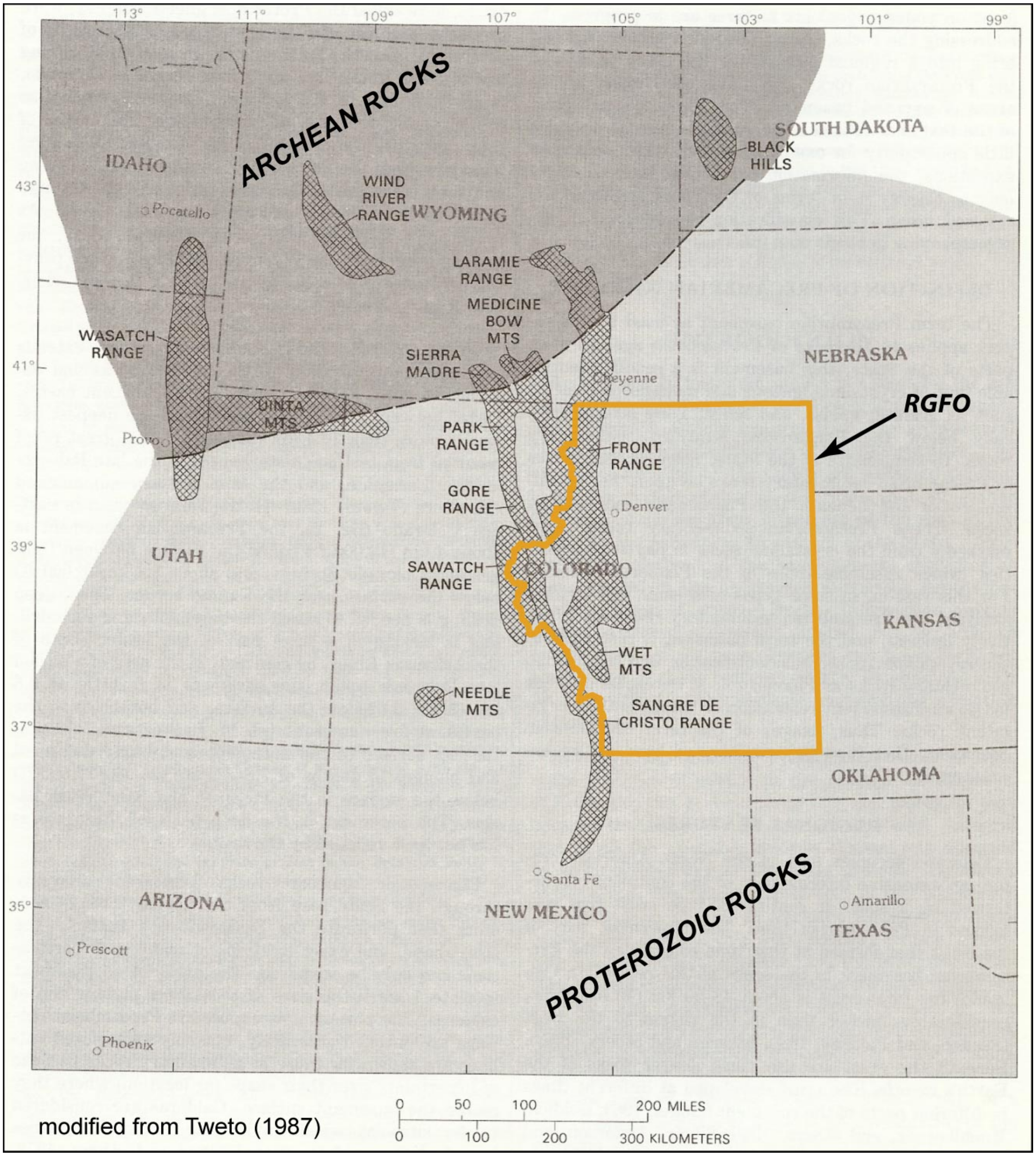


Figure 2-3. Map of Proterozoic and Archean basement rocks in and near Colorado (from Tweto, 1987). Cross-hachured areas denote areas of Precambrian outcrop, and light-shaded areas are underlain by Proterozoic rocks. Archean rocks (dark shading) are found only in the northwestern corner of Colorado.

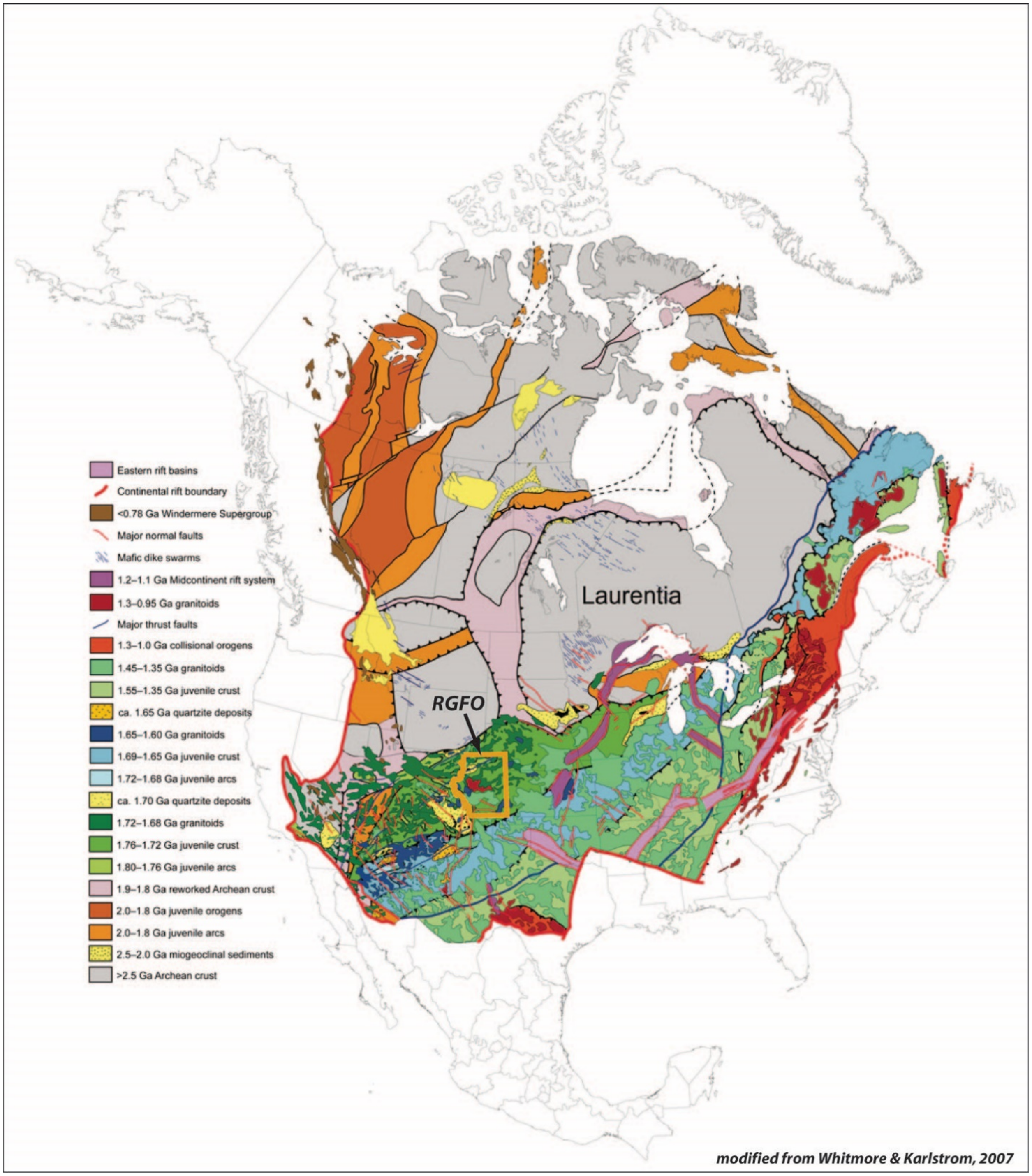


Figure 2-4. Regional Archean through Neoproterozoic basement features of North America (Laurentia) and the location of the RGFO within this complex geologic setting.

Major granitic igneous intrusions during that time metamorphosed the older rocks that they intruded (Tweto, 1977, 1980a). Tweto (1987) grouped these intrusions into the Routt Plutonic Suite, which is typified by the Boulder Creek Granite or Granodiorite. Other major granitic intrusions were subsequently emplaced during the Mesoproterozoic Era (Berthoud Plutonic Suite) and the Neoproterozoic Era (Pikes Peak Plutonic Suite). They also metamorphosed the rocks they intruded (Tweto, 1987). At least two of the more that 100 kimberlite diatremes in the Colorado-Wyoming kimberlite province that were emplaced during the Neoproterozoic are within the RGFO management area (Lester et al., 2001). Knowledge of Precambrian history is especially poor in areas where these rocks are buried beneath younger rocks, and they are concealed across much of the RGFO region (Figure 2-3). In these areas, only the occasional, widely spaced, deep drill hole provides hints of the Precambrian rocks and their history. A thorough summary of Precambrian rocks in Colorado is found in Tweto (1987).

2.2.3 The Great Unconformity

A major period of erosion marked the latter part of the Precambrian and the beginning of the Paleozoic Era. The Precambrian mountains were flattened by erosion, resulting in a very gently rolling landscape. Paleozoic sediments were deposited on the erosional surface or unconformity. The Great Unconformity is so named because over 1 billion years of time are missing worldwide from the geologic record, including areas within the RGFO region.

2.2.4 Lower and Middle Paleozoic

During the early and middle parts of the Paleozoic Era, the RGFO region was episodically covered by shallow seas. At other times, the land was elevated above sea level and subject to erosion. Little is known about Early and Middle Cambrian time in the RGFO region, because rocks of this time period are not known to exist in the RGFO region. In the traditional interpretation of Cambrian and Ordovician stratigraphy (e.g., Lochman-Balk, 1970), the northern and southern parts of the RGFO region were broad uplifts, with the Souixia Uplift in the north and the Sierra Grande Uplift in the southern part of the RGFO region. Between these uplifts was the Colorado Sag, where sediments were episodically deposited. Recent work by Myrow et al. (2003) raises questions about the details of the traditional structural and stratigraphic interpretations.

When the episodic seas covered the RGFO region, sandstone, limestone, and mud were deposited. Sediment was also deposited in fluvial plains between the shoreline and uplifts, but when the land was elevated above sea level, erosion stripped off part or all of the previously deposited sediment, creating large gaps of time or unconformities in the sedimentary record. Ross and Tweto (1980) stated that the preserved Lower Paleozoic rocks represent only about 30 to 40 million years of time, whereas as much as 160 million years of time is missing at the unconformities. Localized mafic and ultramafic intrusions also were emplaced in the RGFO region during the Cambrian. Three of these were in the Wet Mountains: the McClure Mountain, Gem Park, and Democrat Creek complexes (Armbrustmacher, 1984).

Silurian formations are not known to exist in the RGFO region, although blocks of Silurian limestone have been found in diatremes in or near the northwestern corner of the RGFO region (Chronic et al., 1969). This indicates that Silurian formations were once present in the area, but were eroded prior to Late Devonian time. The diatremes, which are breccia-filled volcanic pipes formed by a gaseous explosion deep in the earth, were intruded through the earth's crust late during the Silurian, and as they passed through the crust, they plucked Silurian and other rocks from the diatremes' walls and incorporated them into the volcanic pipes.

No large uplifts are thought to have existed during early and middle Paleozoic time, but evidence of active faulting has been documented during this time interval. For example, in the Minturn quadrangle west of the RGFO region, Kirkham et al. (2012b) mapped and described evidence of adjacent fault-bounded blocks with different early and middle Paleozoic stratigraphic sequences preserved on them. The blocks that have missing stratigraphic sections were episodically uplifted by the faults, and rock layers overlying the blocks were stripped off by erosion prior to deposition of other early or middle Paleozoic strata.

Mississippian time was a period of intermittent, shallow-shelf, carbonate sedimentation. Limestone and dolomite deposited during the Mississippian may have once blanketed the entire RGFO region. However, stratigraphic evidence contained in the Mississippian rocks suggests that local uplifts were not always submerged by the intermittent Mississippian marine incursions (Ross and Tweto, 1980). These uplifts included the western end of a major, northeast-trending structural high in the northern part of the RGFO region called the Transcontinental Arch. Another large, north-trending, low-relief area is thought to have approximately coincided with the modern Front Range and Wet Mountains (De Voto, 1980a). Stratigraphic evidence also suggests that several faults in central Colorado along the western edge of the RGFO region also were active during the Mississippian and may have affected depositional and erosional patterns (De Voto, 1980a).

The exact original extent of the lower and middle Paleozoic rocks is uncertain. One complicating factor is the deep erosion that took place on the uplifts that rose during subsequent periods of mountain building when the Pennsylvanian-Permian Ancestral Rocky Mountains formed, and also during subsequent periods of mountain building associated with the Laramide Orogeny and the Rio Grande Rift. Another factor that complicates our understanding of lower and middle Paleozoic rocks is that in some areas, especially beneath the Great Plains, part of the RGFO region, these rocks are buried deep in the subsurface. Knowledge of these rocks is almost exclusively based upon information from the few very deep oil test wells drilled in these areas.

Another major episode of erosion beveled the landscape during the latter part of the Mississippian. Deep dissolution of the Mississippian carbonate rocks during this period of erosion resulted in the development of an extensive karst system that included sinkholes, caves, carbonate-breccia rubble, and locally thick regolith (a mantle of fragmental and unconsolidated rock material from residual weathering and transported rock debris).

2.2.5 Upper Paleozoic and Ancestral Rocky Mountains

The Pennsylvanian Period was a time of widespread mountain building or tectonism in Colorado. The older, lower, and middle Paleozoic rocks as well as Precambrian rock were eroded from the uplifts; non-marine sediment was deposited in large alluvial fans and alluvial plains on the flanks of the uplifts; and marine sediment was deposited in deep basins that formed between or near the uplifts. Sea level changes during the Pennsylvanian affected sedimentary deposition, as the shoreline of the sea repeatedly migrated through parts of the RGFO region and produced cyclic sequences equivalent to the cyclothems found in the midcontinent (Houck, 1997).

Mallory (1972a) presented a Pennsylvanian paleogeographic map for the region. Figure 2-5 shows a more recent and simplified paleogeographic map of Colorado as envisioned by Cappa and Wallace (2007) based on a figure in Lindsey et al. (1986a). A more modernistic regional view of the paleogeography of the western United States at about 300 million years ago at the end of the Pennsylvanian is shown in Figure 2-6. The Ancestral Rocky Mountains formed during the Pennsylvanian Period. Many of these mountain ranges were located in Texas and Oklahoma, but two major uplifted mountain ranges also formed in the RGFO region during the Pennsylvanian Period. A part of the Ancestral Front Range Uplift rose up in the northwestern part of the RGFO region, and the Apishapa Uplift developed in the southwestern part of the RGFO region (De Voto, 1980b). For many years, the Ancestral Rocky Mountains were thought to be a result of extensional block faulting (e.g., Tweto, 1980c; De Voto, 1980b). More recent work suggests compressional tectonics as the force that formed the mountains and basins during the Pennsylvanian (e.g., Hoy and Ridgeway, 2002), but many questions remain regarding the style of deformation during the late Paleozoic.

Nomenclature of the late Paleozoic uplifts has varied over time. Mallory (1958) proposed the name *Frontrangia* for the Ancestral Front Range Uplift; however, authors of other papers in the same book preferred simply Front Range Uplift. Kluth (1986) preferred to call it Frontrange. Recently, Nesse (2007) pointed out that that late Paleozoic uplifts were not coincident with the modern uplifts after which they are named, and suggested that new names be used for the late Paleozoic uplifts. Rather than calling the ancient mountains the Ancestral Rocky Mountains, he preferred Anasazi Uplifts; instead of Ancestral Front Range, he proposed Arapahoe Uplift. For this report, we continue to use the currently more widely accepted Ancestral Rocky Mountain nomenclature.

Figure 2-5. Paleogeographic map of the Pennsylvanian Period showing uplifts (salmon color) and areas of sediment deposition (white areas) (modified from Cappa and Wallace, 2007; based on Lindsey et al., 1986a).

As much as several thousand feet of non-marine and marine sediment accumulated on the piedmonts and in the basins adjacent to or between the Ancestral Rocky Mountains. Very thick sequences of marine shale, evaporite, and carbonate rocks and non-marine clastic rocks were deposited in the Central Colorado Trough in the southwestern part of the RGFO region; locally they can be as much as several thousand feet thick (Mallory, 1972b; De Voto, 1980b). A near continuous belt of coarse-grained arkosic sediments was deposited along the eastern side of the Ancestral Front Range. This material grades into chiefly carbonate rocks farther east in the RGFO region.

Erosion of the uplifted Ancestral Rocky Mountains and deposition of sediment in the basins continued into the Permian Period. Deposition of marine sediment in the Central Colorado Trough in the southwestern part of the RGFO region ended before the end of the Pennsylvanian Period (Figure 2-6). It was replaced by deposition of continental sediment, chiefly in alluvial fan

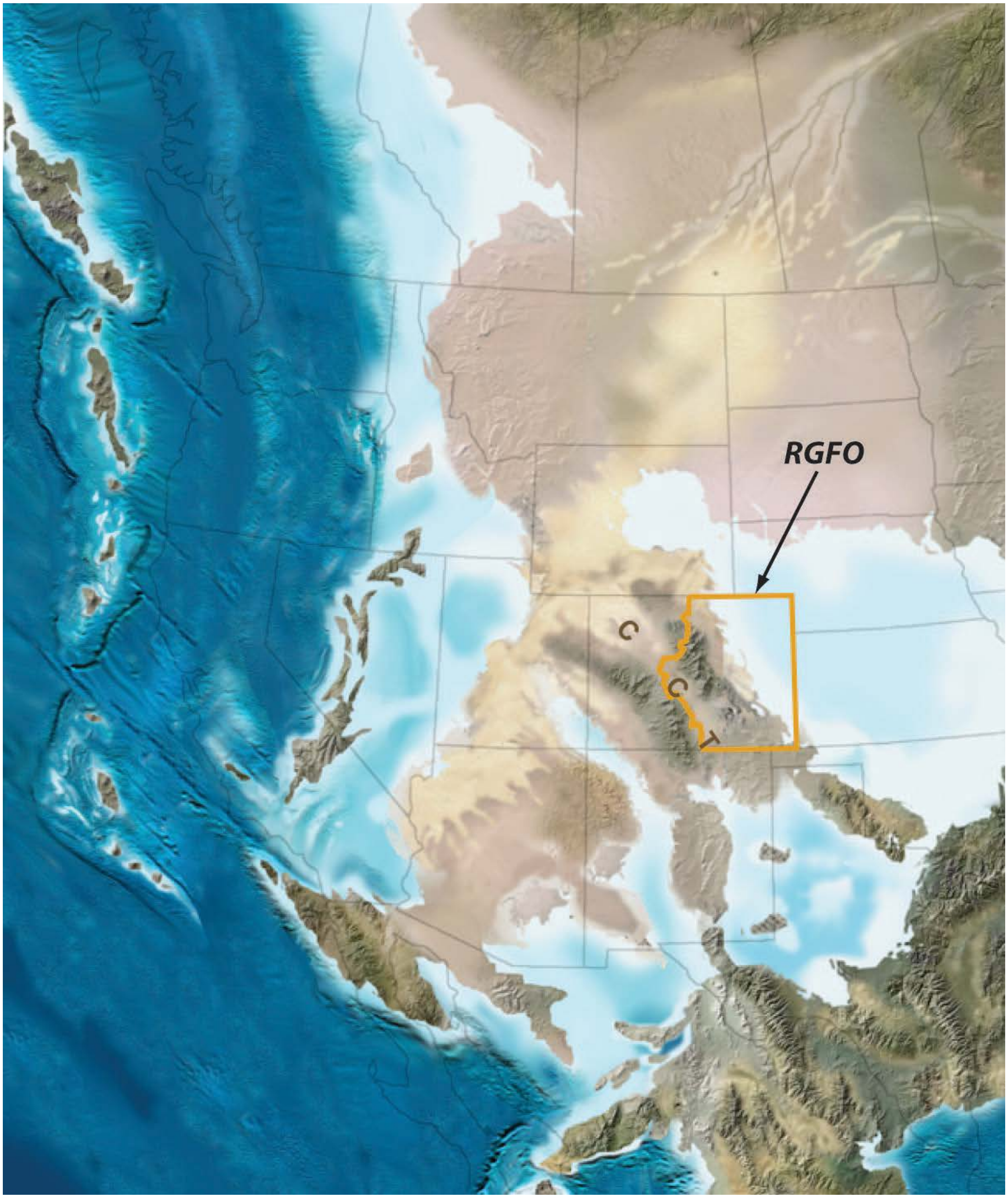


Figure 2-6. Paleogeographic map of the western United States about 300 million years ago during the Pennsylvanian Period (modified from image by Ron Blakey, available at http://cpgeosystems.com/images/WNA_300_PPvir-sm.jpg). CCT denotes general location of the Central Colorado Trough.

and alluvial plain environments. The mountains were eventually eroded away, and continental sediment locally buried the uplifts. By Middle Permian time, sediment was deposited in lowland, tidal flat, and evaporite environments; by Late Permian time, the entire State was apparently emergent above sea level and an area of non-deposition (Maughan, 1980). At times, widespread eolian sediment blanketed parts of the RGFO region during the Permian.

The Paleozoic Era ended with what is thought to be the largest mass extinction event during the earth's history, the Permian-Triassic extinction event. About 90 to 95 percent of marine species and about 70 percent of land species went extinct at this time. The cause of the extinction event is uncertain. Major environmental stresses associated with massive extrusion of basaltic lavas in Siberia, ocean venting of hydrogen sulfide, and the impact of a huge meteorite have been suggested as possible causes of the extinction.

2.2.6 Triassic and Jurassic

During the Triassic and Jurassic Periods, the RGFO region was elevated above sea level. Continental sediment probably was episodically deposited in the RGFO region during this time, but much of it was removed during several major periods of erosion (Maughan, 1980; Berman et al., 1980). Recurrent uplift of the ancient basement structures such as the Apishapa Uplift, Transcontinental Arch and perhaps the Front Range Uplift, influenced depositional patterns during this time period.

The Triassic Period ended with another mass extinction, although it was not as severe as the Permian-Triassic extinction event. A regional unconformity was eroded across the (top of the) Jurassic rocks prior to deposition of overlying Cretaceous rocks. Although the strata within the Jurassic beds below the unconformity and the Cretaceous beds above it are essentially parallel, about 20 to 25 million years of time apparently are missing at the unconformity (Berman et al., 1980). This type of unconformity is more specifically termed a disconformity.

2.2.7 Cretaceous and Western Interior Seaway

During the early part of the Cretaceous Period, a major incursion of the sea spread across the RGFO region. It is often called the Western Interior Seaway, but it has also been known as the Cretaceous Seaway, the Niobraran Sea, and the North American Inland Sea.

The lowering of the earth's crust in the interior of the North American continent, which allowed the sea to encroach upon it, is attributed to plate tectonics. During the Cretaceous, the Farallon tectonic plate began to subduct under the North American Plate. Because the subducted Farallon plate consisted of younger and more buoyant lithosphere, the angle of the subduction zone is believed to have gradually decreased to a shallower angle, resulting in what is known as a "flat slab." The shallow subduction of the Farallon plate exerted traction on the base of the North American plate, pulling it downward. This topographic depression was filled by the high eustatic sea levels that existed during the Cretaceous. Waters from the Arctic Ocean in the north and from the Gulf of Mexico in the south flowed into the depression and eventually met, flooding the central lowlands and forming the Western Interior Seaway.

As the seas transgressed (advanced) and regressed (retreated) across the continental interior, thick sequences of sediment were deposited. The sedimentary rocks deposited in and adjacent to the Western Interior Seaway provide a nearly continuous record of geologic time during much of the Cretaceous. Few unconformities exist within the Cretaceous strata. Fossils are common in much of the Cretaceous strata. The relatively rapid evolution of some of the marine fossils, especially ammonites (Cobban, 1993), allows for precise biostratigraphic correlation of strata deposited across the seaway. Thin beds of altered volcanic ash (bentonite) can be radiometrically age dated using techniques such as 40Ar/39Ar. Because each ash was erupted at essentially an instant of geologic time (i.e., a few days) and rather rapidly settled to the bottom of the ocean, and because they were widely deposited across large parts of the Western Interior Seaway, they serve as excellent time lines for chronostratigraphic purposes.

Organic-rich mud deposited on the floor of the Western Interior Seaway is the source of much of the oil and gas in the RGFO region. Contrary to popular belief, the dinosaurs did not provide the organic materials for the oil and gas; microorganisms like plankton and algae were the primary sources of the organics that would become thermogenic oil and gas. Thick deposits of peat that accumulated in the coastal swamps adjacent to the advancing and retreating shorelines eventually became coal after burial by younger sediment.

A series of paleogeographic maps by Ron Blakey (http://cpgeosystems.com/paleomaps.html) depicts the transgression and regression of the Western Interior Seaway onto the interior of the continent (Figure 2-7). About 130 million years ago (Figure 2-7A) the Arctic Ocean was encroaching onto the continental interior from the north and the Gulf of Mexico from the south. About 100 million years ago (Figure 2-7B) the southern end of the Arctic Ocean was at or near the western and northern edges of the RGFO region. About 85 million years ago (Figure 2-7C) the entire State of Colorado was submerged. At about 70 million years ago, as the seaway regressed, the shoreline was near the southwestern border of the RGFO region (Figure 2-7D). The shoreline continued to regress until the RGFO region was once again elevated above sea level. The ocean has not returned to the RGFO region since the time of the Western Interior Seaway.

2.2.8 Late Cretaceous to Early Tertiary Laramide Orogeny

Near the end of the Cretaceous, tectonic forces once again caused major deformation affecting the crust in a large part of the western United States, including the RGFO region. Major igneous intrusions and local volcanism accompanied the crust deformation. This period of tectonism and igneous activity is called the Laramide Orogeny (Tweto, 1975; 1980b), and it lasted for about 20 million years. These forces are also thought to be related to subduction on the western side of the North American plate (W. Dickinson 1981; Dickinson and Snyder 1978; Lipman et al., 1971). The Cretaceous-Tertiary extinction event occurred while the Laramide Orogeny was underway.

Mountains were uplifted in the RGFO region during the Laramide Orogeny, mostly by thrust and high-angle reverse faults. As is discussed in the following section on structural geology and tectonics (section 2.3), there is considerable debate whether horizontal compression or vertical forces were responsible for the uplifts. The Laramide uplifts formed in large part in the same areas affected by the late Paleozoic Ancestral Rocky Mountains. The modern mountains in the western part of the RGFO region are chiefly a result of the Laramide Orogeny, although subsequent regional and local tectonism, as well as erosion, greatly modified them locally.

Uplift and igneous activity during the Laramide Orogeny started in southwestern Colorado about 72 to 70 million years ago with the reactivation of the late Paleozoic Uncompahgre-San Luis highland a short distance west of the RGFO region (Tweto, 1980b). Rejuvenation of the late Paleozoic Ancestral Front Range Uplift within the RGFO region began shortly thereafter, about 70 to 65 million years ago. Orogenic activity continued into the early Tertiary, but it ended at different times in different places. The youngest Laramide structures, including the Laramide Front Range, were active through the Paleocene and into the Eocene. The Mesozoic and Paleozoic rocks were stripped off the Laramide uplifts by erosion, exposing their Precambrian cores and subjecting them to erosion. Deep structural basins formed between and adjacent to the uplifts, and thick sequences of synorogenic sediment were eroded from the uplifts and accumulated in the basins. Excellent outcrops of the iridium-rich K-T boundary that marks the Cretaceous-Tertiary boundary are found in the synorogenic rocks of the RGFO region (Pillmore et al., 1999; Barclay and Johnson, 2004; Nichols and Johnson, 2008). Figure 2-8 shows the approximate locations of the Laramide uplifts and basins relative to the RGFO region.

Laramide igneous activity was mostly restricted to the northeast-trending Colorado Mineral Belt (CMB), which extends from southwestern Colorado into the mountainous, west-central part of the RGFO region (Tweto, 1980b; Cunningham et al., 1994). Many of the precious metal deposits in that part of the RGFO region are associated with the Laramide intrusions. At least some of the Laramide intrusions extended to the ground surface and vented to form volcanoes, because clasts of volcanic rocks are often contained in Laramide synorogenic sediments, and lava flows of Laramide age are locally preserved, as at North and South Table Mountains near Golden.

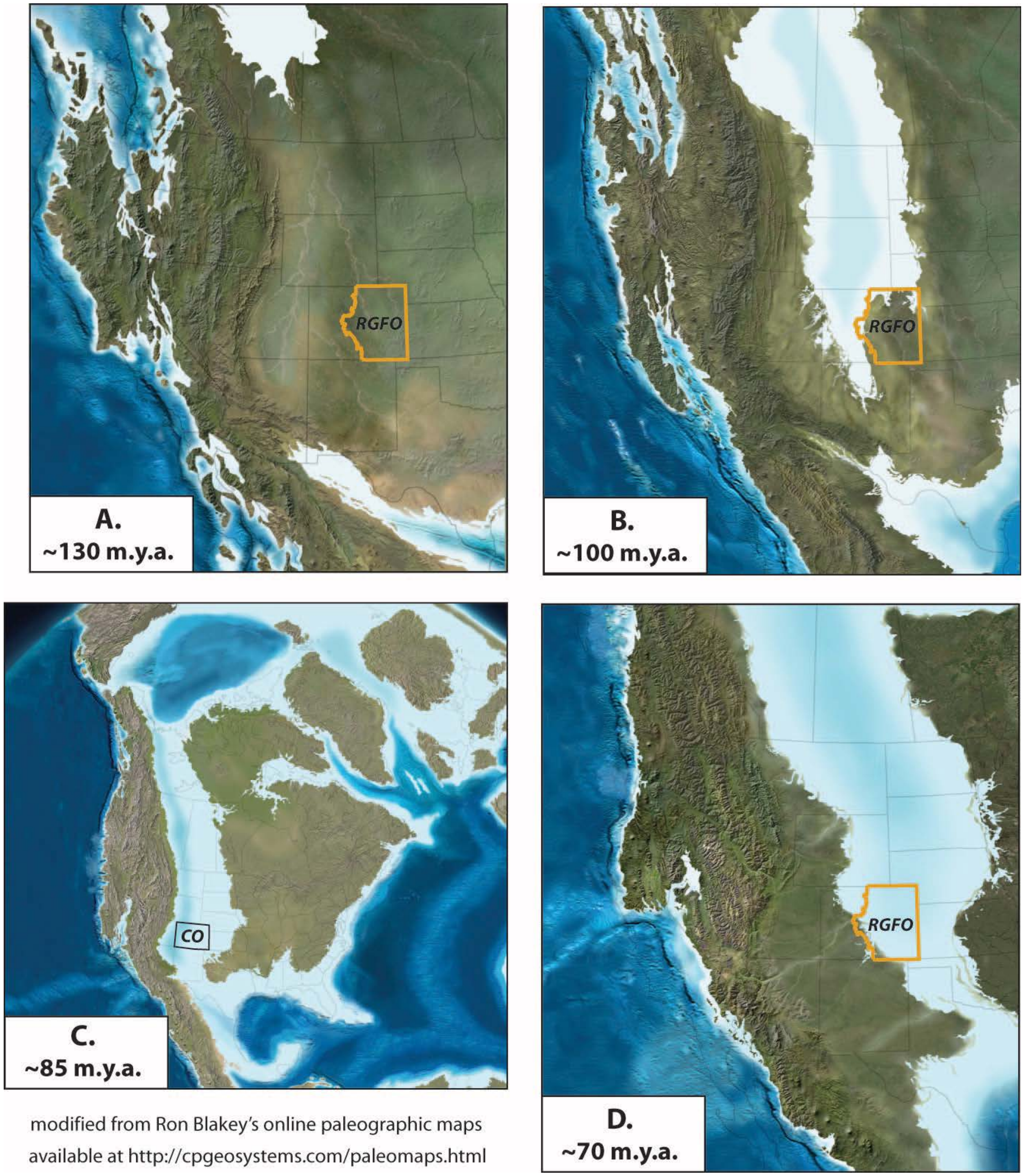


Figure 2-7. Paleogeographic maps showing the transgression and regression of the Western Interior Seaway onto the interior of the North American continent.

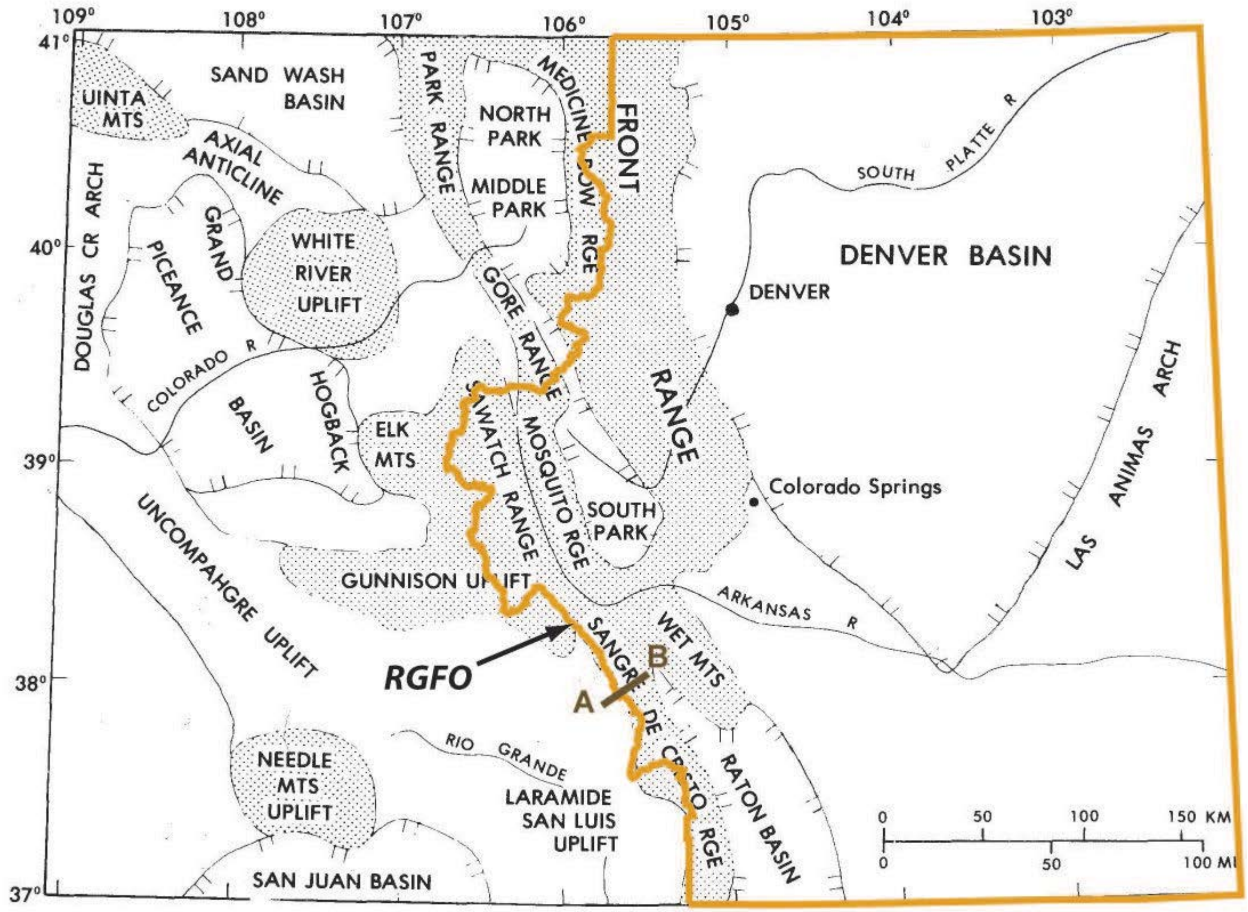


Figure 2-8. Map of approximate locations of Laramide uplifts and basins (modified from Tweto, 1980b). Shaded areas are Laramide uplifts that were topographically prominent. Those that are buried, subsided, or topographically inconspicuous are labeled but not shaded. Outlines of the Laramide basins are denoted by the thin lines with paired couplets of tick marks. See Figure 2-22 for cross section A-B.

Erosion of the Laramide uplifts is thought to have somewhat kept pace with uplift, resulting in low mountains or rolling hills that may never have been very prominent above the adjacent basins (Epis et al., 1980). Scott and Taylor (1986) map the erosion surface and its paleovalleys in parts of the RGFO region. This erosion surface was initially called the late Eocene erosion surface and thought to be a topographic surface of low relief that extended across most of the Southern Rocky Mountains (Epis and Chapin, 1974). Subsequent work indicates that there were multiple periods of widespread erosion that cut surfaces of low topographic relief during not only the late Eocene but also during the Oligocene and Miocene (e.g., Steven, 2002; Steven et al., 1997; Kirkham et al., 2012a).

2.2.9 Middle Tertiary Volcanism

Near the end of the Eocene, starting at about 36 million years ago, a major phase of igneous activity initiated (Steven, 1975). By the time it ended around 25 million years ago, the middle Tertiary volcanic field may have blanketed much of the Southern Rocky Mountains, including the western part of the RGFO region (Figure 2-9). Intermediate composition stratovolcanoes dominated the initial phase of middle Tertiary volcanism, and they continued to be part of it until it ended. Andesitic flows and widespread volcaniclastic lahars were generated by the stratovolcanoes. The volcanism evolved into silicic eruptions of ash-flow tuff and associated rocks from collapsing calderas. This phase of the middle Tertiary volcanism is often referred to as the “ignimbrite flare-up.”

Several of the middle Tertiary volcanoes and calderas were within the RGFO region. Four calderas formed at the location of the modern Sawatch Range, two within the RGFO region (Grizzly Peak and Mount Aetna), and two just outside of it (Bonanza and Marshall Pass) (McIntosh and Chapin, 2004). Remnants of the middle Tertiary lavas, ash-flow tuffs, intrusive

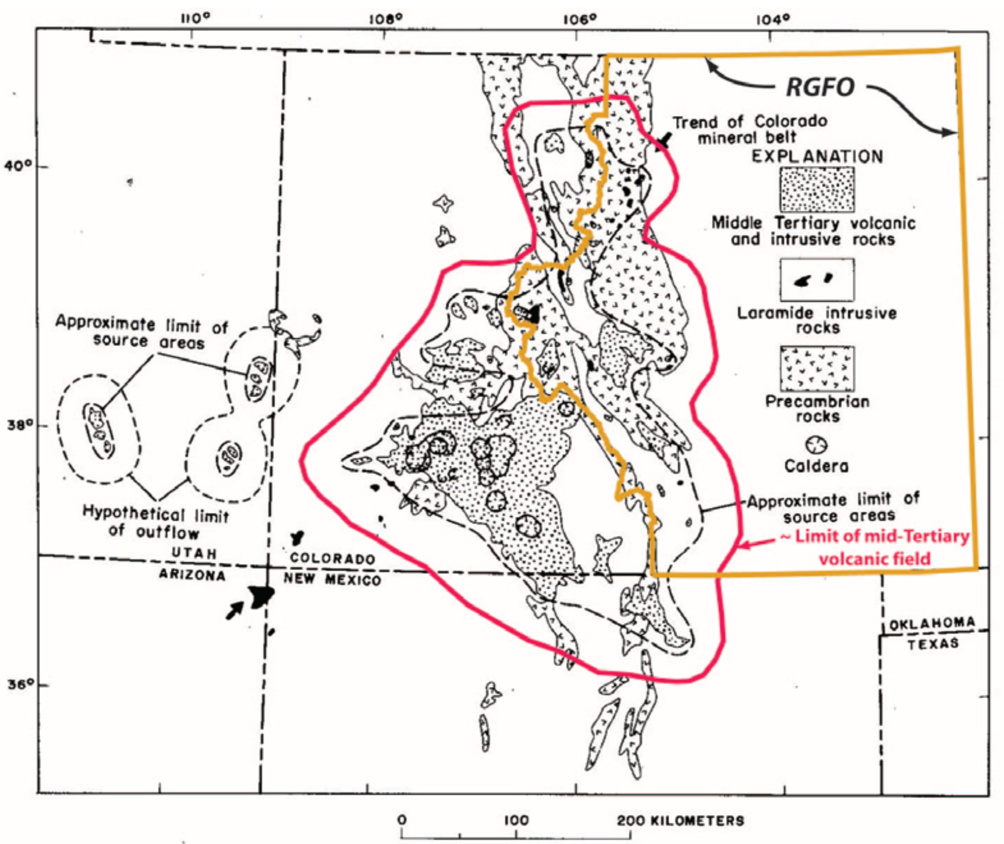


Figure 2-9. Map showing approximate extent of the middle Tertiary volcanic field, locations of preserved middle Tertiary volcanic and intrusive rocks, calderas, and the CMB within the Southern Rocky Mountains (modified from Steven, 1975).

rocks, and volcaniclastic deposits are preserved at many scattered locations across the western part of the RGFO region. The largest remnant is the Thirtynine Mile volcanic field in the southern part of South Park. Other significant remnants of the middle Tertiary volcanic field in the RGFO region are found at Spanish Peaks, in the Wet Mountains near Westcliffe, in the Culebra, northern Sangre de Cristo, Tenmile, and Sawatch Ranges, and at Cripple Creek, Signal Butte, Montezuma, and Empire in the Front Range. Thick deposits of wind-blown volcanic ash from the middle Tertiary volcanoes accumulated in and were preserved in the northeastern part of the RGFO region. Remnants of one of the older middle Tertiary ash-flow tuffs also cap many of the buttes and mesas in the Castle Rock area.

Many of the metallic mineral deposits in the RGFO region are associated with the middle Tertiary volcanic field and its intrusive rocks. The eolian volcanic ash deposits in the northern part of the RGFO region may be the source of the uranium roll-front deposits in underlying sedimentary deposits.

2.2.10 Late Tertiary and Quaternary Tectonism, Volcanism, and Sedimentation

As the middle Tertiary volcanism waned, bi-modal basaltic and rhyolitic volcanism began, starting around 25-27 million years ago. This phase of volcanism was triggered by extensional tectonism, much of it associated with the Rio Grande Rift. The rift is a major north-south-trending tear in the earth’s crust that extends from Mexico and west Texas northward, through New Mexico, and into Colorado. Figure 2-10 depicts the well-known rift basins, including the Upper Arkansas Graben. Modern crustal extension based on permanent GPS stations (Berglund et al., 2012), as well as the distribution of late Cenozoic faults and volcanic activity and historical seismicity, indicate rifting affects a much larger part of the RGFO management area than the extent of the well-known rift basins shown in Figure 2-10.

As the rift gradually pulled apart, normal faults down-dropped the crust within the rift, and sediment and volcanic rocks accumulated in the tectonically lowered basins within the rift. Several of the faults in the RGFO region have undergone movement during the late Cenozoic. Some have experienced thousands of feet of normal displacement during the late Cenozoic, and late Quaternary activity has been documented on several of the faults in the RGFO region (e.g., Kirkham and Rogers, 1981; Widmann et al., 1998). Refer to Morgan et al. (2012) for an online map server with current summary information on the late Tertiary and Quaternary faults in Colorado. Information on Quaternary faults can also be accessed online at the USGS and CGS (2006).

The generally recognized rift basins are shown in Figure 2-10. The Upper Arkansas Valley Graben in the west-central part of the RGFO region is within the rift, as is the San Luis Basin immediately southwest of the RGFO region. The Wet Mountain Valley also contains graben-filling sediment that was deposited during the late Tertiary and is included within the rift or rift system by some (e.g., Tweto, 1975, 1978). Late Tertiary sediment preserved in a few other locations in mountainous parts of the RGFO region potentially may also be related to the rift or be part of the rift system.

Remnants of late Cenozoic volcanism, much of it related to the Rio Grande Rift, is widespread in the southernmost part of the RGFO region. For example, Raton Mesa, Barela Mesa, Mesa de Mayo, Tecolete Mesa, Black Mesa, and Carrizo Mountain are capped by basaltic rift-related flows. Late Tertiary intrusive dikes and sills are found in the Raton Basin (Miggins, 2002). Late Tertiary igneous rocks are also widespread in the Thirtynine Mile volcanic field (Scott et al., 1978) and are locally present elsewhere in the mountainous part of the RGFO region.

An extensive blanket of late Tertiary sediment extends across much of the eastern part of the RGFO region. In ancient paleovalleys, the late Tertiary sediment can be as much as several hundred feet thick (Borman and Meredith, 1983). Scott (1982) shows locations of some of the late Tertiary paleovalleys in the northeastern part of the RGFO region. The late Tertiary sediment in the Great Plains was eroded from the mountains, either as the mountains were uplifted by regional and/or local tectonism (Trimble, 1980; Epis and Chapin, 1974; Eaton, 1975), or perhaps due to climatic factors (Molnar and England, 1990). More recent studies demonstrate that the late Tertiary sediment in the Great Plains has also been tilted by post-depositional forces and that the Rocky Mountains probably rose in elevation by regional uplift during the late Cenozoic (Steven et al., 1997; Leonard, 2002; McMillan et al., 2002, 2006), but questions remain about the role of climate (McMillan et al., 2002).

During the Quaternary, the climate repeatedly cooled during multiple, relatively long periods of glaciation, and then warmed during relatively short, warm, intervening interglacial periods between the ice ages. This part of the Quaternary is referred to as the Pleistocene. Glaciers slowly grew in preferential locations in the mountains during the ice ages and advanced down the valleys, carving U-shaped valleys. As the glaciers melted during the final phases of an ice age, tremendous volumes of glacial melt water flowed down the mountain valleys and out onto the Great Plains, depositing glacial outwash.

The last major glacial advance, called the Pinedale glaciation, began about 30,000 years ago and peaked about 20,000 years ago (Madole et al., 1998). By about 12,000-13,000 years ago, the glaciers had retreated to their cirques and completely melted. The current interglacial stage that we live in is the Holocene Epoch. Minor ice ages or neoglaciations have occurred during the Holocene, but all have ended with another warming trend. Whether or not the current warming period will end with another major ice age poses interesting questions. One such question is whether the modern period of global warming/climate change, which is the subject of much research and is thought by many climatologists to be human-caused, could prevent the next ice age from happening.

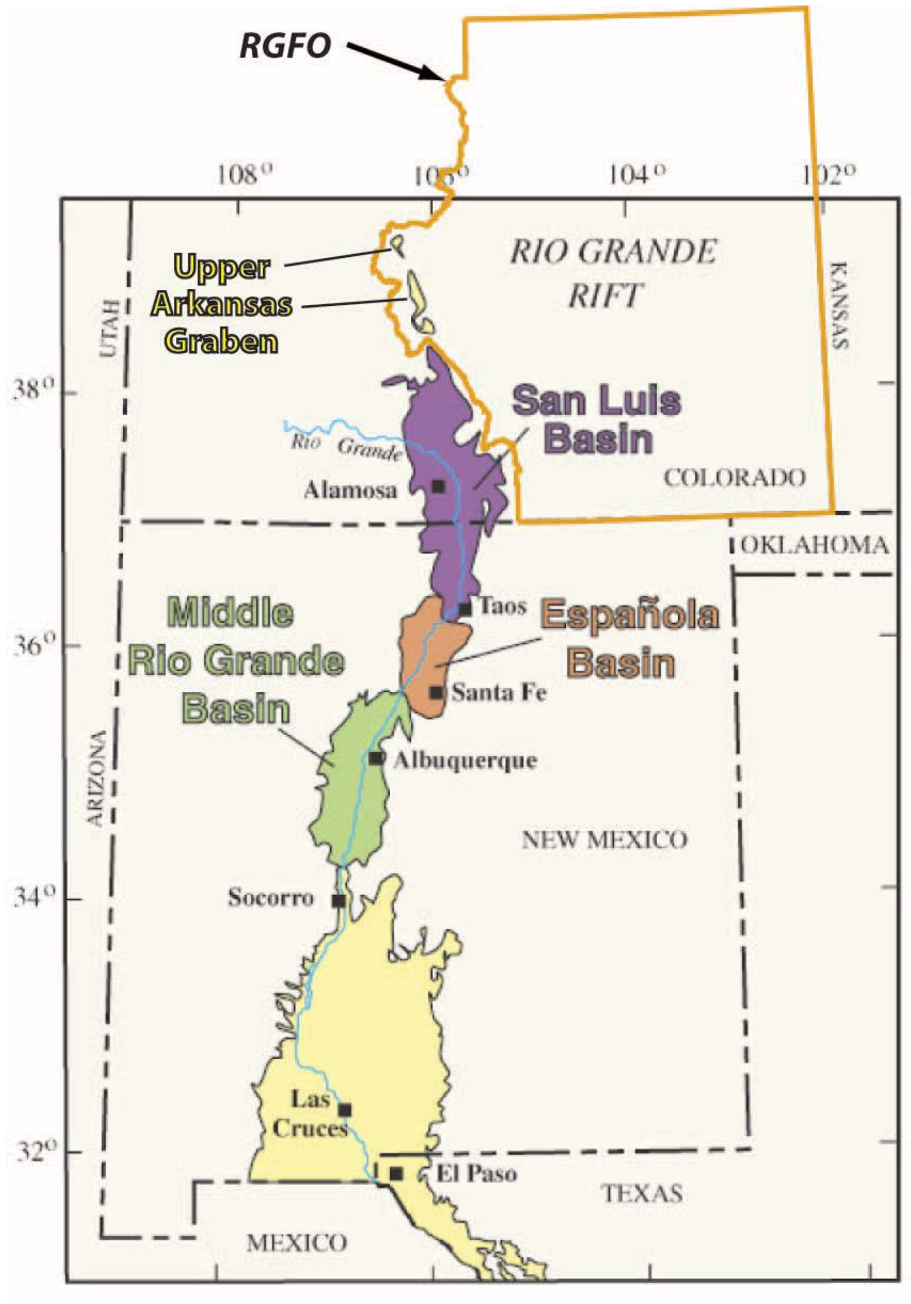


Figure 2-10. Basins of the Rio Grande Rift (modified from image provided courtesy of USGS).

Large areas within the eastern part of the RGFO region, particularly the northeastern and east-central parts, are blanketed by wind-blown eolian sediment deposited during the Quaternary. Eolian sediment deposition, especially loess deposition, was often related to deglaciation, when large areas of freshly deposited, unvegetated glacial till and outwash were available for wind erosion.

2.3 Structural Geology and Tectonics

2.3.1 Introduction

The structural geology and tectonic history of the RGFO region ranges from very complex in the west to moderately complex in the east. As described in the previous section on geologic history (section 2.2), several periods of tectonism have affected the rocks in the RGFO region. The cumulative effect of these episodes of tectonism can generally be seen in the structure contour map on the top of the Precambrian basement rock (Figure 2-11).

Precambrian rocks have been uplifted by faults and folds, and they crop out in the Front Range, Wet Mountains, Sangre de Cristo Mountains, Mosquito Range, and Sawatch Range in the western part of the RGFO region. The eastern margin of these uplifted blocks forms the topographically abrupt mountain front of Colorado’s modern Rocky Mountains, which is one of the most striking physiographic features of the RGFO region. The Precambrian basement rocks have also been uplifted by the Las Animas Arch in the southeastern part of the RGFO region and by the Sierra Grande Uplift in the south-central part, although in those areas, the top of the basement rocks is thousands of feet below ground level.

Precambrian basement rocks were lowered several thousand feet in two major structural basins within the RGFO region, the Denver Basin and Raton Basin. The top of the basement rocks is over 7,000 feet below sea level in the Denver Basin and over 2,000 feet below sea level in the Raton Basin. Both basins are asymmetrical; their western flanks are very steep, whereas their eastern flanks are fairly gentle. Both basins are elongated in a north-south direction. A much smaller and shallower structural basin, the complexly deformed South Basin, lies in the west-central part of the RGFO region. Precambrian rocks are also down-dropped in the geologically young, rift-related Wet Mountain Valley Graben and Upper Arkansas Valley Graben, which are relatively small in areal extent compared to the Denver and Raton Basins.

2.3.2 Precambrian Structural Features

The Precambrian rocks in the RGFO region are broken by numerous brittle faults and a few ductile shear zones (Caine et al., 2010). The brittle faults formed at relatively shallow crustal depths, and the ductile shear zones formed at greater depths. That faults are common in the Precambrian rocks of the RGFO region is apparent on the 1:500,000-scale geologic map of Colorado by Tweto (1979a), a part of which is included in this report as Figure 2-26, adapted from Green (1992).

Morgan (2003) prepared an interesting series of maps showing faults in the Front Range. Parts of the Front Range have been mapped at the somewhat detailed scales of 1:24,000 to 1:62,500, whereas other parts have only been mapped at regional scales (e.g., 1:250,000). As more of the

Front Range is mapped at detailed scales, more faults will be documented in the Precambrian rocks in the RGFO region.

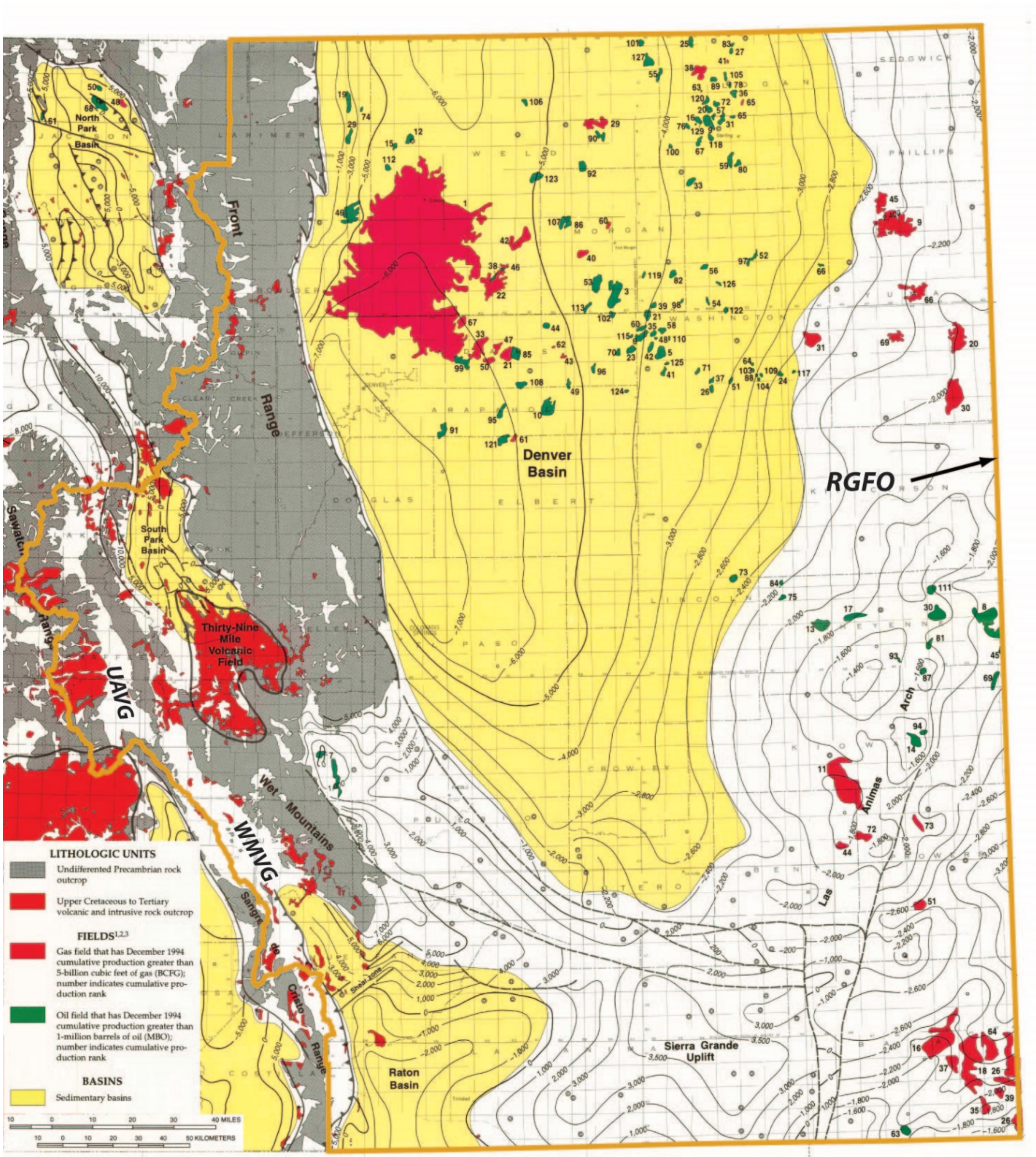


Figure 2-11. Basement structure map of the RGFO region showing altitude below sea level (modified from Hemborg, 1996). Contour interval = 1,000 feet.

Most of the faults and shear zones in the Precambrian rocks exposed in the RGFO region probably were only active during the Precambrian, but some, and perhaps many, were active or reactivated during the episodes of tectonism during the late Paleozoic (Ancestral Rocky Mountains), Laramide Orogeny, and/or late Cenozoic rifting. Tweto and Sims (1963) described a major Precambrian shear zone in the west-central part of the RGFO region that trends southwest-northeast across the Front Range; they called it the Idaho Springs-Ralston Shear Zone. This shear zone, or parts of it, has been the subject of much subsequent work, including the 1:24,000-scale geologic quadrangle mapping of Widmann et al. (2000) and the detailed structural study of Caine et al. (2010). The faults and fractures in the Precambrian rocks host many metallic ore deposits and play important roles relating to the mineral potential of the RGFO region.

Tweto (1980a) suggested that many of the Precambrian faults and shear zones within Colorado and the RGFO region probably initiated as strike-slip structures. Their direction of lateral slip may have reversed during the Precambrian, and perhaps evolved into dip-slip faults later. The direction of dip-slip movement also may have changed over time. Tweto (1980a) groups the faults and shears in the Precambrian rocks into four categories depending chiefly on their trends: faults of north-northwest trend; shear zones and faults of northeast trend; faults of west-northwest trend; and faults of east trend. Examples of each of the structures are found in the RGFO region.

Figure 2-12 shows the spatial relationship of known ductile shear zones, Late Cretaceous and Tertiary intrusive rocks, and polymetallic mineralized areas to the CMB. Figure 2-13 shows spatial relationships between the Idaho Springs-Ralston Shear Zone, brittle fault zones, Late Cretaceous to Tertiary monzonitic intrusions, and polymetallic quartz veins. Caine et al. (2010) used the information on these maps, along with existing data published by others and new data collected during their study, to raise questions about the existing theories on the Precambrian structures and their relationships to the metallic mineral deposits. For example, they question whether the Idaho Springs-Ralston Shear Zone is a major, through-going, crustal scale structure. The brittle faults cut the shear zone at near right angles, suggesting they are much younger.

As described previously in section 2.2.2 (Precambrian Era), there are two current theories that attempt to explain the Precambrian structural history of the region. One relies upon the addition of newly formed crust to the craton by suturing, and a second upon modification of the crust beneath the RGFO region by rifting, magmatism, and sedimentation that involved recycling and alteration of existing crust. Refer to Hill and Bickford (2001), Bickford and Hill (2006), Gonzales and Van Schmus (2007), and Whitmeyer and Karlstrom (2007) for descriptions of these interpretations.

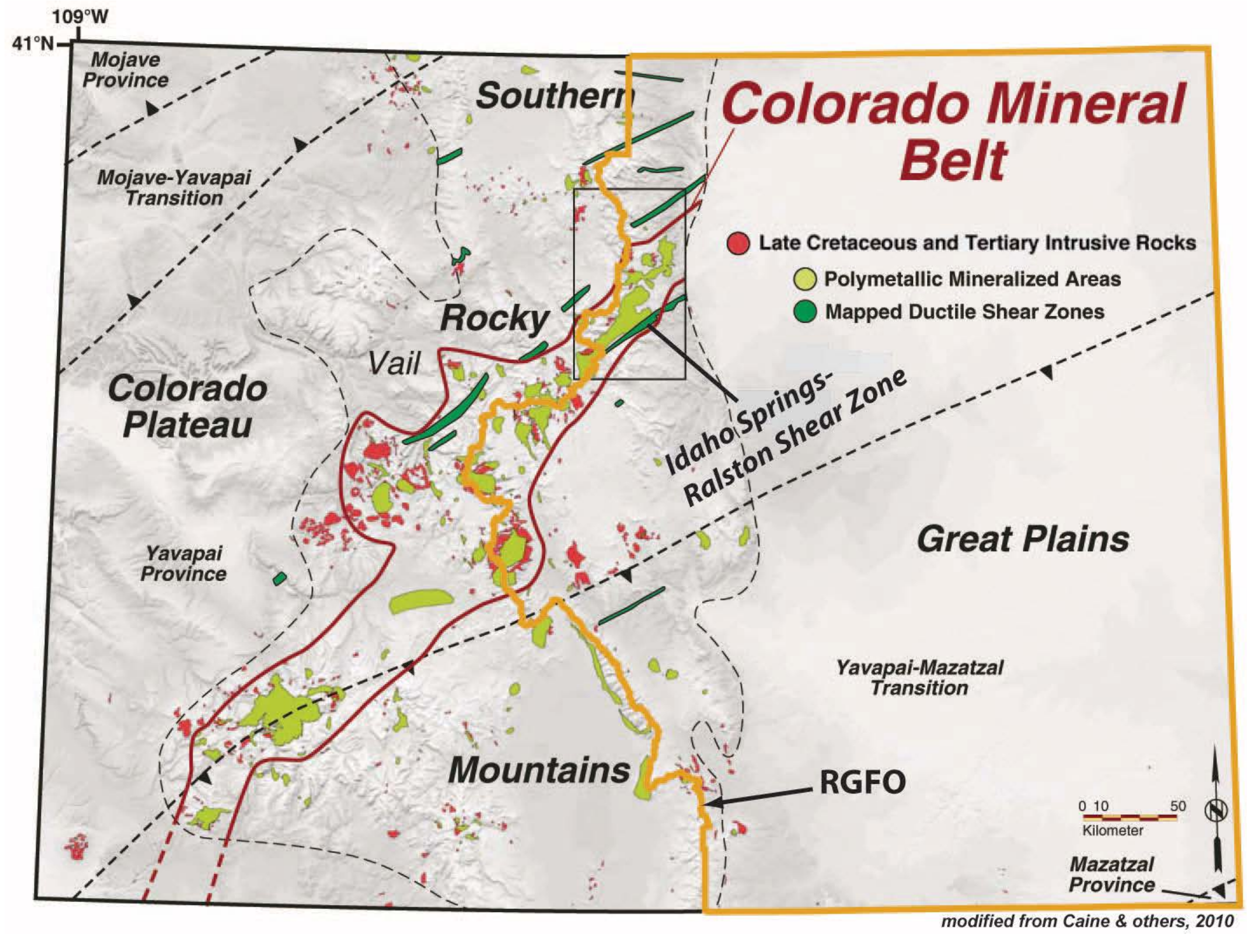
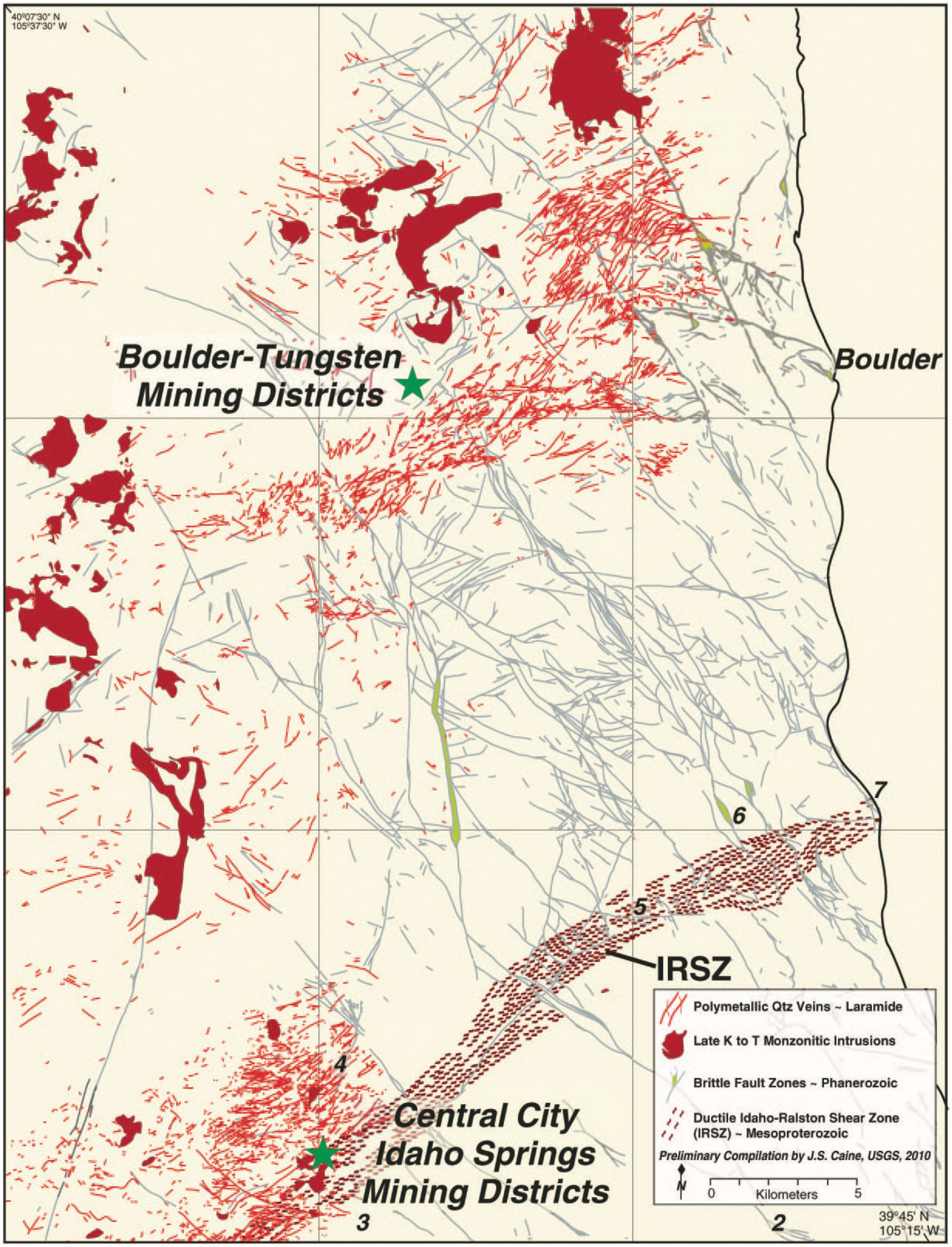


Figure 2-12. Relationships between Precambrian ductile shear zones, Late Cretaceous and Tertiary intrusive rocks, polymetallic mineralized areas, and the CMB. Note the approximate boundaries of the Mazatzal, Yavapai, and Mohave accretionary provinces that were sutured to the Laurentia craton during the Precambrian, and also the transition zones between them. Laramide-age plutons and related mineral veins have little correlation with the shear zone and the brittle faults.



from Caine and others, 2010

Figure 2-13. Mapped extent of the Idaho Springs-Ralston Shear Zone relative to major brittle faults, Late Cretaceous to early Tertiary plutons, and polymetallic quartz veins in the vicinity of the Central City, Idaho Springs, Boulder, and Tungsten mining districts within the RGFO region.

In summary, much remains to be learned about the Precambrian shear zones and brittle faults, as well as their relationships to younger igneous activity and mineralization.

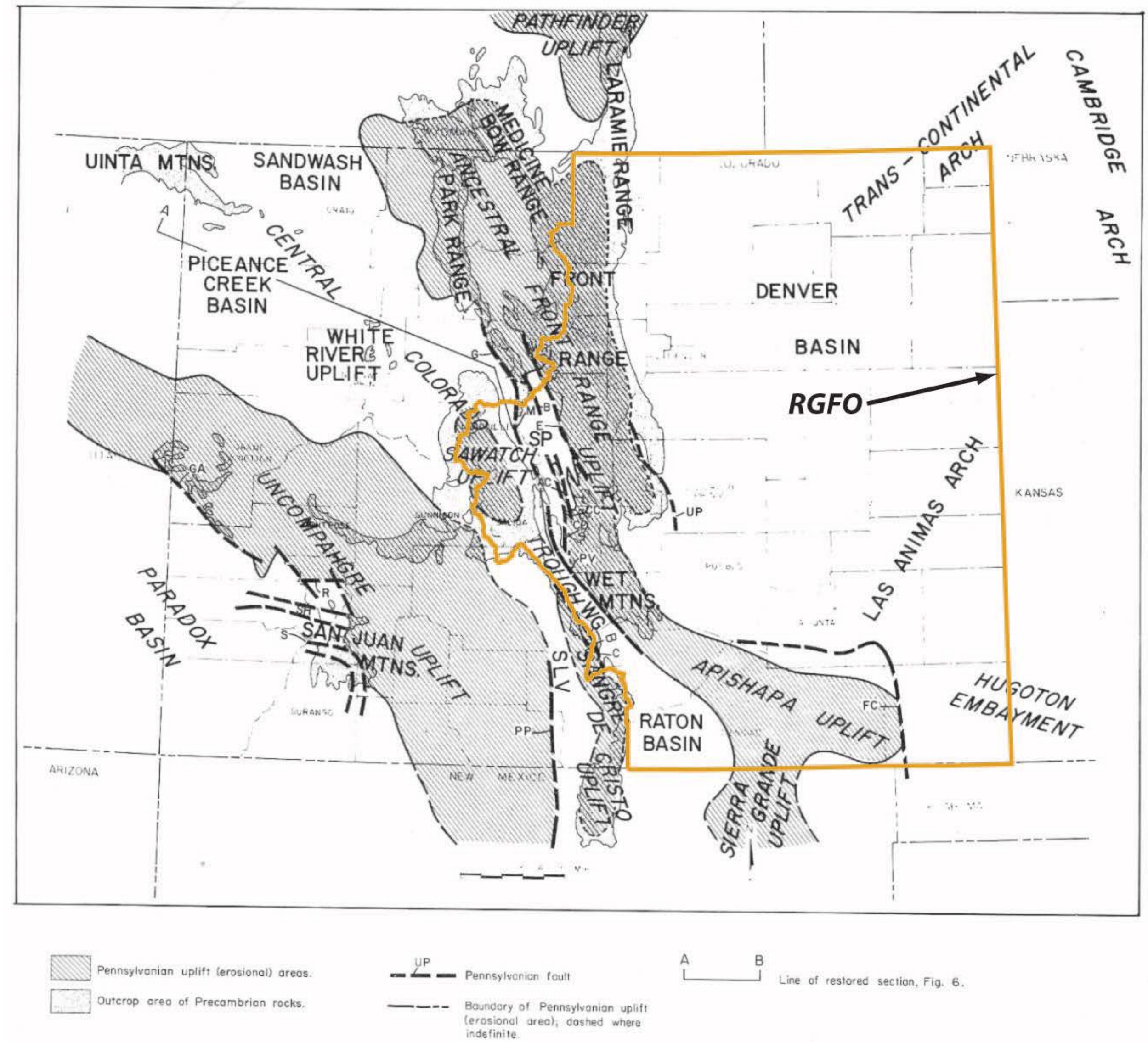
2.3.3 Late Paleozoic Structural Features

There is little to no controversy among geoscientists about the existence and approximate locations of most late Paleozoic Ancestral Rocky Mountain uplifts within the RGFO region. All or parts of the Ancestral Front Range and Apishapa Uplifts lie within the RGFO region. Most of the Ancestral Uncompahgre Uplift or Highland (also known as the Uncompahgre-San Luis or San Luis Uplift) was west of the RGFO region, but a short section of the uplift's eastern flank is coincident with the southwestern boundary of the RGFO region in part of the Northern Sangre de Cristo Range. Also, sediment eroded from the southern part of the uplift was deposited in the Central Colorado Trough in the southwestern part of the RGFO region. De Voto (1980b) proposed the existence of two additional late Paleozoic uplifts, the Sawatch Uplift and Sangre de Cristo Uplifts (Figure 2-14). He located them, respectively, in the west-central and southwestern parts of the RGFO region. Sweet and Soreghan (2010) described a structural trough (Woodland Park Trough) that they thought separated a late Paleozoic uplift they named the Ute Pass Uplift from the main part of the Ancestral Front Range Uplift.

In contrast, there is much uncertainty and limited consensus on which faults were active during the late Paleozoic and responsible for uplift of the mountains (Houck, 2012, personal communication; Kellogg, 2012, personal communication; Lindsey, 2012, personal communication). Determining whether a fault was active during the late Paleozoic is challenging. The late Paleozoic uplifts are no longer topographically apparent in the RGFO region. The Apishapa Uplift is buried by thousands of feet of younger sediment, effectively concealing evidence of this late Paleozoic uplift. The Ancestral Front Range trends obliquely across the modern Front Range.

Most of the eastern edge of the ancestral uplift lies west of the eastern margin of the modern range, well up into its Precambrian core, where evidence of a possible late Paleozoic fault on the eastern side of the Ancestral Front Range, if it existed, would have been removed by erosion long ago. Only a very small section of the eastern margin of the Ancestral Uncompahgre Uplift is within the RGFO region. This section is essentially coincident with the southwestern boundary of the RGFO region or slightly west of it. However, sediment eroded from the uplift is preserved within the RGFO region, which, as described below, is essential to understanding the uplift history.

Unequivocal evidence of late Paleozoic structures is difficult to demonstrate, because subsequent tectonism during the compressional Laramide Orogeny and extensional faulting during the late Cenozoic in part coincided with and overprinted the late Paleozoic structures. In some areas, the subsequent tectonism resulted in uplift of areas containing late Paleozoic structures and erosional



Pennsylvanian and Cenozoic tectonic features. Pennsylvanian features shown with inclined lettering; Cenozoic features, with vertical lettering. Sawatch and Sangre de Cristo uplifts interpreted as Pennsylvanian tectonic features at general locations of similar Cenozoic features. Pennsylvanian faults: AC, Agate Creek; B, Boreas Pass; C, Crestone; CC, Currant Creek; CO, Cotopaxi; E, Elkhorn; FC, Freezeout Creek; G, Gore; GA, Gateway; M, Mosquito; PP, Pecos-Picuris; PV, Pleasant Valley; R, Ridgeway; S. Snowden; UP, Ute Pass; WR, Williams Range. Other geologic structures: SH, Sneffels horst; SP, South Park, WG, Wet Mountain Valley graben; SLV, San Luis Valley.

Figure 2-14. Pennsylvanian and Cenozoic tectonic features (modified from De Voto, 1980b). Refer to the caption and legend in the figure for an explanation of map symbols.

removal of the evidence of it. Elsewhere, the late Paleozoic faults and rocks were lowered by younger tectonism and buried by sediment or covered by younger volcanic rocks.

Two basic approaches are typically employed to locate late Paleozoic faults associated with the Ancestral Rocky Mountains. The more-or-less time-honored approach involves detailed study of the sediments eroded from the mountains. Evidence, such as the size of clasts in conglomerates eroded from the ancient uplifts (which should increase towards the uplift), paleocurrent indicators in the fluvial sediments deposited by rivers and streams, and angular unconformities in proximal syn-orogenic sediment can provide constraints on locations of the ancient uplift margins. Seldom, however, does this type of evidence precisely point to the fault or faults that bordered a late Paleozoic uplift. A more recently developed technique involves the observation and interpretation of kinematic indicators on fault surfaces, which can be used to assess direction and style of fault movement. These types of evidence can be convincing, but overprinting by more recent episodes of tectonism during the Laramide Orogeny and/or late Cenozoic extension frequently complicates interpretations.

Tweto (1980c) suggested that Colorado’s late Paleozoic uplifts were bounded by major faults and steep only on one side. Their other flanks, in his opinion, apparently were only relatively gently upwarped by folding and minor faulting. The only late Paleozoic fault that he mapped (Figure 1 in Tweto 1980c) was the Gore Fault on the west side of the Ancestral Front Range. All but the southern end of the Gore Fault is west of the RGFO region. Presence of coarse conglomerate against the Gore Fault, the very abrupt thinning of the Pennsylvanian rocks in the vicinity of the fault, and onlapping relationships (Figure 2-15) have over the years convinced many geologists that the fault was active during the late Paleozoic. Based on recent detailed mapping of the fault, Kellogg et al. (2011) described the fault as a zone of high-angle reverse faults that have undergone movement during several different periods of tectonism, including the late Paleozoic, but that most of the observed displacement probably occurred during the Laramide Orogeny.

Tweto (1980c) described the buried Apishapa Uplift as being steep and bounded by the Apishapa Fault on its north side, and less topographically prominent on its west side where bounded by an extension of the Ilse Fault and on its eastern side where bounded by the Freeze Creek Fault. To the south, he thought the Apishapa Uplift “irregularly extended” to the Sierra Grande Uplift in northeastern New Mexico. In contrast, De Voto (1980b) shows the Sierra Grande Uplift as extending into and joining the Apishapa Uplift in southeastern Colorado in the south-central part of the RGFO region.

De Voto (1980b) described several late Paleozoic faults in the RGFO region (Figure 2-16). From southeast to northwest, these are the Freezeout Creek, Pleasant Valley, Crestone, Agate Creek, Ute Pass, Elkhorn, Boreas Pass and Mosquito Faults, as well as the southern end of the Gore Fault. De Voto also pointed out that not all faults were active at all times during the Pennsylvanian. Evidence of late Paleozoic fault activity in the northern Sangre de Cristo Range near the southwestern boundary of the RGFO region and evidence of Permian deformation in the Wet Mountains late during the episode of Ancestral Rocky Mountain tectonism were described by De Voto et al. (1971).

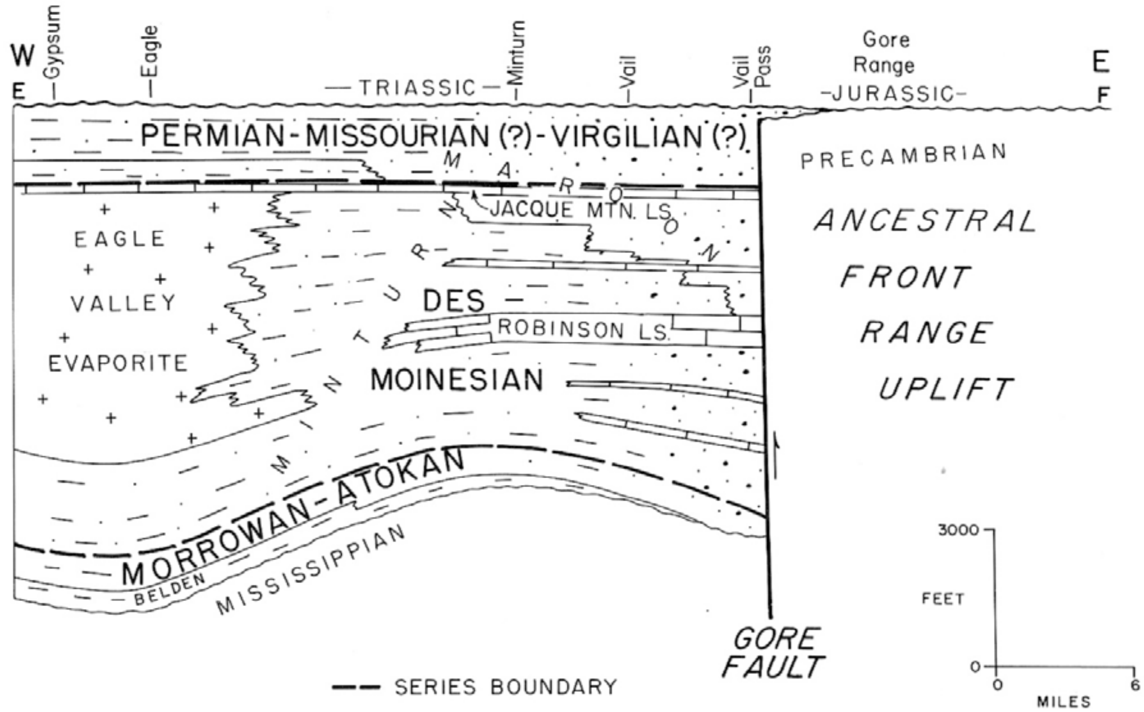


Figure 2-15. Restored cross section across the Gore Fault (modified from De Voto, 1980b). Note abrupt thickness change in Pennsylvanian and Permian rocks at the fault.

Hoy and Ridgway (2002) described the Central Colorado Trough in the southwestern part of the RGFO region as a flexural basin resulting from east-west crustal shortening. Their evidence for this conclusion involved the Gibson Peak growth syncline in the footwall of the Crestone Thrust Fault; the Sand Creek Thrust Fault, which only cuts the lower part of the Pennsylvanian Crestone Conglomerate; and an angular unconformity within the Pennsylvanian Crestone Conglomerate that separates underlying folded rocks from less deformed overlying rocks. In contrast to the large number of late Paleozoic faults described by De Voto (1980b) in the RGFO region, Hoy and Ridgway (2002) show only four late Paleozoic faults within the RGFO region on their map (Figure 2-17): the Freeze Creek Fault, Ute Pass Fault, southern end of the Gore-Mosquito Fault System, and part of the Sand Creek Thrust Fault.

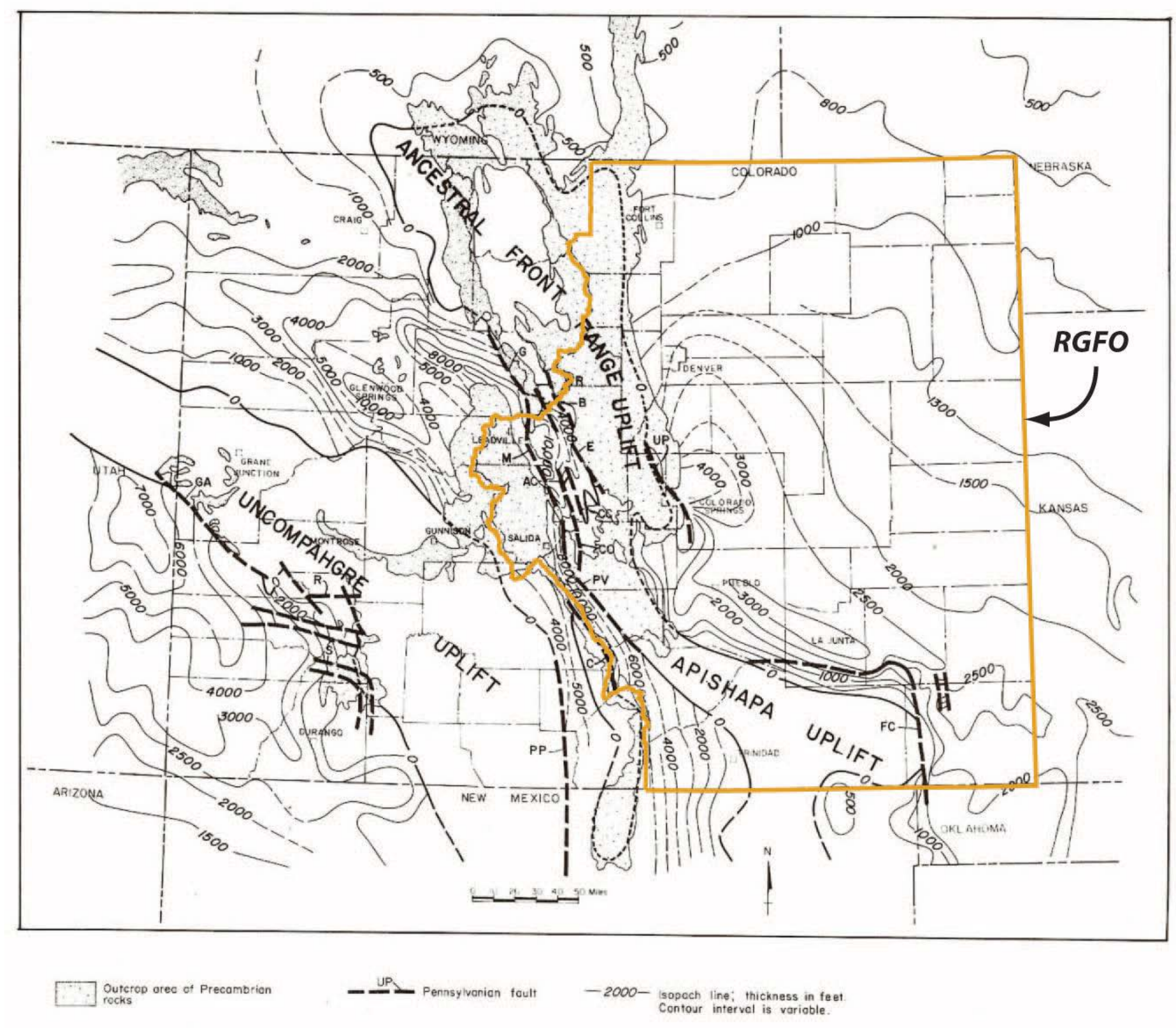


Figure 2-16. Late Paleozoic uplifts and faults and thickness of Pennsylvanian rocks (modified from De Voto, 1980b).

Hoy and Ridgway (2002) presented a series of schematic cross sections showing the tectonic evolution of the Northern Sangre de Cristo Mountains and adjacent parts of south-central Colorado (Figure 2-18). It begins in the Middle Pennsylvanian with (1) thrusting associated with the Sand Creek-Crestone Thrust System, (2) erosion of the overthrust block of the Ancestral Uncompahgre Uplift in the west and deposition of fan alluvium in the Crestone Conglomerate and the marine Minturn Formation in the Central Colorado Trough to the east, and (3) broad uplift of the Apishapa "forebulge" (cross section A in Figure Q). By Late Pennsylvanian-Early Permian time (cross section B), continued movement on the Sand Creek-Crestone Thrust System further raised the Ancestral Uncompahgre Uplift. Deposition of the Crestone Conglomerate was

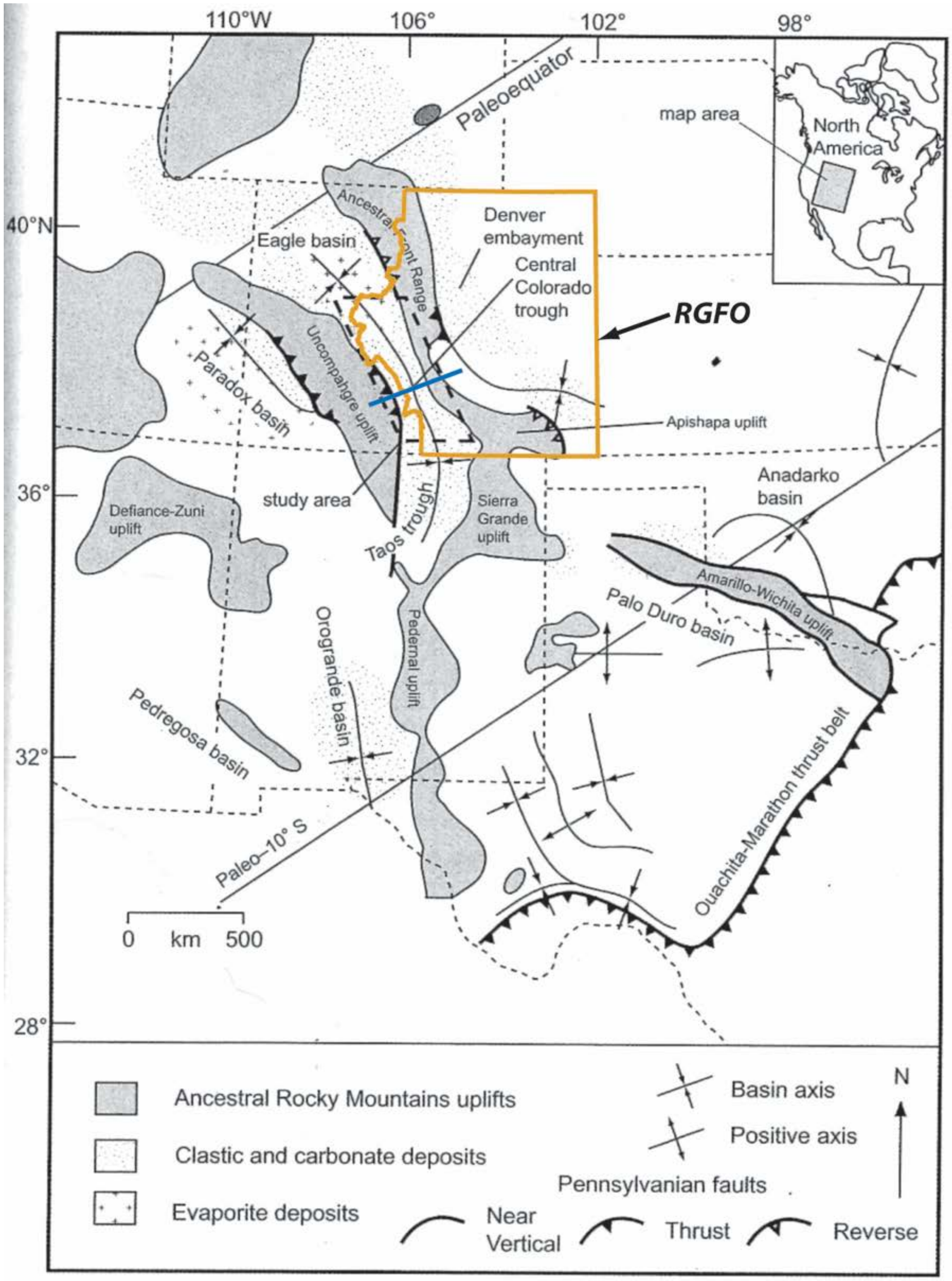


Figure 2-17. Map showing paleogeography of southwestern North America during the Pennsylvanian Period (modified from Hoy and Ridgway, 2002). Blue line denotes the approximate line of the cross sections shown in Figure 2-18.

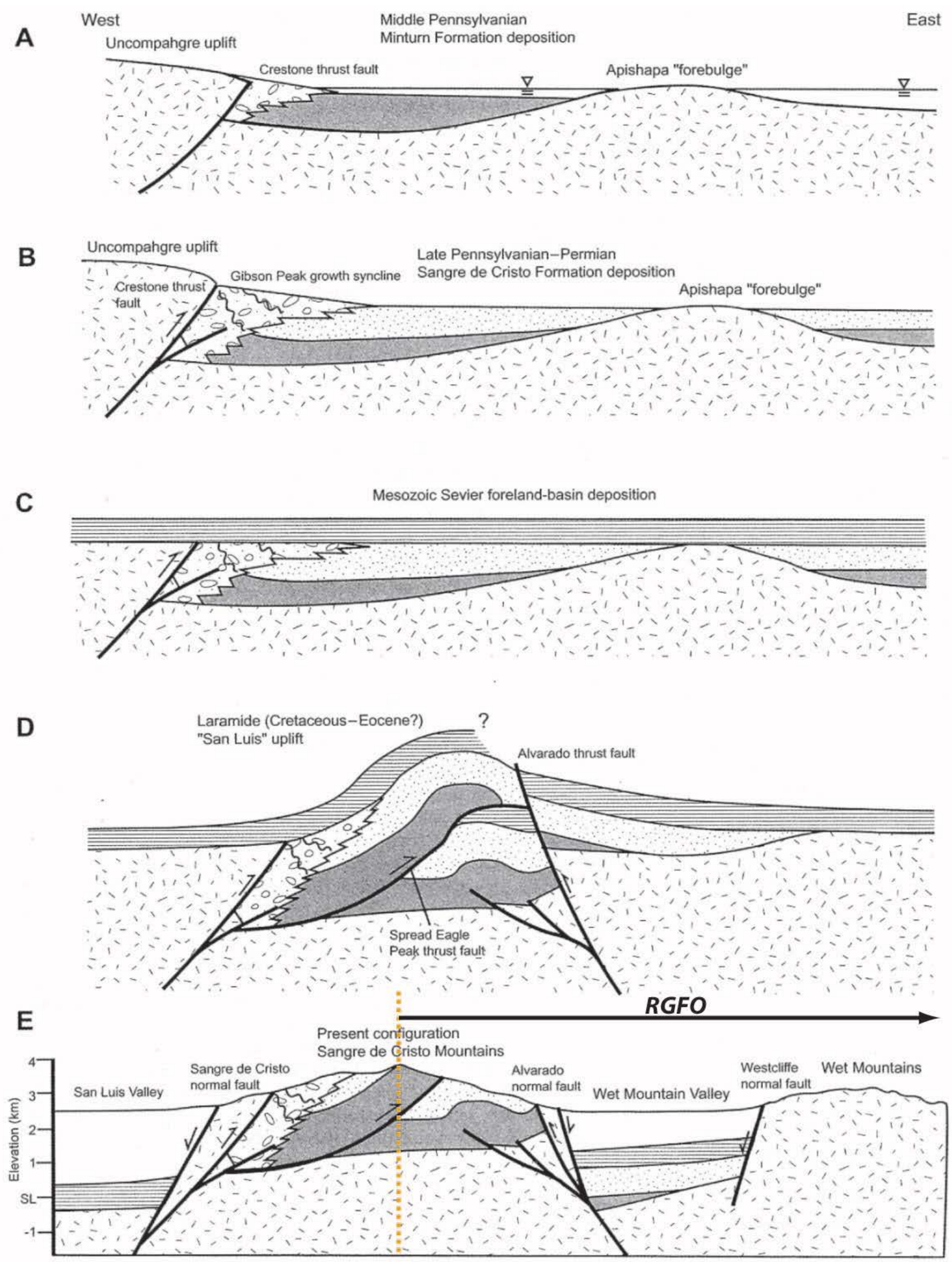


Figure 2-18. Schematic tectonic evolution of the Sangre de Cristo Mountains and south-central Colorado (modified from Hoy and Ridgway, 2002). The RGFO region lies east (right) of the crest of the Sangre de Cristo Mountains, which is denoted by the dotted gold vertical line in cross section E. Approximate line of cross section is shown by blue line in Figure 2-17.

periodically temporarily interrupted and intraformational angular unconformities developed within it, and the continental Sangre de Cristo Formation was deposited over the Minturn Formation. Regional uplift or lowering of sea level was thought to be responsible for the transition from the marine Minturn sediments and the continental Sangre de Cristo Formation.

Sweet and Soreghan (2010) focused on the Ancestral Ute Pass Fault, the synorogenic sediment in the Fountain Formation that was eroded from the Ancestral Ute Pass Uplift, and the paleogeography of the Ancestral Front Range. They described the Ancestral Ute Pass Fault as a thrust fault that was active during deposition of the lower tectonostratigraphic unit of the Fountain Formation, but not active or much less active during deposition of the upper unit of the formation.

There has been considerable debate about the type of structural deformation responsible for the Ancestral Rocky Mountains. Explanations have included near-vertical block faulting, compressional thrust and reverse faults, strike-slip faulting, and normal faulting (e.g., De Voto, 1980b; Goldstein, 1981; Kluth and Coney, 1981a, 1981b, 1983; Warner, 1983; Budnick, 1986; Kluth, 1986, 1998; and Lindsey et al., 1986b). Recent work by Sweet and Soreghan (2010) supports the compressional thrust and reverse fault style of deformation. Placing the Ancestral Rocky Mountains into a plate-tectonic setting is also challenging and has more than one potential explanation (e.g., Kluth and Coney, 1981a, 1981b, 1983; Kluth, 1986, 1998; Warner, 1983; Burchfiel et al., 1992; Ye et al., 1996, 1998). Definitive evidence supporting one style or cause of deformation over another has yet to be found.

2.3.4 Laramide Orogeny

The Late Cretaceous-early Tertiary Laramide Orogeny created mountain uplifts and deep adjacent structural basins (Figure 2-14). Older sedimentary rocks were often eroded from the uplifts, but they were preserved in the structural basins. Synorogenic sediments also were sometimes deposited within the structural basins. Tweto (1975, 1980b) summarized the structural history and synorogenic sedimentation of the Laramide Orogeny in Colorado, and many geoscientists have published on various aspects of this episode of tectonism in subsequent years. Within the RGFO region the major Laramide uplifts include the Front Range, Wet Mountains, San Luis Uplift, and Sawatch Anticline (Tweto, 1975, 1980b). Numerous igneous intrusions accompanied the Laramide tectonism. Many of the metallic ore deposits in the RGFO region are associated with the Laramide intrusions.

The Laramide uplifts in part coincide with late Paleozoic uplifts (Figure 2-19). There are several areas where the uplifts formed during the two periods of tectonism involved at least part of the same terrane; however, as pointed out by Kluth (1997), the reactivation of specific late Paleozoic faults during the Laramide Orogeny is not common, and discerning late Paleozoic movement on faults with significant Laramide displacement is challenging.

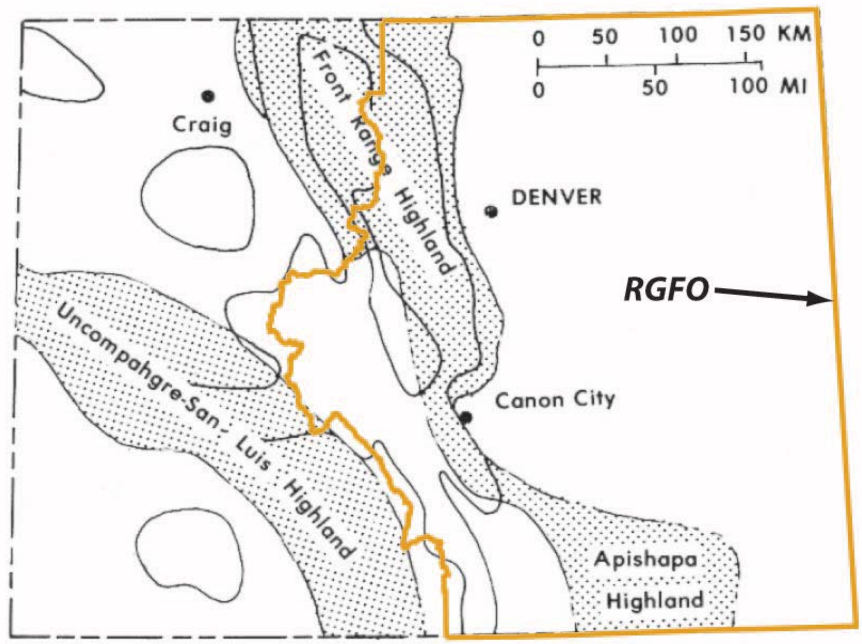


Figure 2-19. Generalized relationship between major Laramide uplifts and Late Paleozoic uplifts(shaded) (modified from Tweto, 1980b).

The major Laramide uplifts in the RGFO region have been altered to one degree or another by subsequent tectonic, volcanic, and/or erosional events, but they are still at least partially topographically apparent and can be examined in outcrop. Indeed, the abrupt topographic escarpment between the Great Plains and Southern Rocky Mountain Province coincides with the eastern flanks of the Laramide Front Range, Wet Mountains, and Sangre de Cristo Uplifts. The modern Sawatch Range and Mosquito Range preserve evidence of the east and west flanks, respectively, of the Sawatch Anticline. Sedimentary formations older than the Late Cretaceous-early Tertiary Laramide Orogeny typically dip west in the Sawatch Range and to the east in the Mosquito Range. The crest of the Sawatch Anticline was breeched by late Cenozoic rifting and now, for the most part, is buried beneath younger sediments on the floor of the Upper Arkansas Valley, mostly a result of down-to-east movement on the Sawatch Fault at the base of the Sawatch Range and of down-to-west movement on faults in or adjacent to the Mosquito Range, such as the Mosquito Fault.

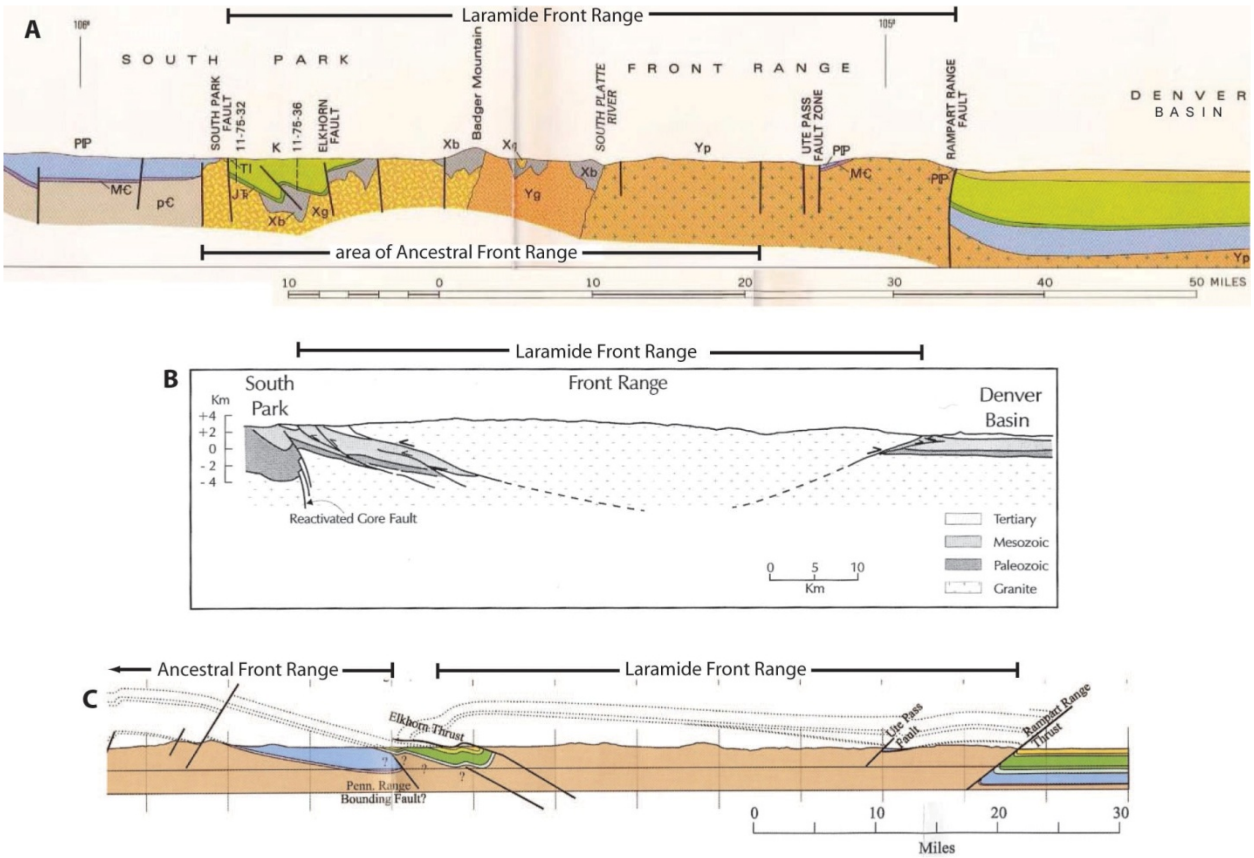
Only the eastern margin of the San Luis Uplift is preserved in outcrop in the RGFO region (Tweto, 1975, 1980b). The vast majority of the Laramide San Luis Uplift now lies far below ground level beneath San Luis Valley to the southwest of the RGFO region. Major late Cenozoic rift-related extension associated with the Sangre de Cristo Fault is responsible for the structural inversion of most of the San Luis Uplift, which Sales (1983) described as late Cenozoic collapse of a Laramide uplift by gravity failure.

Structures that flank the Laramide uplifts have been interpreted differently by different geologists. Tweto (1980b) described the Laramide uplifts as being formed by “up-arching or a combination of up-arching and up-faulting”, and he thought the thrusts exposed at the surface and in the shallow subsurface transitioned into steep, sub-vertical faults at depth. Kluth (1997) called the Front Range Uplift “a large block of Proterozoic basement that has been uplifted and shortened by reverse or thrust faults on both its east and west sides.” Raynolds (1997) proposed that the thrusts on the east and west sides of the Front Range maintained their flat dips deep into the subsurface and may even flatten with depth. His cross section suggests the Proterozoic rocks in the Front Range may be rootless. Nesse (2006) described west-vergent Laramide thrusts along much of the western margin of the Front Range. These are, from north to south, the Canadian River Thrust, Cameron River Thrust, Never Summer Thrust, Williams Range (or Williams Fork Mountains) Thrust, and Elkhorn Thrust. He shows a sequence of twenty-one east-west cross sections spaced at intervals of 7’30” latitude that depict the structure of the Front Range. The east-west cross sections in **Error! Reference source not found.** show the structural interpretations by Tweto (1983), Raynolds (1997), and Nesse (2006) at the latitude of South Park.

The eastern flank of the Front Range has been the object of much study, but remains somewhat controversial. Nesse (2006) described the east flank north of Boulder as an east-dipping monocline broken locally by small, east- or northeast-dipping, high-angle reverse faults, and fault-propagation folds that are oblique to the mountain front. From Boulder south, he described the flanking structure as a monocline cut by a series discontinuous east-directed thrusts that generally parallel the mountain front and had net slips of less than about three kilometers. Thrusts on the east flank of the Laramide Front Range include the Boulder, Golden, Jarre Creek, Perry Park, Rampart Range, and Cheyenne Mountain (or Ute Pass) Thrusts.

The various interpretations of the Golden Fault over time illustrate how different geoscientists have tried to explain the nearly 9,000 feet of missing stratigraphic section near the town of Golden. Over the years, this fault has received the attention of many geoscientists, perhaps because of its proximity to Denver where many geologists in academia, government, and industry reside. The first published interpretation attributed the missing strata tentatively to either a fault or an unconformity, but apparently preferred the unconformity explanation since a fault was not shown on their map (Marvine, 1874). Eldridge (1888) also preferred an unconformity to explain the missing strata. Some of the earliest scientists to suggest high-angle reverse faulting as the cause include Richardson (1912), Lee (1916), Zeigler (1917), Johnson and Baltz (1925), and Van Tuyl and McLaren (1932). Stewart (1952) was apparently the first to describe the Golden Fault as a low-angle thrust.

Van Horn (1957) returned to the steep reverse fault interpretation, but Boos and Boos (1957) described the Golden Fault as a thrust fault belt. Osterwald (1961) and Harms (1961) rejected



the thrust interpretation and concluded the fault was a high-angle reverse fault. In the following year, Berg (1962) described the fault as a thrust that dipped only 35° to 50° southwest. Van

Figure 2-20. East-west Front Range cross sections at the South Park latitude showing various structural interpretations. Section A (Tweto, 1983) has 2x vertical exaggeration; Section B (Raynolds, 1997) has no vertical exaggeration; Section C (Nesse, 2006) has no vertical exaggeration. Please refer to original publications for explanations of unit symbols.

Horn (1972, 1976), who studied in detail the geology of the Golden 7.5-minute quadrangle, described the Golden Fault as a moderately to steeply west-dipping reverse fault. Matthews (1976) favored vertical faulting. Weimer (1996) modified the thrust interpretation by describing a “Basin Margin Fault” that splits off the main Golden Fault a couple of thousand feet (several hundred meters) in the subsurface, has a flatter dip than the Golden Fault, and crops out east of the Golden Fault. Sterne (2006) proposed a modified triangle zone model with backthrusts to explain structural features along the southeastern flank of the Front Range, including the Golden Fault. Figure 2-21 shows the cross sections across the Golden Fault by Weimer (1996) and Sterne (2006).

A series of generally northeast-trending faults cut the Upper Cretaceous rocks at the ground surface and in the shallow subsurface of the Boulder-Weld coal field in the northwestern part of the Denver Basin east of Boulder. These faults are the near-surface expression of a complex structural zone whose origin, similarly to that of the Golden Fault, has also been the subject of much debate. The following paragraphs briefly summarize the evolving interpretations of the faults in the Boulder-Weld coal field.

The coal miners who encountered faults in the Boulder-Weld coal field considered them to be chiefly dip-slip normal faults. Haun (1968) had a similar interpretation and described them as high-angle dip-slip faults that extended upwards from the Precambrian. In contrast, Spencer (1961) interpreted them as a result of right-lateral strike-slip movement on the Coal Creek Shear zone, one of the faults exposed in the Precambrian rocks in the Front Range.

Weimer (1973) described the faults in the Boulder-Weld coal field as growth faults. He indicated the coal deposits would primarily be located only in the structurally low areas where marshes existed, and coal would be thin or absent in the structurally high areas. Interpretation of seismic reflection lines led Davis (1974, 1985) to conclude the near-surface faults were shallow, normal, listric faults that soled out in detachment or decollement zones. Other disconnected listric faults were also detected by Davis in deeper strata such as the Pierre Shale and in the Niobrara-Carlile-Greenhorn interval, and he also described high-angle, sub-vertical faults in the Precambrian and older Phanerozoic sedimentary rocks that extended up to about the top of the Dakota Sandstone and were disconnected from the shallower listric faults. Rahmanian (1975) mapped faults east of the town of Marshall as vertical dip-slip faults, whereas Selvig (1994) mapped them as curvilinear reverse faults.

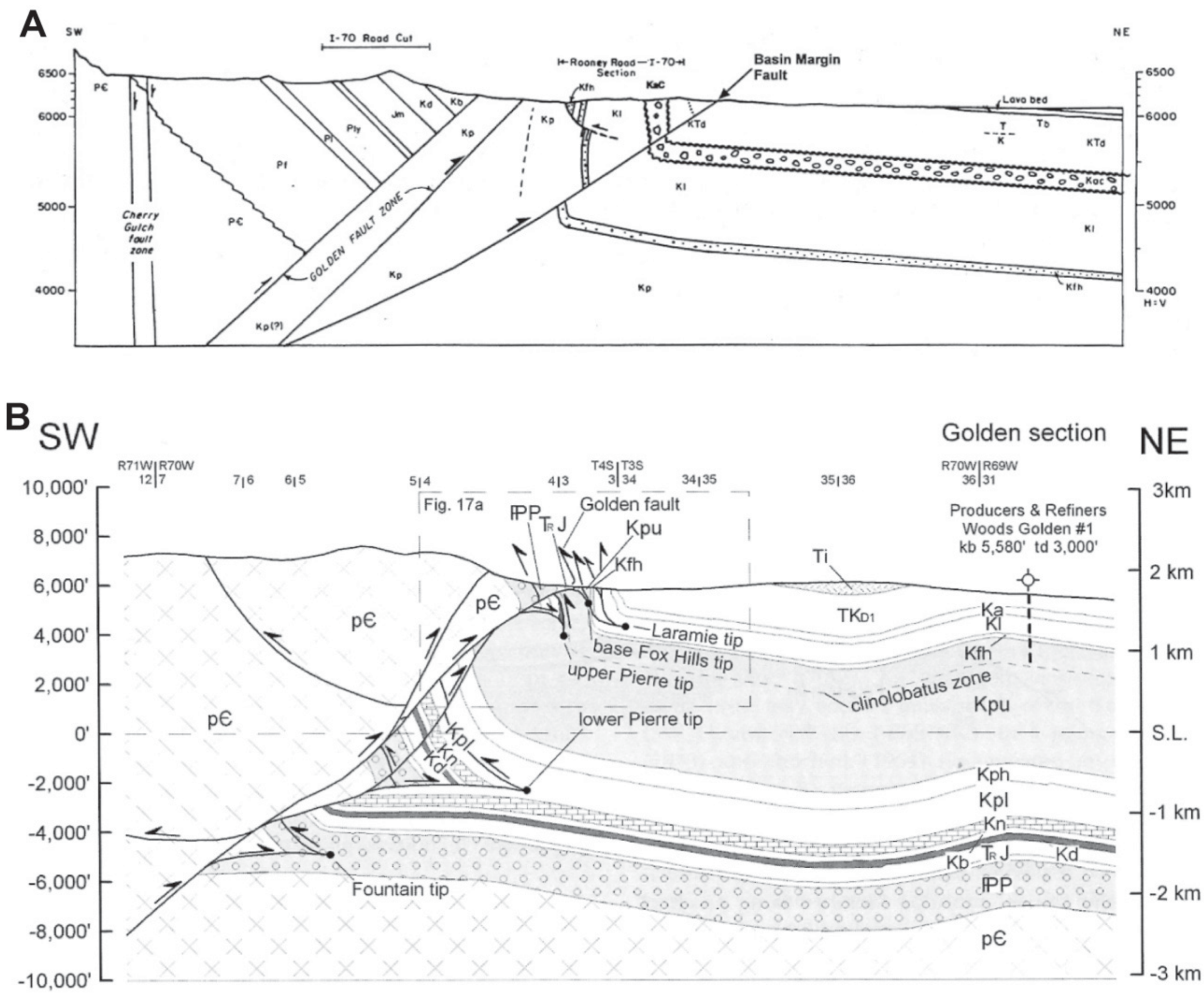


Figure 2-21. Southwest-northeast cross sections across the Golden Fault. Section A (Weimer, 1996) and Section B (Sterne, 2006); no vertical exaggeration. Please refer to original publications for explanations of unit symbols.

Davis and Weimer (1976) interpreted the faults in the Boulder-Weld coal field as growth faults that formed in the deltaic environment associated with deposition of the section of strata that included the upper Pierre Shale to lower Laramie Formation. Spencer (1986) described the faults as high-angle normal faults that formed a series of horsts and grabens. In contrast to the growth fault model of Davis and Weimer (1976), Spencer noted that there was no appreciable difference in the thickness of the coal beds in these structural blocks except where post-deposition erosion had removed the coal from some horst blocks. Weimer (1996) interpreted this complex structural zone in the Phanerozoic rocks as being controlled by several Laramide-age wrench faults in the basement. Kittleson (1992) interpreted the faults as high-angle, listric, reverse faults with as much as 600 feet of offset that sole out or flatten in the upper part of the Pierre Shale. However, he later described the structures as part of a decollement feature associated with the Longmont Fault (Kittleson, 2004, 2009).

These structures in the northwestern part of the Denver Basin have influenced the coal, oil, and gas resources. The faults displace the coal-bearing Laramie Formation, creating a series of structural blocks in which the coal beds in one block are disconnected from the coal beds in an adjoining structural block. This affected the extent of many of the underground coal mines in the Boulder-Weld coal field, because mining ceased when a fault was encountered and the coal bed was cut off. As noted by Kittleson (1992), although much of the subhorizontal coal beds within the Boulder-Weld coal field have been mined out, coal suitable for strip mining may remain in the footwall ramp of the Longmont Fault. Proximity to the Denver metropolitan area, however, will deter future mining.

In South Park, several generally north-south-trending, down-to-west, Laramide-age, reverse faults disrupt the rocks. Existence of many of these faults has been known for many decades (e.g., Singewald, 1942; Stark et al., 1949; Lozano, 1965; Sawatzky, 1967; De Voto, 1971; Tweto et al., 1978; and Bryant et al., 1981). Recent mapping by Kirkham et al. (2007b, 2012a), Widmann et al. (2011), and Houck et al. (2012) led to the discovery of several east-west-trending, Laramide-age faults that interact with the north-south-trending faults. The east-west-trending faults separate blocks with widely varying styles of structural deformation and may be compartmental faults.

The Echo Park Graben is a Laramide-age structure that is partially concealed beneath the middle Tertiary Thirtynine Mile volcanic field (Chapin and Cather, 1983). It extends north-northwest from Devils Hole on the north side of the Arkansas River canyon into the south-central part of South Park near Hartsel. The graben is a narrow, highly elongate, fault-bounded basin filled with syn-orogenic sediment. It contains a through-going stream drainage, and it is believed to be of strike-slip origin.

The eastern margin of the Laramide San Luis Uplift is well exposed in the modern Northern Sangre de Cristo Range and Culebra Range. Several thrust faults mark the eastern margin of the uplift (e.g., Lindsey, 2010; Lindsey et al., 1983, 1986c; Kirkham et al., 2005; and Fridrich and Kirkham, 2008). The complex thrust relationships are shown in Figure 2-22, a southwest to northeast cross section across the Northern Sangre de Cristo Range north of Great Sand Dunes National Park and Preserve.

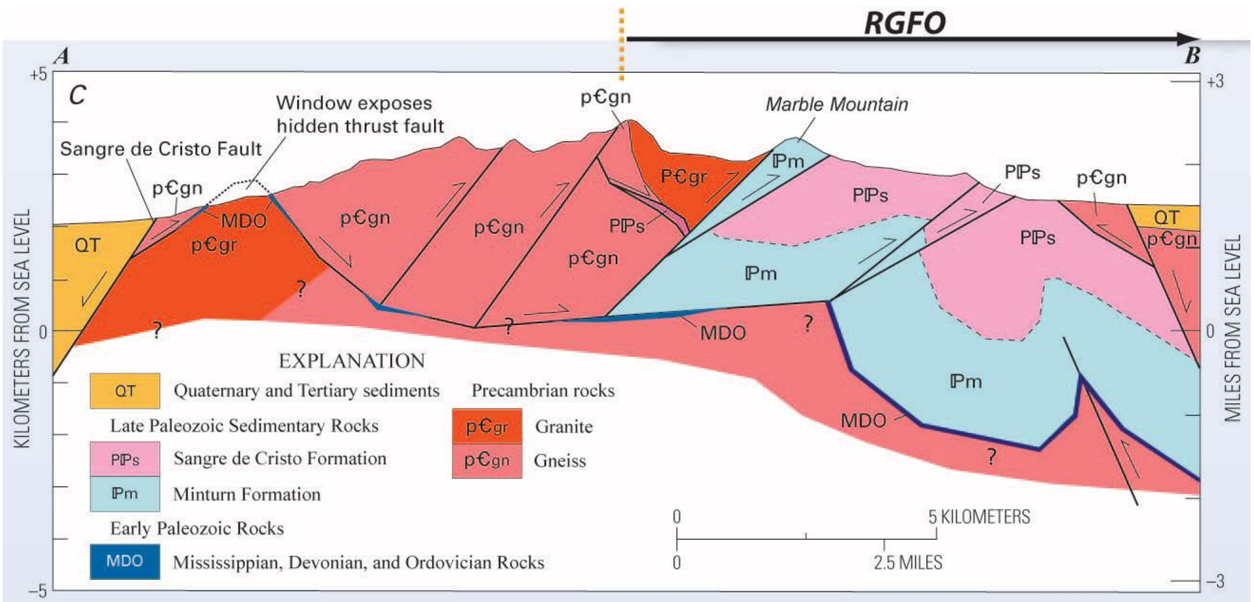


Figure 2-22. Cross section showing thrust-faulted Laramide structure of the Northern Sangre de Cristo Range north of Great Sand Dunes National Park and Preserve (modified from Lindsey, 2010). The RGFO region lies east (right) of the crest of the Sangre de Cristo Mountains, which is denoted by the dotted, gold, vertical line. Please see Figure 2-8 for the general location of the cross section, and refer to Lindsey (2010) for a more specific location.

Nesse (2006) and Erslev and Larson (2006) summarize the primary models used to explain the Laramide structures on the flanks the Front Range (Figure 2-23 and Figure 2-24). The vertical models include a "classic" model and one with lateral flowage. The classic model was described by Lee (1923) and improved by Prucha et al. (1965). Many subsequent authors adopted this model or part of it (e.g., Davis and Young, 1977; De Voto, 1971; and Tweto, 1979a and 1983). The lateral flowage modification to the vertical model accounted for the gentle dips of thrust faults in the shallow subsurface (e.g., Osterwald, 1961; Eardley, 1963; and Jacob, 1983).

Horizontal forces are invoked as the driving mechanism in the shortening models. They include a crustal wedging and uplift model (Nesse, 2006), which Erslev and Larson (2006) call the detachment and crustal wedging model, and also a low-angle thrust model, similar to that shown by Raynolds (1997). Horizontal forces are also invoked in the strike-slip flower structure model of Kelley and Chapin (1997).

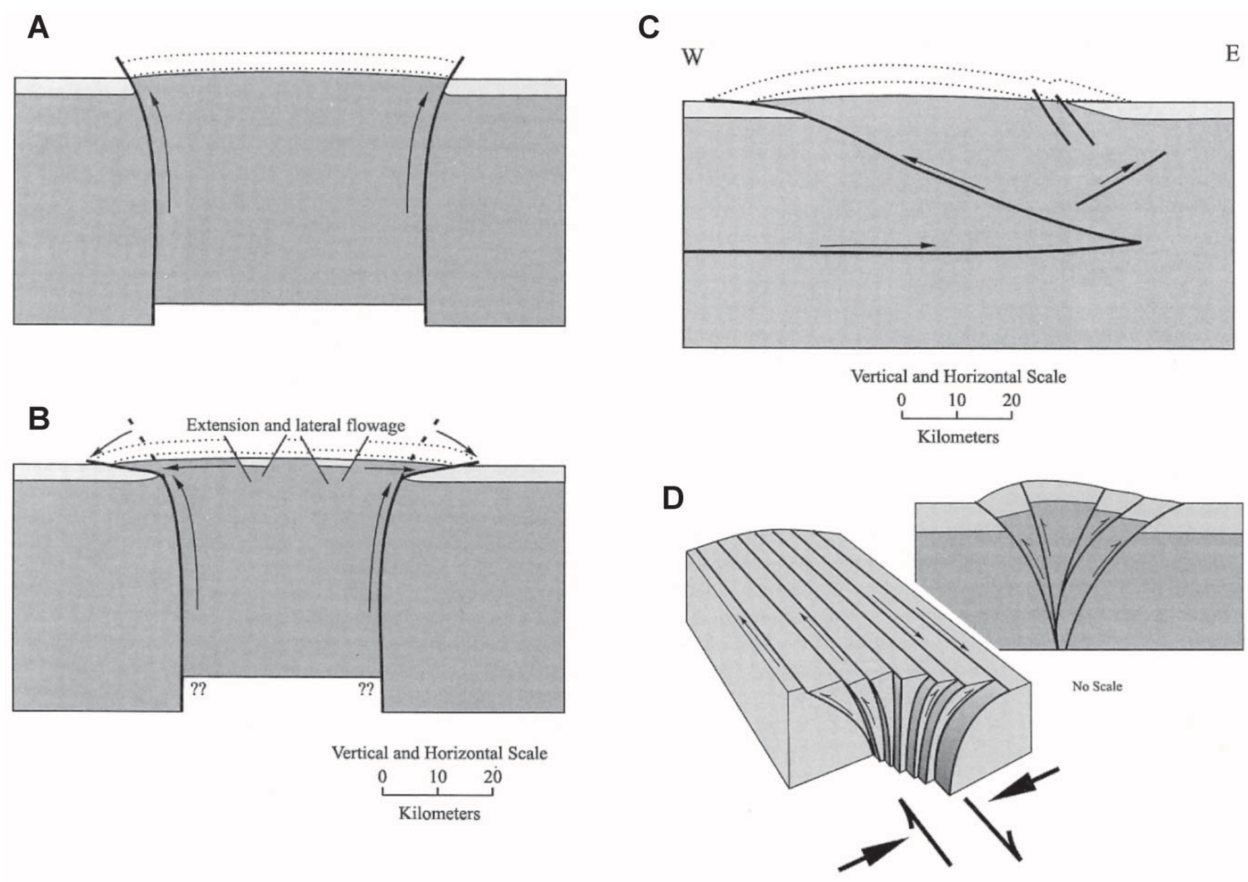


Figure 2-23. Laramide tectonic models by Nesse (2006). Model A—classic vertical uplift; Model B—vertical with lateral flowage; Model C—crustal wedging and uplift; Model D—flower structure.

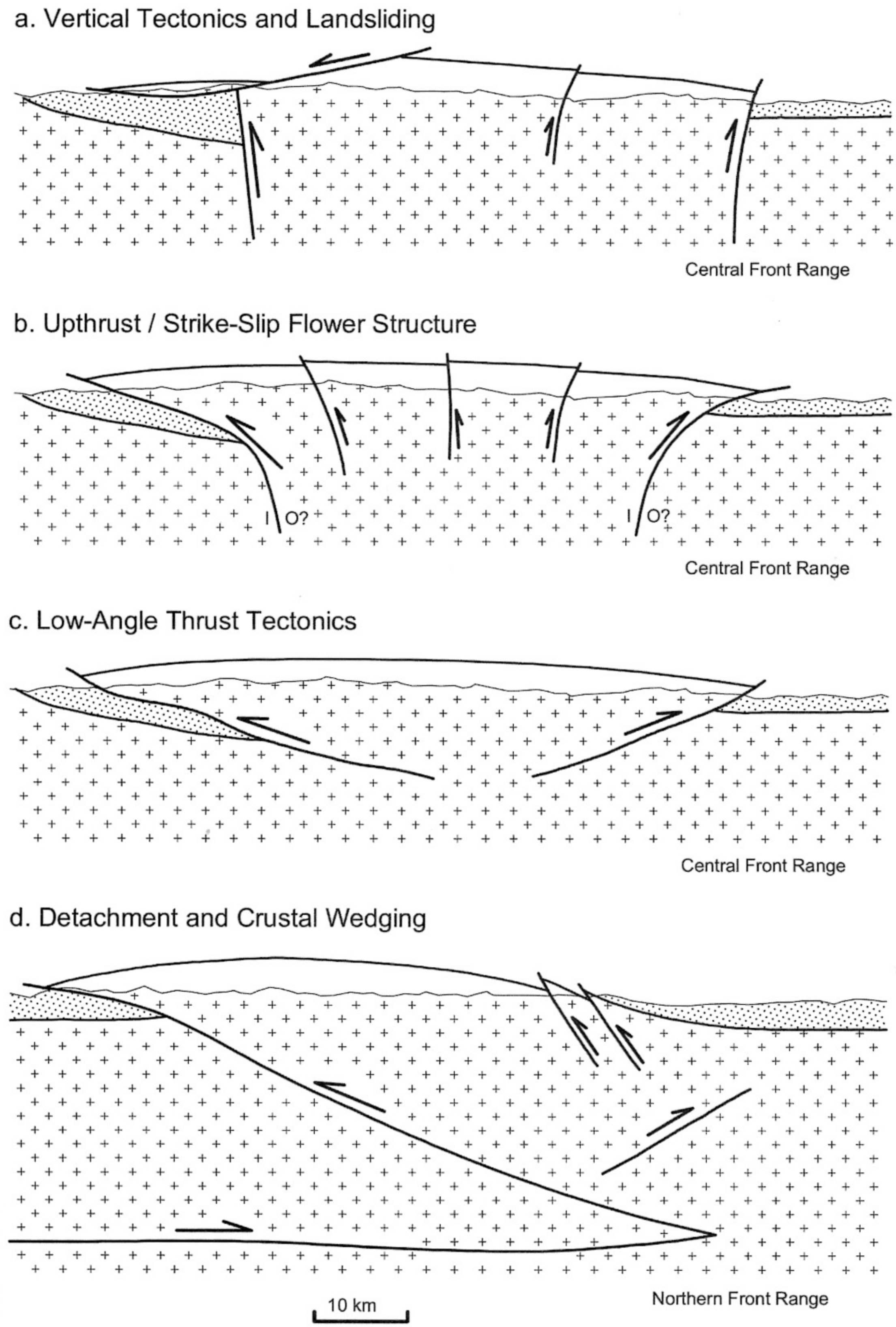
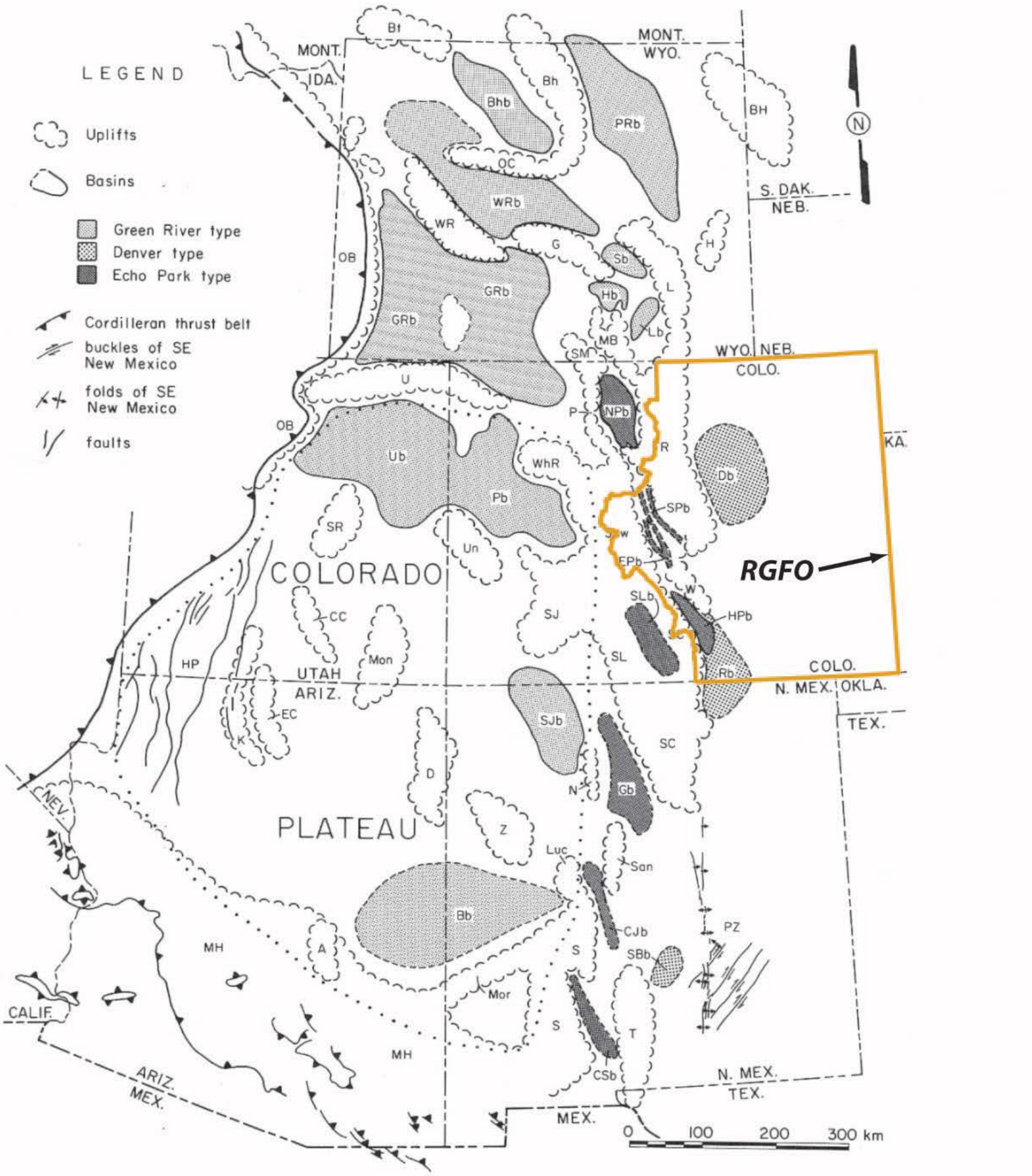


Figure 2-24. Laramide tectonic models by Erslev and Larson (2006).

The debate about the character of the Laramide uplifts continues. For example, Stone (2005) discussed the "illogical interpretation" of geologic structures in the Rocky Mountain Foreland Province, which includes the Laramide uplifts within the RGFO region. Stone, who depended in part upon subsurface seismic information, discounted the forced fold vertical model of Stearns (1978) and other similar models. Stone's paper prompted a reply from Matthews (2006), who pointed out some of the limitations of seismic, especially that it is subject to multiple interpretations and reprocessing can affect interpretations. A similar discussion and reply involving the same original paper came years later (Gay, 2010; Stone, 2010). Minor faults have been used to better understand the forces that created Laramide structures (e.g., Erslev et al., 2004; Clarey et al., 2004; and Erslev and Larson, 2006). These studies of minor faults support horizontal shortening and thrust faulting.

From a regional perspective, three relatively large asymmetrical structural basins and one much smaller structurally complex basin formed within the RGFO region during the Laramide Orogeny (Figure 2-8 and Figure 2-11). The Denver Basin, Cheyenne Basin, and Raton Basin are in the Great Plains east of and adjacent to the Southern Rocky Mountains. Denver Basin is east of the Front Range; Cheyenne Basin is east of the Front Range in Colorado and the Laramie Range in Wyoming; and Raton Basin is east of the Sangre de Cristo Mountains and south of the Wet Mountains. Note that some geologists consider the Denver Basin and Cheyenne Basin a single structure that they call the Denver Basin or D-J Basin. The intermontane South Park Basin, located in the west-central part of the RGFO region, is flanked by the Front Range on the east and by the Mosquito Range on the west. These basins contain synorogenic sediment eroded from the uplifts. Some of the Laramide synorogenic sediment contains mineral commodities such as coal, uranium, and coalbed methane. The ages and characteristics of the synorogenic sediment within the basins provide the principal record of the history of the Laramide uplifts.

Chapin and Cather (1983) further subdivided some Laramide basins, including the Raton and South Park Basins, based on the presence of late Laramide, Eocene-age sediments. They consider the northern end of the Raton Basin the Huerfano Park Basin, and they call the western and southern parts of the South Park Basin the Echo Park Basin (Figure 2-25). Chapin and Cather described three types of Laramide basins: a Green River type, a Denver type, and an Echo Park type. The Green River-type basins are "large, equidimensional to elliptical basins bounded on three or more sides by uplifts, and they commonly contain lacustrine strata. The Denver-type basins are "elongate, open, asymmetrical, synclinal downwarps with a related uplift on one side." The Echo Park-type basins are "narrow, highly elongate, fault-bounded basins with through drainage and of strike-slip origin." The Denver Basin is the classic example of the Denver type. Raton Basin is also classified as a Denver type of basin. Echo Park Basin is the Echo Park type, as are the South Park and Huerfano Park Basins.



Map of the Colorado Plateau-Rocky Mountain area showing Eocene uplifts, basins, and selected structural features. Dotted line indicates approximate boundary of the Colorado Plateau in Eocene time. The overthrust belt (OB), and the Mogollon Highland (MH) are two thrust-related uplifts that border the area to the west and south, respectively. *Monoclinal uplifts* of the Colorado Plateau are the White River (WhR), San Rafael (SR), Uncompahgre (Un), San Juan (SJ), Circle Cliffs (CC), Monument (Mon), Kaibab (K), Echo Cliffs, (EC), Defiance (D), Zuni (Z), Lucero (Luc), Apache (A), and Morenci (Mor) uplifts. *Basement-cored uplifts* of the Laramide Rocky Mountains are the Beartooth (Bt), Bighorn (Bh), Black Hills (BH), Owl Creek (OC), Wind River (WR), Granite (G), Laramie (L), Hartville (H), Uinta (U), Sierra Madre (SM), Park (P), Medicine Bow (MB), Front Range (FR), Sawatch (Saw), San Luis (SL), Sangre de Cristo (SC), Wet (W), Nacimiento (N), Sandia (San), Sierra (S), and Tularosa (T) uplifts. *Green River-type basins* are the Bighorn (Bhb), Powder River (PRb), Wind River (WRb), greater Green River (GRb), Shirley (Sb, Hanna (Hb), Laramie (Lb), Uinta (Ub), Piceance (Pb), San Juan (SJb), and Baca (Bb) basins. *Denver-type basins* are the Denver (Db), Raton (Rb), and Sierra Blanca (SBb) basins. *Echo Park type basins* are the North Park-Middle Park (NPb), South Park (SPb), Echo Park (EPb), Huerfano Park (HPb), San Luis (SLb), Galisteo-El Rito (Gb), Carthage-La Joya (CJb), and Cutter sag-Love Ranch (CSb) basins. Pecos zone (PZ) data from Kelley (1971, 1972). Data for High Plateaus faults (HP) from Lovejoy (1976). Distribution of Eocene southwest-vergent thrust faults in southern Arizona and adjacent areas from Keith (1982, and personal communication). Apache uplift data from G.H. Davis, 1981, oral communication. Base map modified from the Tectonic Map of North America by King (1969).

Figure 2-25. Late Laramide-Eocene uplifts, basins, and selected structural features (modified from Chapin and Cather, 1983).

2.3.5 Middle and Late Cenozoic Tectonism

Although the middle Tertiary was a time characterized by widespread volcanism and relatively little documented evidence of major regional tectonism, local volcano-tectonic faulting was associated with the collapse of calderas (Steven, 1975). Middle Tertiary tectonic activity perhaps occurred on other faults, but subsequent late Cenozoic tectonism, volcanism, and/or sediment deposition may have obscured the evidence of the middle Tertiary faulting. The known mid-Tertiary volcanic-tectonic structures sometimes had large vertical displacement, but the faults were typically of limited lateral extent and were often restricted to the immediate vicinity of the volcano. Locations where middle Tertiary faulting probably occurred include the Thirtynine Mile volcanic field, Cripple Creek, the Westcliffe-Silver Cliff area, and perhaps the Sawatch Range. Erslev et al. (2004) also briefly described limited evidence of possible strike-slip movement on north-south-trending faults at Cripple Creek during the middle Tertiary.

In contrast, abundant evidence of late Cenozoic tectonism is well documented. Some, and perhaps much of it, is related to extensional stresses associated with the Rio Grande Rift. Most of the late Cenozoic faults have normal displacement and trend north-northwest. Although late Cenozoic tectonism is now widely recognized, it wasn't until the 1970s that evidence of its regional extent within the RGFO region was published. It was at about this same time that evidence of Quaternary faulting also was documented in the RGFO region.

Taylor (1975) was one of the first to describe evidence of late Cenozoic faulting in the Wet Mountain Valley, Upper Arkansas Valley, and South Park, and within and on the flanks of the Wet Mountains and southern end of the Front Range. Tweto (1978, 1979b) also described evidence of late Cenozoic faulting in these areas. Scott (1970) provided some of the first descriptions of Quaternary faulting in the RGFO region and pointed out their earthquake potential.

Kirkham and Rogers (1981) compiled data on late Cenozoic faults throughout Colorado, collected new data on them, and discussed the earthquake potential in the State. Colman (1985) prepared a map showing the tectonic features of late Cenozoic faults. The CGS maintains a database on late Cenozoic faults and folds and historical earthquakes at www.geosurvey.state.co.us/hazards/Earthquakes/Pages/Maps.aspx. The USGS has an online database that describes faults and folds with Quaternary movement. This database is located at www.earthquake.usgs.gov/hazards/qfaults.

Most late Cenozoic faults within the RGFO region are in or adjacent to the mountainous areas from about Golden southward to the Colorado-New Mexico border. Most trend north-northwest. Within the RGFO region, the Sawatch Fault and the Mosquito Fault in the Upper Arkansas Valley probably have the greatest amount of late Cenozoic vertical displacement. These faults form the west and east sides, respectively, of the graben in which the Upper Arkansas Valley is located. Thick deposits of late Cenozoic sediment (Dry Union Formation) are preserved within the graben. The down-to-east Sawatch Fault borders the east side of the uplifted Sawatch Range, and the down-to-west Mosquito Fault is on the west of the uplifted Mosquito Range.

Wallace et al. (1968) reported about 9,000 feet of vertical movement on the Mosquito Fault at the Climax mine during the late Cenozoic. Tweto and Case (1972) described the total vertical displacement across the Mosquito Fault and its subsidiary faults as being perhaps as much as 14,000 feet. The total late Cenozoic dip slip on the Sawatch Fault may be of a similar or perhaps greater magnitude. Paleoseismic studies of the Sawatch Fault indicate the fault is sectioned. The southern section (south of Granite) has strong evidence of late Quaternary movement (Ostenaa et al., 1981). Their paleoseismic investigation of the southern segment of the Sawatch Fault documented at least six surface faulting events in the past 100,000 to 150,000 years, including at least one during the Holocene that happened less than 4,000 years ago.

The Wet Mountain Valley also contains thick deposits of late Cenozoic sedimentary fill. The Alvarado Fault bounds the west side of the Wet Mountain Valley graben, and the Westcliffe Fault forms the east side of the graben (Taylor, 1975). The Ilse Fault and Wet Mountain Fault are on the west and east sides, respectively, of the uplifted Wet Mountains. Some of the lowering of the Wet Mountain Valley Graben probably was also accommodated by the down-to-west Ilse Fault. There may have been as much as 3,500 feet of dip-slip movement on the Wet Mountain fault and as much as about 1,600 feet of displacement on the Ilse Fault during the late Cenozoic (Taylor, 1975; Kirkham and Rogers, 1981).

Paleoseismology investigations by Shaffer (1980, 1981) and Shaffer and Williamson (1986) led to the discovery of three faults with late Quaternary movement in the southeastern part of South Park. The East-Side Chase Gulch Fault and West-Side Chase Gulch Fault are on the flanks of Spinney Mountain, and the Eleven Mile Fault is south of Elevenmile Canyon Reservoir.

Several faults in and adjacent to the Front Range were evaluated for Quaternary activity by Dickson et al. (1986), Dickson (1986), Dickson and Paige (1986), Yadon (1986), Hornback (1986), and Steele (1986) for the Denver Water Department’s proposed Two Forks dam. The investigated faults included the Rampart Range, Floyd Hill, Ken Caryl, Kennedy Gulch, Ute Pass, Oil Creek, and Perry Park-Jarre Canyon Faults, all of which had reported evidence of late Cenozoic movement. Evidence of post-middle Pleistocene movement was documented on the Rampart Range Fault during these studies, and a faulted Quaternary colluvial deposit was found along the Oil Creek Fault. No evidence of late Quaternary movement was detected on any of the other studied faults, and some were demonstrated to have last moved over at least 125,000 to 190,000 years ago.

Two faults with evidence of Quaternary movement were located in the Great Plains in the southeastern part of the RGFO region: the Cheraw Fault and an inferred fault near Fowler (Scott, 1970; Sharps, 1976; Kirkham and Rogers, 1981). Crone et al. (1997) conducted a paleoseismic investigation of the Cheraw Fault and documented three late Quaternary surface ruptures on the fault. They occurred between 8,000 and 12,000 years ago, and between 20,000 to 25,000 years ago. The total fault displacement during the past 20,000 to 25,000 years amounts to about 12 feet (~3.7 m). In contrast, subsequent work by Unruh et al. (1994) and Jack Benjamin and Associates and Geomatrix Consultants (1996) discounted the evidence of Quaternary activity on the inferred fault near Fowler, and they questioned whether it is a tectonic structure.

Kirkham (1977) described evidence of post-middle Quaternary movement on a fault near Golden based on exposures in a paleoseismic trench. This investigation was one of the first efforts outside of California to use trenching to evaluate the Quaternary behavior of a fault. He assumed the trenched fault was part of the Golden Fault system. Dames & Moore Group (1981) and Darrow and Krusi (1982) conducted investigations of the main trace of the Golden Fault as part of a seismic hazard evaluation for Rocky Flats. They concluded that the Golden Fault had not moved during the past 500,000 years, but anomalous features exposed in their trenches prompted Rogers (1981) and Colman et al. (1981) to question this conclusion (Widmann et al., 1998).

2.4 Rock Units (Lithology and Stratigraphy)

The RGFO region extends across a large area with a very complex geologic history. Because of this, the stratigraphy and types of rocks in the RGFO region are also very complex. A generalized geologic map of the RGFO region is presented in Figures 2-26, 2-27, and 2-28. A generalized stratigraphic nomenclature chart of Phanerozoic sedimentary rocks is depicted in Figure 2-29, which is modified from the stratigraphic chart by Pearl (1980) using references cited in this section of the MPR.

The stratigraphic chart shows the formations in various parts of the RGFO region, including (1) South Park and Sawatch Range, (2) Front Range Piedmont area, (3) Denver and Cheyenne Basins and northeastern Colorado area, (4) southeastern Colorado area, and (5) Raton Basin; as depicted in Figure 2-8 and Figure 2-14, above. Note that some formations are only locally present within these areas.

Precambrian and Paleozoic rocks are exposed only in mountainous areas in the western part of the RGFO region and in the foothills adjacent to the mountain front (see Map 2.1). Elsewhere within the RGFO region, these older rocks are covered by younger rocks and surficial deposits. The only exceptions are found in the canyons cut by the Purgatoire River, the Dry Cimarron River, and their tributaries in the southernmost part of the RGFO region, where rocks as old as the Permian are locally exposed. Mesozoic rocks crop out extensively across much of the RGFO region, but they are also covered by widespread mantles of Quaternary surficial deposits and the late Pliocene Ogallala and Arikaree Formations. Knowledge of the older rocks that are covered by younger rocks chiefly comes from deep drill holes, which are relatively sparse in many areas.

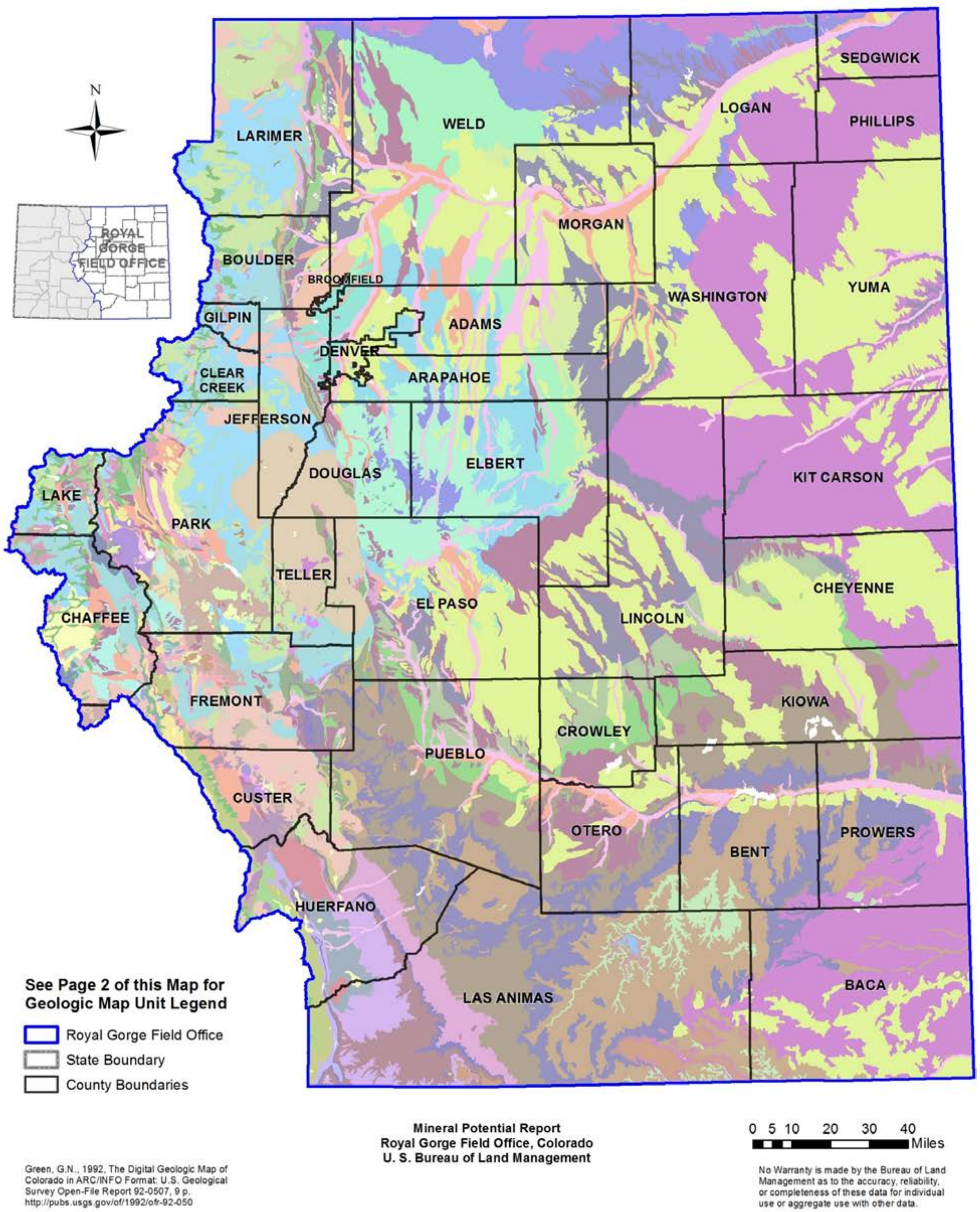


Figure 2-26. Geologic map of the Royal Gorge Field Office.

Figure 2-27. Legend for Figure 2-26, Geologic map of the Royal Gorge Field Office.

Figure 2-28. Legend (cont'd) for Figure 2-26, Geologic map of the Royal Gorge Field Office.

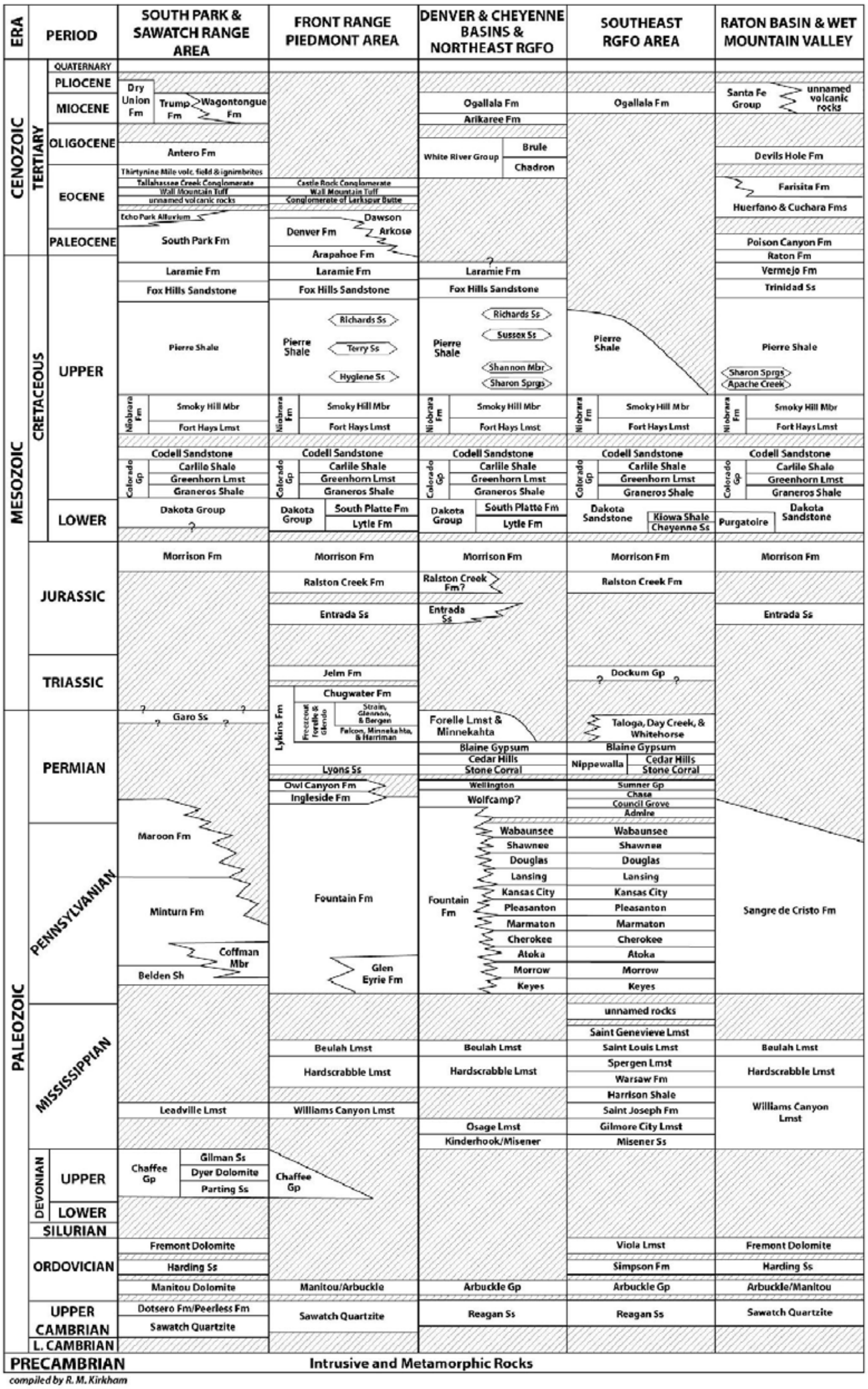


Figure 2-29. Generalized stratigraphic nomenclature chart of Phanerozoic sedimentary rocks.

An online reference to access relevant stratigraphic information and references for bedrock formations can be found at http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html. This website currently is a few years out of date, but it may be updated in the future.

2.4.1 Precambrian Rocks

No universally accepted nomenclature has been developed for the Precambrian rocks in the RGFO region. In many cases, the Precambrian rocks are named using their age (e.g., Paleoproterozoic, Mesoproterozoic, and Neoproterozoic) and lithology (e.g., felsic gneiss, granodiorite). Note that no Archean rocks are known to exist in the RGFO region. Tweto (1987) described the Precambrian rocks in Colorado and defined a general system of rock units that continues to be used by many geologists. He also published a map showing the distribution of the Precambrian rocks in outcrop and in the subsurface across the RGFO region.

The oldest rocks are included in a Paleoproterozoic gneiss complex by Tweto (1987). Ball (1906) was the first to apply the name Idaho Springs Formation to biotite gneisses in the Idaho Springs-Georgetown area. However, the name was used by other geologists for similar rocks in varying stratigraphic positions across much of the Front Range, and the name has lost its stratigraphic significance (Tweto, 1987). Lovering (1935) applied the name Swandyke Hornblende Gneiss to a large body of hornblende gneiss in the Montezuma area in the Front Range, but this name also was indiscriminately applied, and the name no longer has stratigraphic significance.

Major igneous intrusions about 1.7 billion years old were grouped into the Routt Plutonic Suite by Tweto (1987). The Boulder Creek Granodiorite is a widespread batholith that typifies the rock types in the Routt Plutonic Suite within the RGFO region. Boreholes in eastern Colorado encountered rocks of the Routt Plutonic Suite in the subsurface in several areas.

Another major episode of igneous intrusion occurred during the Mesoproterozoic about 1.4 billion years ago. Tweto (1987) included these rocks in the Berthoud Plutonic Suite. Examples of the named intrusive rocks of this age include the widespread Silver Plume Granite (also called the Silver Plume Quartz Monzonite), the Cripple Creek Granite in the southern Front Range, and the San Isabel Granite in the Wet Mountains. The rocks in the Kenosha, Longs Peak-Saint Vrain, Log Cabin, and Sherman batholiths are also included in this rock suite. Rocks of the Berthoud Plutonic Suite are also widespread in the subsurface in the southern part of the RGFO region. Drill holes in the southern part of the RGFO region also led to the discovery of a thick sequence of moderately metamorphosed sedimentary and volcanic rocks of Mesoproterozoic age that are included in the Las Animas Formation (Tweto, 1987).

The granitic rocks associated with the Neoproterozoic Pikes Peak Batholith are the third major suite of igneous rocks in the RGFO region. The batholith was intruded into older Proterozoic rocks about 1 billion years ago. The best known rock unit in this suite is the Pikes Peak Granite.

Numerous scattered mafic intrusions of late Neoproterozoic or early Paleozoic age locally occur within the southwestern part of the RGFO region (e.g., Kirkham et al., 2005). These intrusions typically are gabbroic in composition. At least two of the kimberlitic diatremes in the Colorado-Wyoming kimberlite province, some of which contain diamonds, were emplaced during the Neoproterozoic (Lester et al., 2001).

2.4.2 Lower and Middle Paleozoic Rocks

The Lower and Middle Paleozoic rocks are best understood where they outcrop in the western part of the RGFO region, but even in this area the correlation of some strata is not clearly established. Less is known about these rocks in the Great Plains Province where these rocks lie deep in the subsurface and knowledge about them comes from relatively few and widely spaced drill holes. Lower and/or Middle Paleozoic rocks crop out on the east flank of the southern Front Range, but they are missing from the east flank of the central and northern Front Range.

The Upper Cambrian Sawatch Formation, a white, silica-cemented quartzite that is also sometimes called the Sawatch Quartzite, is the oldest Phanerozoic sedimentary formation in the RGFO region. It is variable in thickness, locally absent, and called the Reagan Sandstone in the eastern and southern parts of the RGFO region (Lochman-Balk, 1972; Ross and Tweto, 1980; Myrow et al., 1999, 2003). The Upper Cambrian Dotsero Formation overlies the Sawatch Formation in the westernmost part of the RGFO region. The Dotsero Formation, which is well developed in the White River Plateau area west of the RGFO region, consists of shale, sandstone, dolomite, and dolomitic sandstone that locally is glauconitic. In contrast to prior studies that subdivided the Dotsero into two members, Myrow et al. (2003) subdivided the Dotsero into four members. In ascending order, they are the Sheep Mountain, Red Cliff, Glenwood Canyon, and Clinetop Members.

Many of the older studies (e.g., Lochman-Balk, 1972; Ross and Tweto, 1980) included the Upper Cambrian strata that overlie the Sawatch Quartzite in the central and eastern parts of the RGFO region in the Peerless Formation, which is composed chiefly of siliciclastic and carbonate rocks. Relationships between the Dotsero and Peerless were not well understood until Myrow et al. (2003) conducted detailed studies that involved the tracing of the members of the Dotsero in the White River Plateau area eastward into the Mosquito Range. They concluded that much of the strata previously included in the Peerless in the central and eastern parts of the RGFO region should be included in the Sawatch Quartzite, and that the Peerless Formation may be restricted to only the Mosquito and eastern Sawatch Ranges. Houck et al. (2012) recently mapped and described the uppermost Cambrian rocks in the Marmot Peak quadrangle as the Dotsero Formation. Apparently both the Peerless and Dotsero Formations may exist in the Mosquito Range.

Three alkaline intrusive complexes of Cambrian age are recognized in the Wet Mountains (Armbrustmacher, 1984). A variety of mineral resources are associated with these intrusive rocks, collectively called the Wet Mountain Alkalic Intrusive Complex.

A major unconformity separates the Cambrian rocks from overlying Ordovician rocks (Myrow et al., 2003). Three Ordovician formations exist in the west-central part of the RGFO region: the Lower Ordovician Manitou Dolomite, the Upper Ordovician Harding Sandstone, and overlying Fremont Dolomite (Houck et al., 2012). The Harding and Fremont crop out along the east flank of the southern Front Range in the vicinity of Colorado Springs, and they are also found to the west of this area. The Manitou is also present in these areas. Lindsey (2010) indicates the southern extent of these formations in the Sangre de Cristo Range is north of La Veta Pass. An isopach map by Ross and Tweto (1980; Figure 4) suggests the Manitou and its equivalents should exist most places in the subsurface beneath the Great Plains Province in the central and southern parts of the RGFO region.

The Manitou Dolomite is also known as the Manitou Limestone or Manitou Formation. In addition to carbonate rocks, the formation locally includes chert nodules, lenses, and beds. The Manitou is in part equivalent to the upper part of the Arbuckle Group, found locally in the subsurface beneath the Great Plains. Myrow et al. (2003) divide the Manitou into a thin basal unit called the Taylor Pass Member and an overlying much thicker Ptarmigan Chert Member (not shown in Figure 2-29). The Harding Sandstone is composed chiefly of silica-cemented sandstone with local minor amounts of shale and siltstone. The Fremont Dolomite (or Formation) consists of crystalline dolomite and sandy dolomite in the Marmot Peak quadrangle (Houck et al., 2012).

Upper Ordovician rocks also exist in the subsurface in the southeastern corner of the RGFO region (Ross and Tweto, 1980). These include the Simpson Group, which is age-equivalent to the Harding Sandstone, and the Viola Formation, which is age-equivalent to the Fremont Dolomite. The Harding and the Fremont are on the western side of the buried Las Animas Arch and the Simpson and Viola are on the eastern side of the arch (Foster, 1972).

No stratified Silurian rocks are known to exist within the RGFO region. However, blocks of Silurian limestone occur within kimberlitic diatremes in the Colorado-Wyoming kimberlite province in the northwestern part of the RGFO region (Chronic et al., 1969). These diatremes with blocks of Silurian and Ordovician rocks are thought to have formed before the period of erosion that removed the Silurian strata from this area prior to sedimentation during the Devonian, and they certainly were emplaced prior to deposition of the Pennsylvanian sediments (Chronic et al., 1969).

The Upper Devonian Chaffee Group represents all Devonian strata within the RGFO region. It is found in the Sawatch and Mosquito Ranges and in and near the southern end of the Front Range. Formations within the Chaffee include, in ascending order, the Parting Sandstone, Dyer

Dolomite, and—locally—the Gilman Sandstone (Tweto and Lovering, 1977). As the name implies, the Parting is chiefly composed of sandstone that locally is hard indurated quartzite, and minor shale and/or dolomitic sandstone. The Dyer typically is a microcrystalline dolomite or limestone that locally contains layers of chert and/or eolian sand grains (Tweto and Lovering, 1977; Houck et al., 2012).

The Lower Mississippian Leadville Limestone is the only Mississippian Formation in the Sawatch and Mosquito Ranges (De Voto, 1980a). It often is dolomitic, contains black chert nodules and lenses, and is also known as the Leadville Dolomite, Dolostone, or Formation. Locally it is recrystallized into alternating black and white layers known as zebra rock. In the eastern piedmonts of the Front Range and Wet Mountains, the Williams Canyon, Hardscrabble, and Beulah Limestones represent the Mississippian Section (De Voto, 1980a); however, Scott and Taylor (1975) considered the Hardscrabble and Beulah Limestones to be equivalent to the Leadville Limestone. The Williams Canyon Limestone crops out locally along the eastern piedmont of the Front Range from Douglas County southward and also in Custer County (Maher, 1950). Ross and Tweto (1980) assigned a Late Devonian age to the Williams Canyon Limestone and correlated it with the Dyer Dolomite, but Poole and Sandberg (1991) modified the age to Early Mississippian and reported that it intertongued with the Leadville Limestone.

The Mississippian Madison Limestone may be locally present in the subsurface in the north-central part of the RGFO region (De Voto, 1980a). Pearl (1980) indicates that the Kinderhook Limestone, Osage Limestone, Hardscrabble Limestone, and Beulah Limestone exist in the subsurface beneath the northeastern part of the RGFO region. In the southeastern part of the RGFO region, De Voto (1980a) reported that the subsurface Mississippian Section includes, in ascending order, the Misener Sandstone, Gilmore City Limestone, Saint Joseph Formation, Harrison Shale, Warsaw Formation, Spergen Formation, Saint Louis Formation, Saint Genevieve Formation, and unnamed Chesterian-age rocks. These units are shown in Figure 2-29. Pearl (1980) described a somewhat different Mississippian stratigraphy for the southeastern part of the RGFO region.

2.4.3 Upper Paleozoic Rocks

Upper Paleozoic sedimentary rocks were deposited in the Central Colorado Trough in the west-central and southwestern parts of the RGFO region and also east of the Ancestral Front Range Uplift and Apishapa Uplift in the eastern part of the RGFO region. Sea level changes during the Pennsylvanian affected sedimentary deposition, as the shoreline of the sea repeatedly migrated and produced cyclic sequences equivalent to the cyclothems found in the midcontinent (Houck, 1997).

The Pennsylvanian stratigraphy in the South Park area has been variably interpreted over the years by different geologists. In support of the recent CGS geologic mapping program in South Park, a series of stratigraphic sections were measured from Hoosier Pass to southwestern South

Park by K. J. Houck and correlated with the section by Tweto (1949) in the Pando area. The interpretative results of this effort are described and mapped by Kirkham et al. (2005; 2007; 2012a), Widmann et al. (2005, 2011), and Houck et al. (2012). This stratigraphy is used in this report.

In the central part of the Central Colorado Trough, in the Sawatch and South Park areas, the Pennsylvanian strata include, in ascending order, the Belden Shale, Minturn Formation, and Maroon Formation. The Lower and Middle Pennsylvanian Belden Shale consists of mainly black to dark-gray shale with thin limestone and rare thin sandstone interbeds. The Middle Pennsylvanian Minturn Formation is several thousand feet thick, lithologically variable, and locally subdivided into as many as four members or facies: the lower, upper, and Coffman members and an evaporite facies (Kirkham et al., 2012; Houck et al., 2012).

The upper member of the Minturn Formation is very thick and locally comprises almost all of the Minturn strata. It contains sandstone, siltstone, shale, calcareous shale, limestone, and gypsiferous shale. The evaporite facies is locally present within the upper member. Sandstone and shale are the main rock types in the much thinner lower member. The conglomeratic Coffman Member usually occurs between the upper and lower members, but in the Jones Hill quadrangle it also interfingers with the upper part of the Belden Shale (Widmann et al., 2011).

The Maroon Formation overlies the Minturn. Strata within the Maroon Formation are mostly Late Pennsylvanian in age, but may range from Middle Pennsylvanian to Early Permian in age. Maroon Formation rocks are chiefly sandstone and siltstone. De Voto (1965) identified the Garo Sandstone above the Maroon and assigned a Permian age to it. Other workers considered it to be Jurassic in age, and Bryant et al. (1981) correlated it with the late Middle Jurassic Entrada Sandstone.

Most Permian and Pennsylvanian rocks in the southern part of the Central Colorado Trough (Sangre de Cristo Range) are included in the thick Sangre de Cristo Formation, which is mainly composed of sandstone, siltstone, and conglomerate. A well-known member of the formation is the Crestone Conglomerate. Near the Colorado-New Mexico line, the Middle Pennsylvanian Madera Formation underlies the Sangre de Cristo Formation (Bolyard, 1959; Kirkham et al., 2005; Fridrich and Kirkham, 2008). It includes the Whiskey Creek Pass Limestone Member. Further north in the Sangre de Cristo Range and in the southernmost end of the Mosquito Range the Kerber, Sharpsdale, and Minturn Formations underlie the Sangre de Cristo Formation (Pierce, 1972; De Voto et al., 1971; Wallace et al., 2000). A chart showing the stratigraphic nomenclature by these authors is in Wallace et al. (2000; Figure 2). Not all of the above described Pennsylvanian Formations are shown in Figure 2-29.

On most of the eastern side of the Front Range, the Pennsylvanian rocks, chiefly sandstone with minor conglomerate and siltstone, are included in the Fountain Formation. The upper part of the Fountain Formation is Early Permian in age. De Voto (1980b) indicates the Upper

Pennsylvanian Casper Formation may be present in the stratigraphic section near the Colorado-Wyoming line. These rocks are overlain in ascending order by the Lower Permian Ingleside Formation, Owl Canyon Formation, and Lyons Sandstone, and the Upper Permian-Lower Triassic Lykins Formation, which consists of several members (Maughan, 1980) (Figure 2-29). A poorly exposed and poorly understood rock unit called the Glen Eyrie Formation underlies (or is a facies of) the Fountain Formation in the Colorado Springs area (Chronic and Williams, 1978). Maher (1946) extended the Glen Eyrie into the subsurface beneath Otero County. The Lyons Sandstone is correlated with the Stone Corral Dolomite in the subsurface in the eastern part of the RGFO region.

In the subsurface of the Denver Basin and in the eastern and southeastern Colorado areas, the Fountain Formation and other Pennsylvanian rocks grade into other rock units. In ascending order they include the Keyes Sandstone, Morrow Formation, Atoka Formation, Cherokee Shale, Marmaton Formation, Pleasanton Group, Kansas City Formation, Lansing Formation, Douglas Formation, Shawnee Formation, and Wabaunsee Formation (Rascoe, 1978; Pearl, 1980). These rocks are overlain by Wolfcampian rocks and the Wellington Formation and Stone Corral Dolomite. In the subsurface of the Denver Basin, near the Front Range piedmont, the upper part of the Lykins Formation grades into the Permian Minnekahta, Harriman, Falcon, Freezeout, Forelle, Glendo, and Chugwater Formations (Pearl, 1980). Deeper in the Denver Basin and in eastern Colorado, the Lykins grades into the Cedar Hills Formation, Blaine Gypsum, Minnekahta Limestone, and Forelle Limestone (Pearl, 1980). In southeastern Colorado, the Lykins transitions into the Permian Nippewalla Group, Blaine Gypsum and overlying Permian Whitehorse Group, Day Creek Dolomite, and Taloga Formation.

2.4.4 Triassic and Jurassic Rocks

Except for the upper part of the Lykins Formation, which is Lower Triassic in age and locally includes the Chugwater Formation, Triassic rocks are relatively scarce in the RGFO region. The Upper Triassic Jelm Formation locally exists east of the northern end of the Front Range, and the Upper Triassic Dockum Group is present locally in the subsurface beneath the southern and east-central parts of the RGFO region (MacLachlin, 1972).

Triassic rocks also crop out in a small area on the eastern side of the Culebra Range immediately north of the Colorado-New Mexico line (Kirkham et al., 2005). Johnson and Baltz (1960) included these rocks in the Johnson Gap Formation and described 11 units within it. Lucas et al. (1990) restricted the formation to only the upper two units (units 10 and 11) and reassigned units 1 to 9 to the Trujillo Formation. Because these Triassic rocks are limited to a very small area, they are not shown on Figure 2-29.

The Middle Jurassic Entrada Sandstone is the oldest Jurassic formation in the RGFO region (Berman et al., 1980; Peterson, 1972). It crops out along the east sides of the Front Range, Wet Mountains, and Culebra Range and probably lies beneath much of the Great Plains. The Late

Jurassic Ralston Creek Formation locally overlies the Entrada east of the Front Range and in southeastern Colorado (Berman et al., 1980; Pearl, 1980). The Late Jurassic Morrison Formation apparently was originally deposited everywhere in the RGFO region and is still preserved there except where it was eroded during the Laramide and late Tertiary uplifts. The Morrison Formation consists of variegated mudstone, sandstone, and limestone deposited in continental environments.

2.4.5 Cretaceous Rocks

As the Western Interior Seaway transgressed and regressed across the RGFO region during the Cretaceous, thick sequences of clastic and carbonate sediment accumulated. Because the strata contain rich mineral resources, they have been studied in detail. This has resulted in many interpretations of the stratigraphy and numerous formation names and nomenclature changes over the years. The following is a generalized summary of the Cretaceous rock units in the RGFO region.

The Lower Cretaceous Dakota Group was deposited over the Morrison Formation as the seaway transgressed across the RGFO region (Berman et al., 1980). The Dakota contains sandstone, shale, siltstone, and locally thin coal beds. Because it is one of the premier hydrocarbon reservoir rocks, it has received much attention by geologists over the years. Robert Weimer authored many of the more recent studies of the Dakota in the Denver Basin. In some areas, such as South Park, it is generally mapped as a single unit and called the Dakota Sandstone (e.g., Kirkham et al., 2007a,b), but in the Denver Basin and much of eastern Colorado it is often subdivided into two formations: the Lytle Formation and overlying South Platte Formation. The South Platte Formation is often further subdivided into members and/or facies, such as the Plainview Sandstone, Skull Creek Shale, Muddy or “J” Sandstone, Huntsman Shale, and “D” Sandstone (Berman et al., 1980). In western Colorado, the Mowry Shale is usually considered to overlie the Dakota, but within the RGFO region the Mowry is considered to be within the uppermost part of the Dakota Group. In the Raton Basin, the Dakota includes a basal unit called the Purgatoire Formation, which some have considered to be a separate formation. In southeastern Colorado, some workers recognize the Cheyenne Sandstone and Kiowa Shale, which has been considered equivalent to the Purgatoire Formation, as basal members of the Dakota Group.

Upper Cretaceous strata overlying the Dakota Group have been variously classified as the Colorado Group and Benton Group, and no clear consensus seems to exist as to which nomenclature system best categorizes the rocks. This report relies primarily upon the stratigraphic charts of Pearl (1980) and Berman et al. (1980).

The Colorado Group overlies the Dakota Group in the RGFO region. The marine Graneros Shale is the basal member of the Colorado Group. It is overlain by the Greenhorn Limestone, which is sometimes further subdivided into the Lincoln Limestone Member, Hartland Shale

Member, Jetmore Chalk Member, and Bridge Creek Limestone Member. Berman et al. (1980) describe the Pfeifer Shale Member at the top of the Greenhorn, but a search of the online USGS GEOLEX stratigraphic database did not result in any sources of information for this member. The upper unit in the Colorado Group is the Carlile Shale.

Overlying the Colorado Group is the Codell Sandstone, which some consider to be a member of the Carlile Shale. For example, Berman et al. (1980) describe the Carlile in eastern Colorado as containing in ascending order the Fairport Chalky Shale Member, Blue Hill Shale, Codell Sandstone, and Juana Lopez Member.

All geologists are in agreement that the marine Niobrara Formation overlies the Carlile. They also agree that the basal member of the Niobrara is the Fort Hays Limestone and that strata overlying the Fort Hays are within the Smoky Hill Shale Member of the Niobrara. There is also consensus that the thick marine Pierre Shale overlies the Niobrara. Numerous members of the Pierre Shale have been described in the literature, and not all geologists agree upon the internal stratigraphy of the Pierre. In the Front Range piedmont area, the Pierre Shale includes occasional sand bodies such as the Hygiene Sandstone, Terry Sandstone, and Richards Sandstone. Further east, members in the Pierre include the Sharon Springs, Shannon, Sussex, and Richards Members (Pearl, 1980). One of the more detailed studies of the Pierre Shale in the northern Denver Basin is by Kiteley (1978). She recognized several other members within the Pierre. In ascending order, they include the Gammon Ferruginous Member, Sharon Springs Shale Member, Mitten Black Shale Member, Hygiene Sandstone Member, Terry Sandstone Member, Rocky Ridge Sandstone Member, Larimer Sandstone Member, and Richard Sandstone Member. She also recognized several unnamed or generically named members. In the Walsenburg area, Scott and Cobban (1963) described the Apache Creek Sandstone and its relationship to the overlying Sharon Springs Member. No attempt is made to show the all the numerous and variously defined members of the Pierre in Figure 2-29.

As the Western Interior Seaway regressed across the RGFO region, shoreline and near-shore deposits blanketed the deeper marine sediments of the Pierre Shale. The interbedded shale and sandstone in the transitional zone between the dominantly marine mud of the Pierre and the massive shoreline sands are included in the uppermost part of the Pierre by some geologists. Others include the transitional zone with the overlying massive shoreline sandstones. In the Denver and Cheyenne Basins, and also in South Park, these shoreline sandstones are called the Fox Hills Sandstone, whereas in the Raton Basin and Cañon City Embayment they are known as the Trinidad Sandstone. These are the youngest marine deposits in the RGFO region.

2.4.6 Laramide Synorogenic Sedimentary and Volcanic Rocks

Laramide synorogenic sediment overlies the Fox Hills Sandstone and Trinidad Sandstone. The coal-bearing, continental, Upper Cretaceous Laramie Formation was deposited over the Fox Hills Sandstone in the Denver and Cheyenne Basins and in South Park. In the Raton Basin and

Cañon City Embayment, the equivalent coal-bearing formation is named the Vermejo Formation. In the northern and central parts of the Denver Basin, the Laramie is overlain by the Upper Cretaceous Arapahoe Formation, a conglomeratic unit that is in turn overlain by the lignite-bearing Upper Cretaceous-Paleocene Denver Formation. In the southern part of the Denver Basin, the Dawson Arkose/Dawson Formation replaces the Denver Formation and perhaps all of the Arapahoe Formation. This traditional stratigraphic interpretation is used in Figure 2-29.

Recent work by Thorson (2011) and Raynolds (1997, 2002) has modified this traditional stratigraphy. The interpretation by Thorson (2011) is based on recent geologic mapping in the southwestern part of the Denver Basin. He replaces the Arapahoe and Denver Formations with what he calls the Denver Basin Group. In ascending order, it consists of the Upper Cretaceous Pikeview Formation (new name); Upper Cretaceous-Paleocene Pulpit Rock Formation (new name); Upper Cretaceous-Paleocene Jimmy Camp Formation (new name); Upper Cretaceous-Paleocene Denver Formation; Paleocene Black Squirrel Formation (new name); and Paleocene-Eocene Dawson Arkose.

In contrast, Raynolds (1997, 2002) focused more on the central and northern parts of the Denver Basin and used data from two complete core holes, as well as geophysical logs from bore holes. Raynolds subdivides these rocks into only two unconformity bounded units: a lower D1 sequence and an upper D2 sequence. In Raynold's model, the D1 sequence was deposited in the Denver Basin as the central Front Range was uplifted during the Laramide Orogeny and andesitic volcanic rocks, presumed to cap the Front Range, were eroded from the uplift. A widespread paleosol formed at the top of the D1 sequence prior to uplift of the southern part of the Front Range. Arkosic sediment was eroded from the southern Front Range as it rose and was deposited in the D2 sequence over the D1 sequence.

The Laramie Formation is very thick in the Cheyenne Basin, and younger Laramide synorogenic rocks, such as the Arapahoe, Denver, and Dawson Formations, have not been recognized in this basin. It is possible that rocks age-equivalent to the Arapahoe, Denver, and Dawson may exist in the Laramie Formation in the Cheyenne Basin.

In the Raton Basin, the coal-bearing Upper Cretaceous-Paleocene Raton Formation overlies the Vermejo Formation; it is, at least in part, age-equivalent to the above described strata in the Denver basin. Overlying the Raton Formation are the Paleocene Poison Canyon Formation and Eocene Cuchara Formation, Huerfano Formation, and Farisita Conglomerate (Scott and Taylor, 1975; Lindsey, 1996). The Poison Canyon Formation is also present in the Cañon City Embayment. In South Park, the Laramie Formation is overlain by the Upper Cretaceous-Paleocene South Park Formation, which Kirkham et al. (2007a,b), Ruleman and Bohannon (2008), and Bohannon and Ruleman (2009) have subdivided. Another Laramide-age synorogenic sedimentary unit in the RGFO region is the Eocene Echo Park Formation in southeastern South Park and the Thirtynine Mile volcanic field (Epis and Chapin, 1974).

Many Laramide intrusive rocks exist within the mountainous western part of the RGFO region, including the Montezuma stock in the central Front Range and Whitehorn Granodiorite in the southern Mosquito Range. Laramide-age volcanic rocks are mostly known from their eroded clasts preserved in formations such as the Denver Formation and South Park Formations. Laramide volcanic flows are preserved in the Upper Cretaceous-Paleocene Reinecker Ridge Volcanic Member and Paleocene Link Springs Tuff Member of the South Park Formation. The lava flows that cap North and South Table Mountain near Golden are also Laramide-age volcanic flows.

2.4.7 Mid-Tertiary Rocks

Three mid-Tertiary deposits have been identified in the piedmont area of the Front Range near Castle Rock. They are the recently discovered conglomerate of Larkspur Butte and the long-recognized Wall Mountain Tuff and Castle Rock Conglomerate, all late Eocene in age (e.g., Thorson, 2005). The conglomerate of Larkspur Butte was deposited on an unconformity eroded into the Laramide synorogenic rocks in this part of the Denver Basin. This conglomerate unit is overlain by the Wall Mountain Tuff, a regional marker bed dated at 36.7 million years (Ma) by McIntosh and Chapin (2004). Remnants of the Wall Mountain Tuff are also found to the west in South Park and the Thirtynine Mile volcanic field. The Castle Rock Conglomerate is the youngest of the three mid-Tertiary units in the Castle Rock area. It contains fossils of Chadronian (late Eocene) titanotheres, indicating the Castle Rock Conglomerate is between 35.7 and 33.7 Ma old (Thorson, 2005).

Mid-Tertiary sediments also accumulated in the northeastern part of the RGFO region, where thick deposits of ashy siltstone in the late Eocene-Oligocene White River Group overlie an unconformity cut across Cretaceous rocks. Tuffs within the White River Group range in age from 35.5 to 29 Ma (Evanoff and Larson, 2007), and the group is subdivided into the Chadron and overlying Brule Formations. The Oligocene Devils Hole Formation was deposited at the southern end of the Wet Mountain Valley (Scott and Taylor, 1975).

The mid-Tertiary sedimentary and volcanic rocks in South Park, the Mosquito Range, Upper Arkansas Valley, and Sawatch Range appear to be the result of a complicated period of episodic volcanism, sediment deposition, and erosion. Many of these rocks occur in disconnected locations, and correlation of the deposits in one area with those in another area requires high-resolution absolute age dates and good paleontological interpretations. The oldest rocks in this area include unnamed, Eocene-age, andesitic flows and tuffs at Buffalo Peaks in the central Mosquito Range and age-equivalent andesitic flows in South Park in the Salt Creek area (Kirkham et al., 2012a; Houck et al., 2012; Widmann et al., 2011).

Seven Late Eocene and Early Oligocene regional ignimbrites (ash-flow tuffs) and several less extensive ones are recognized in the central Colorado volcanic field (McIntosh and Chapin, 2004). They range in age from about 38.2 to 32.9 Ma. Remnants of these flows are best preserved in the Thirtynine Mile volcanic field, and remnants are also locally preserved in other areas within the west-central part of the RGFO region, including in the Great Plains near the town of Castle Rock. McIntosh and Chapin (2004) described the following ignimbrites in the RGFO region:

- Tuff of Buffalo Peaks (38.2 Ma)
- Lower Tuff of Triad Ridge (37.5 Ma)
- Wall Mountain Tuff (36.7 Ma; an excellent regional marker bed possibly erupted from a caldera in the Sawatch Range and is found as far east as near the town of Castle Rock in the Great Plains)
- Tuff of Stirrup Ridge (36.5 Ma)
- Upper Tuff of Triad Ridge (36.2 Ma)
- Grizzly Peak Tuff (34.3 Ma)
- Antero Tuff (33.8 Ma)
- Badger Creek Tuff (33.8 Ma)
- East Gulch Tuff (33.7 Ma)
- Thorn Ranch Tuff (33.7 Ma)
- Gribbles Park Tuff (32.9 Ma)

The Eocene Tallahassee Creek Conglomerate overlies and is clearly younger than the Wall Mountain Tuff in South Park, although its exact age is as yet poorly constrained (Kirkham et al., 2012a). It contains very large boulders as much as 20 feet in length. The origin of these deposits and the hydrodynamic properties that enabled large boulders to be transported long distances are not well understood.

Kirkham et al. (2007) discovered a thick ash-flow tuff in a paleovalley near Fairplay, possibly representing a previously unrecognized ignimbrite or an outflow tuff from the Grizzly Peak Caldera. The ignimbrites were erupted from calderas, four of which have been recognized in the Sawatch Range, including two within the RGFO region: the Grizzly Peak and Mount Aetna calderas. Large plutons and a batholith in the Sawatch Range are thought to be the intrusive remnants of other calderas. Mid-Tertiary plutons in the Sawatch Range include the 34.3 Ma Mount Princeton batholith, 34.1 Ma pluton at Mount Aetna, and the 29.6 Ma pluton at Mount Antero.

The Oligocene Antero Formation overlies the regional ignimbrites in the southwestern part of South Park. The Antero consists of thick deposits of reworked volcanic ash that locally is altered to mudstone, at least one ash-flow tuff, and beds of limestone and conglomerate (De Voto, 1971; Kirkham et al., 2007, 2012).

Other mid-Tertiary eruptive centers in the RGFO region, described by McIntosh and Chapin (2004), include Cripple Creek (32.5-30.0 Ma), Silver Cliff-Rosita Hills (35.4-32.9 Ma), Guffey (36.1 Ma), Waugh Mountain (31.6-31.3 Ma), and Nathrop (30.4-28.9 Ma). Various suites of extrusive rocks are associated with these eruptive centers, several of which host important metallic mineral deposits.

2.4.8 Late Tertiary Rocks

The High Plains in the eastern part of the RGFO region are underlain by the Miocene Ogallala Formation, which consists of non-indurated gravel and sand, ashy sand and silt, volcanic ash, and limestone or pisolitic caliche, and is moderately resistant to erosion (Scott, 1978). The Ogallala is locally underlain by the Lower Miocene Arikaree Formation in the northeastern part of the RGFO region, which comprises indurated conglomerate, sandstone, siltstone, and claystone, as well as non-indurated gravel and sand.

Miocene and/or Pliocene volcanic flows, mainly basaltic in composition, cap mesas in the southern and southeastern parts of the RGFO region (Scott, 1968a; Johnson, 1969; Miggins, 2002). Miocene volcanic flows are also present on the western flank of the Raton Basin on and east of the crest of the Culebra Range (Kirkham et al., 2005). Miocene-age sediments of the Santa Fe Group also exist in this area of the Culebra Range, in a small area adjacent to the New Mexico State line. Pliocene to Miocene mafic dikes and sills intrude the Cretaceous and early Tertiary sedimentary rocks in the Raton Basin, and the stocks at Spanish Peaks, Mount Mestas, Morley Dome, and Goemmer Butte are Miocene or late Oligocene (Miggins, 2002).

Thick Miocene and Pliocene sedimentary deposits of the Santa Fe Group are preserved in the Wet Mountain Valley (e.g., Tweto, 1979a; Scott et al., 1978). Thick sedimentary deposits of the Miocene to Pliocene Dry Union Formation fill the Upper Arkansas Valley Graben between Salida and Leadville (e.g., Scott et al., 1978; Tweto et al., 1976, 1978). The correlative Santa Fe and Dry Union Formations both locally contain volcanic ash beds derived from distant sources. Miocene sediments in the Trump and Wagontongue Formations are preserved in two synclines (Antero and High Creek Synclines) in southwestern South Park (De Voto, 1971; Kirkham et al., 2007, 2012).

2.4.9 Quaternary Deposits

Unconsolidated sand, gravel, silt, and minor clay of Quaternary age mantle the bedrock in many parts of the RGFO region (Tweto, 1979a). These deposits are not shown on Figure 2-26 due to the scale. These sediments include deposits of glacial till, glacial outwash, and stream and sheet-wash alluvium. Mass-wasting deposits are common in the mountains, and eolian deposits blanket much of the bedrock in the Great Plains. The youngest of these deposits are Holocene in age. The ages of pre-Holocene deposits typically are related to the late Pleistocene Pinedale glaciation, the late to middle Pleistocene Bull Lake glaciation, or pre-Bull Lake glaciations as determined by relative age-dating techniques such as pedogenic soil development and weathering characteristics. Absolute age-dating methods, including radiocarbon dating, luminescence dating, and cosmogenic dating methods, have been applied to the deposits in some areas, frequently for engineering geology purposes such as paleoseismology. Beds of volcanic ash are locally present in the Pleistocene deposits; for example, the Lava Creek B ash erupted from the Yellowstone caldera about 639,000 years ago (Lanphere et al., 2002). Volcanic ash can provide absolute age data for the Quaternary deposits.

2.5 Geophysics and Geochemistry

The following section provides a brief discussion of available information sources for geophysical and geochemical data in the RGFO management area. Geophysics and geochemistry are valuable tools for locating, evaluating, and guiding the development of mineral resources. Gravity, aeromagnetic, electrical, and radiometric methods are all types of geophysical methods used in mineral exploration and development. Geochemistry involves the study of the distribution of chemical elements and natural compounds in rock, soil, water, vegetation, and the atmosphere, as well as chemical processes that affect the earth. Geochemical anomalies can be indicators of undiscovered mineral deposits.

Online aeromagnetic and gravity maps and data for the State of Colorado by Oshetski and Kucks (2000) are available at http://pubs.usgs.gov/of/2000/ofr-00-0042/colorado.htm. An earlier version of the aeromagnetic map of Colorado was produced by Zietz and Kirby (1972), and an earlier version of the gravity map was by Behrendt and Bajwa (1974).

Examples of how geophysical data have been used in the RGFO region include Tweto and Case (1972), who used gravity and magnetic features to interpret the geology in the Leadville 30-minute quadrangle, and Sims et al. (2001), who used aeromagnetic data to develop a map of Precambrian basement rocks in Colorado. Much of the recent USGS geophysical work in Colorado has focused on the Rio Grande Rift. Site-specific or area-specific geophysical data are also available in many publications, including the following:

- Bankey (2010), "*A review of aeromagnetic anomalies in the Sawatch Range, central Colorado*"
- Bankey and Goldak Airborne Surveys (2006), "*Digital data from the Leadville/Buena Vista aeromagnetic survey covering parts of Chaffee, Eagle, Lake, Park and Summit Counties, Colorado*"
- Case (1967), "*Geophysical ore guides along the Colorado Mineral Belt*"
- Drenth et al. (2009), "*Digital data from the Great Sand Dunes and Poncha Springs aeromagnetic surveys, south-central Colorado*"

- Moss and Abrams (1985), "*Geophysical maps of the Vasquez Peak Wilderness Study Area and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand and Summit Counties, Colorado*"
- Pearson and Johnson (1980), "*Mineral resources of the Indian Peaks Study Area, Boulder and Grand Counties, Colorado, with a section on interpretation of aeromagnetic data*"
- Sherrard et al. (1984), "*Gravity survey data and a Bouguer gravity anomaly map of the Lost Creek Wilderness and vicinity, Park and Jefferson Counties, Colorado*"

Another source of past, current and future geophysical information for specific areas within the RGFO region is the Geophysics Department at the Colorado School of Mines. Each year the Geophysics Department operates a summer field camp, usually in Colorado. Typically, one or more geophysical theses are produced as a result of the summer field camp, and some of these may be of use to the BLM. The theses are available at the Colorado School of Mines library.

Geochemical analyses on whole-rock samples are typically performed in order to identify fine-grained igneous rocks, although if minor and trace elements are included in the whole-rock analysis they can be useful in the evaluation of mineral potential and mineral deposits. Assays for various metals are more commonly used for mineral exploration, mine planning, and mining. Geochemical analysis of stream-sediment and soil samples is commonly employed in efforts to locate geochemical anomalies, and chemical analyses of groundwater, surface water, and vegetation are also sometimes used.

The USGS is a major source of geochemical information, and much of this is available online, using the National Geochemical Database (NGDB). An overview of the NGDB is described in USGS Mineral News, Volume 1, Number 2 (September 2002), with an online version of the overview found at http://minerals.usgs.gov/news/newsletter/v1n2/2geochem.html.

The USGS chemically analyzed rock, soil, and stream sediments starting shortly after it was established in 1879. Geochemical digital data storage began in the late 1960s. The databases are continuing to evolve and expand, currently containing analyses of nearly 2 million samples of geologic materials. A significant number of the analyzed samples are from the RGFO region.

For many years, the USGS maintained two separate chemical laboratories, each with their own database. From the late 1960s to the late 1980s, the Rock Analysis Storage System (RASS) contained analyses for samples from mineral resource assessments and investigations. Most of these analyses were of stream sediment, although soil, rock, heavy mineral concentrates, and vegetation also were sometimes tested. Nationally, over 700,000 samples were analyzed, and over 23 million analytical determinations were performed during RASS.

The second laboratory database was called PLUTO, which stores analyses from topical studies such as geologic mapping, volcanic hazards, energy resources, etc. from the 1970s through the 1990s. These analyses are primarily whole-rock analyses, but also include stream sediment, soil, and vegetation. Nearly 500,000 samples have been analyzed, and over 20 million analytical determinations have been made during PLUTO. The analytical data in PLUTO and RASS can be located at http://tin.er.usgs.gov/geochem/. This website also has links to other databases, including geophysics, geologic mapping, and geochronology. The USGS Digital Data Series DDS-47 (Baedecker et al., 1998) also contains PLUTO data.

In 1985, the USGS was assigned the responsibility for all data generated by the U.S. Department of Energy's (DOE's) National Uranium Resource Evaluation (NURE). About one-half million samples of stream sediment, soil, and water were collected and analyzed during this project. Originally only uranium was analyzed, but samples were eventually tested for over 50 elements. The NURE data are available at http://pubs.usgs.gov/of/1997/ofr-97-0492/index.html. The NURE data are often retrieved using 1° x 2° USGS quadrangles: for example, 1,060 sediment samples and 1,570 water samples from the Denver 1° x 2° quadrangle were analyzed during NURE.

All data in the above described three geochemical databases have been or are in the process of being incorporated into the NGDB, which continues to be a work in progress. The National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration is also another source of geochemical and geophysical data. Information on the NGDC can be found at www.ngdc.noaa.gov/ngdcinfo/onlineaccess.html.

Other sources of geochemical data include numerous site-specific investigations that have been conducted within the RGFO region. Many of these were performed for wilderness areas, wilderness study areas, and roadless areas, as well as studies of known mining districts. The USGS and U.S. Bureau of Mines (USBM) conducted many of these investigations. Mineral-resource studies of national forests, geologic quadrangle maps, and academic theses may also contain geochemical data. Examples of reports available for the RGFO area include the following:

- Barton (1985), "*Geochemical maps showing the distribution and abundance of selected elements in heavy-mineral concentrates of stream sediments from the Vasquez Peak Wilderness Study Area and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand, and Summit Counties, Colorado*"
- Bielski et al. (1983), "*Mine and prospect map of the Vasquez Peak Wilderness Study Area and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand, and Summit Counties, Colorado*"
- Budding and Lawrence (1983a), "*Geochemical analyses of rock, stream-sediment, and heavy-mineral samples collected from the Spanish Peaks Wilderness Study Area, Huerfano and Las Animas Counties, Colorado*"
- Budding and Lawrence (1983b), "*Geochemical map of the Spanish Peaks Wilderness Study Area, Huerfano and Las Animas Counties, Colorado*"

- Caine and Bove (2010), "*Rock geochemistry and mineralogy from fault zones and polymetallic fault veins of the central Colorado Front Range*"
- Domenico and Sanzolone (1985), "*Analytical results and sample locality map of stream sediment, heavy-mineral-concentrate, and rock samples from the Lost Creek Wilderness Area, Jefferson and Park Counties, Colorado*"
- Ellis et al. (1983), "*Mineral investigation of the Sangre de Cristo Wilderness Study Area, Alamosa, Custer, Fremont, Huerfano, and Saguache Counties, Colorado*"
- Kirkham et al. (1980), "*Hydrogeologic and stratigraphic data pertinent to uranium mining, Cheyenne Basin, Colorado*"
- Leibold et al. (1986), "*Mineral resources of the Browns Canyon Wilderness Study Area (CO-050-002), Chaffee County, Colorado*"
- Leibold et al. (1987), "*Geochemical evaluation of the mineral resources of the Browns Canyon area, Chaffee County, Colorado*"
- Miggins (2002), "*Chronologic, geochemical, and isotopic framework of igneous rocks within the Raton Basin and adjacent Rio Grande Rift, south-central Colorado and northern New Mexico*"
- Nelson-Moore et al. (1978), "*Radioactive mineral occurrences of Colorado and bibliography*"
- Nowlan and Gerstel (1985), "*Stream-sediment and panned-concentrate geochemical maps of the Buffalo Peaks Wilderness Study Area, Lake, Park, and Chaffee Counties, Colorado*"
- Pearson and Johnson (1980), "*Mineral resources of the Indian Peaks Study Area, Boulder and Grand Counties, Colorado, with a section on interpretation of aeromagnetic data*"
- Taylor et al. (1984), "*An assessment of the mineral resource potential of the San Isabel National Forest, south-central Colorado*"

3. DESCRIPTION OF ENERGY AND MINERAL RESOURCES

This section briefly introduces the wide array of known mineral resources identified in the RGFO region, including the types of deposits and general ways that potential was assessed. Potentially valuable minerals on Federal lands are classified according to a "disposition class" as *locatable*, *leasable*, or *salable*.

Locatable minerals are regulated by the General Mining Law of 1872, as amended (30 U.S.C. § 21 *et seq.*) and include most of the metallic minerals (e.g., gold, silver, copper, molybdenum, rare-earth elements, uranium, etc.) and also certain industrial minerals such as high-calcium limestone and gypsum, vermiculite, pegmatite-hosted non-metallic minerals, gemstones, etc. Locatable minerals are typically considered "hard-rock minerals" found in lode, vein, disseminated, or placer deposits, all of which are common in the RGFO region.

Leasable minerals are defined by the Mineral Leasing Act of 1920, as amended (30 U.S.C. § 181 *et seq.*) and include coal, oil and gas, geothermal resources and several other minerals such as potash, sodium, native asphalt, and bituminous rock. The Geothermal Steam Act of 1970, as amended (30 U.S.C. § 1001 *et seq.*) also authorizes and governs the lease of geothermal steam and related resources on public lands.

Salable minerals include nonmetallic minerals and industrial commodities (e.g., sand and gravel, building stone, clay, peat, pumice, fluorspar, etc.), falling under the purview of the Materials Act of 1947, as amended (30 U.S.C. § 601 *et seq.*). Salable mineral commodities are widespread throughout the RGFO region, primarily in surficial deposits.

According to the USGS (Arbogast et al., 2011):

> *Mineral disposition classes are broad, and deposits of a given mineral may fall into more than one class depending upon their location, geologic setting, composition and other factors such as case law, and land and/or mineral tenure. For example, clays and zeolite can be considered locatable, leasable, or salable. Pumice, depending upon its type, may be considered locatable (pumicite, volcanic ash, volcanic dust, and scoria) or it may be considered salable only (for example, volcanic cinders). Gypsum may be considered locatable or leasable (in the form of rock gypsum or anhydrite) or it may be salable only (if it is gypsite).*

Because of overlap in the mineral disposition classification system, this MPR does not attempt to categorize mineral commodities according to locatable, leasable, or salable status. Rather, the following mineral descriptions are grouped according to their occurrence type or anticipated end-use as a mineral commodity (i.e., precious metals, base metals, pegmatite minerals, construction materials, industrial minerals, etc.). Descriptions of these important mineral resources found in the RGFO region include a summary of the current and historic exploration and development of various mineral deposits, along with a discussion of the form and type of the mineral deposits and their geologic relationship. Additionally, descriptions of leasable energy minerals such as oil and gas, coalbed methane, and oil shale *are not* included in this MPR.

The objective of this section and section 4 of the MPR is to analyze the mineral resource potential of the vast area within the RGFO region on a general scale in order to establish a baseline. The USGS defines "mineral resource potential" as the likelihood of the presence of mineral resources in a defined area; however, it is not a measure of the amount of resources or their profitability. "Mineral resource" is defined as "a concentration of naturally occurring solid, liquid, or gaseous material not commonly concentrated in or on the earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" (USBM and USGS, 1980).

The potential for occurrence of mineral resources in the RGFO region is classified using the system outlined in BLM Manual 3031. As stated in Manual 3031, "potential" refers to the potential for the presence (occurrence) of a *concentration* of one or more energy and/or mineral resources. It does not refer to or imply potential for development and/or extraction of mineral resource(s). It does not imply that the potential concentration is or may be economic, that is, could be extracted profitably (BLM, 1985).

The BLM mineral potential classification system has two components (level of potential and level of certainty):

Level of Potential

O The geologic environment, the inferred geologic processes, and the lack of mineral occurrences do not indicate potential for the accumulation of mineral resources.

L The geologic environment and the inferred geologic processes indicate low potential for accumulation of mineral resources.

M The geologic environment, the inferred geologic processes, and the reported mineral occurrences or valid geochemical/geophysical anomaly indicate moderate potential for accumulation of mineral resources.

H The geologic environment, the inferred geologic processes, the reported mineral occurrences and/or valid geochemical/geophysical anomaly, and the known mines or deposits indicate high potential for accumulation of mineral resources. The known mines and deposits do not have to be within the area that is being classified, but have to be within the same type of geologic environment.

ND Mineral potential not determined due to lack of useful data.

Level of Certainty

A The available data are insufficient and/or cannot be considered as direct or indirect evidence to support or refute the possible existence of mineral resources within the respective area.

B The available data provide indirect evidence to support or refute the possible existence of mineral resources.

C The available data provide direct evidence but are quantitatively minimal to support or refute the possible existence of mineral resources.

D The available data provide abundant direct and indirect evidence to support or refute the possible existence of mineral resources.

Maps that accompany the text discussion of mineral occurrences can be found in section 7, Maps of Mineral Occurrence Potential. In general, these maps only depict color-coded areas with mineral potential ratings determined to be low (L), medium (M) or high (H). Areas of the RGFO region considered to have undetermined (ND) or no (O) potential are not included in the color-coding scheme and are displayed only as white or shades of gray associated with topographical relief within the background on individual mineral commodity maps.

In general, occurrence potential within the RGFO management area was generally assessed at a large scale (larger than mining district scale), accounting for general presence of mining districts, historic production, noted occurrences, and appropriate rock types/geologic settings. An area containing all of these features for a commodity will generally be designated as high potential; areas with fewer of these features are determined to be medium or low potential as appropriate. Within this larger scale, the unique geology, structural setting, and history of individual mining districts or locales were analyzed and incorporated into occurrence potential determinations. Occurrence potentials are defined within geologically similar areas, but not all individual locations within a designated area may have that same potential. For example, gold deposits that occur as veins are very localized (with veins sometimes only being several feet wide), but the potential for those veins to occur may cover a wide area made up of a specific rock type and/or structural setting. The area is simply one in which a concentration of mineral resources may occur.

Below is a general description of deposit types, locations, and methodology for determining potential by commodity.

3.1 Coal

In the RGFO management area, four designated coal regions host almost a thousand historic coal mines that operated between 1864 and 2002: the Denver, Cañon City, Raton Mesa, and South

Park Coal Regions (Carroll, 2006; Carroll and Bauer, 202; Landis, 1959a). The Denver Coal Region lies in the Colorado Piedmont Section of the Great Plains physiographic province, east of the Front Range. It extends from near Colorado Springs on the south, beyond the Colorado-Wyoming line on the north, and eastward to near the Town of Limon. The Denver Coal Region is the largest coal region in the RGFO region area and covers about 7,500 square miles. The Raton Mesa Coal Region, in the Raton Section of the Great Plains, lies east of the Sangre de Cristo Mountains and straddles the Colorado-New Mexico State line, covering about 1,250 square miles. The Cañon City Coal Region is also in the Great Plains Province. It occupies a relatively small area (~50 square miles) in the Cañon City Embayment, with the Wet Mountains to the south and west, the Front Range to the north, and the Great Plains to the east. The smallest and historically least-productive South Park Coal Region lies in an intermontane basin in the Southern Rocky Mountains Province between the Mosquito Range and Front Range. This coal region extends across an estimated 86 square miles in an area with very complex geology (Carroll, 2006).

Economically significant coal in all four regions occurs in either Late Cretaceous or early Tertiary rock units. Two formations contain coal in the Denver and Raton Mesa Coal Regions, whereas the Cañon City and South Park Coal Regions have only one coal-bearing formation. Figure 3-1 displays the coal regions and coal fields in the RGFO management area.

A major online source of information on coal resources currently is available from the USGS website at http://energy.usgs.gov/Coal/AssessmentsandData/CoalDatabases.aspx. These databases are part of the National Coal Resource Data System, which was developed by the Energy Resources Program of the USGS. This searchable database contains information on the location, quantity, and physical and chemical characteristics of coal in the United States, as well as published coal resource estimates from 1940 to 1978 and other information. Unfortunately, these databases have not been updated for decades.

Ambrose et al. (2001) and Hatch et al. (2006) contain more recent data on coal quality. Until the online databases are updated by the USGS, the best way to obtain the most current coal quality information is to directly contact the USGS. At the time of preparing this MPR, the contact at USGS for stratigraphic coal data was Joe East (jeast@usgs.gov), and the contacts for coal quality data were Susan Tewalt (stewalt@usgs.gov) or Charles Oman (coman@usgs.gov).

Areas within the Raton Mesa, Denver, and Cañon City Coal Regions, as well as the northern part of the South Park Coal Region, have a high potential for the occurrence of coal resources. Available data indicate that coal reserves in the central and southern parts of the South Park Coal Region are limited (Washburne, 1910). A 1-foot-thick coal bed was observed in one coal prospect and a coal bed less than 1-foot thick was observed in outcrop over a distance of several miles in this part of the South Park Coal Region (Scarbrough, 2001). Because coal may be absent or very thin in the central and southern parts of the South Park Coal Region, this area is assigned a moderate potential for coal occurrence potential. Coal quality and occurrence potential within the RGFO management area are depicted on Map 7-1 in section 7.

All areas where coal has been mined in the past are assigned a high occurrence potential, although the coal may have been partially removed by past underground mining or completely removed by past surface mining. The locations of coal mine sites were gathered from CDRMS (2016), Carroll (2006), Carroll and Bauer (2002), and Kirkham (1978a). Coal resources likely remain in areas between the old mines; in this regional study it is not feasible to depict the extent of past coal mining on maps in this MPR. Also, the size of the symbol that denotes historic coal mines on Figure 3-1 does not accurately portray the extent of the historic mining.

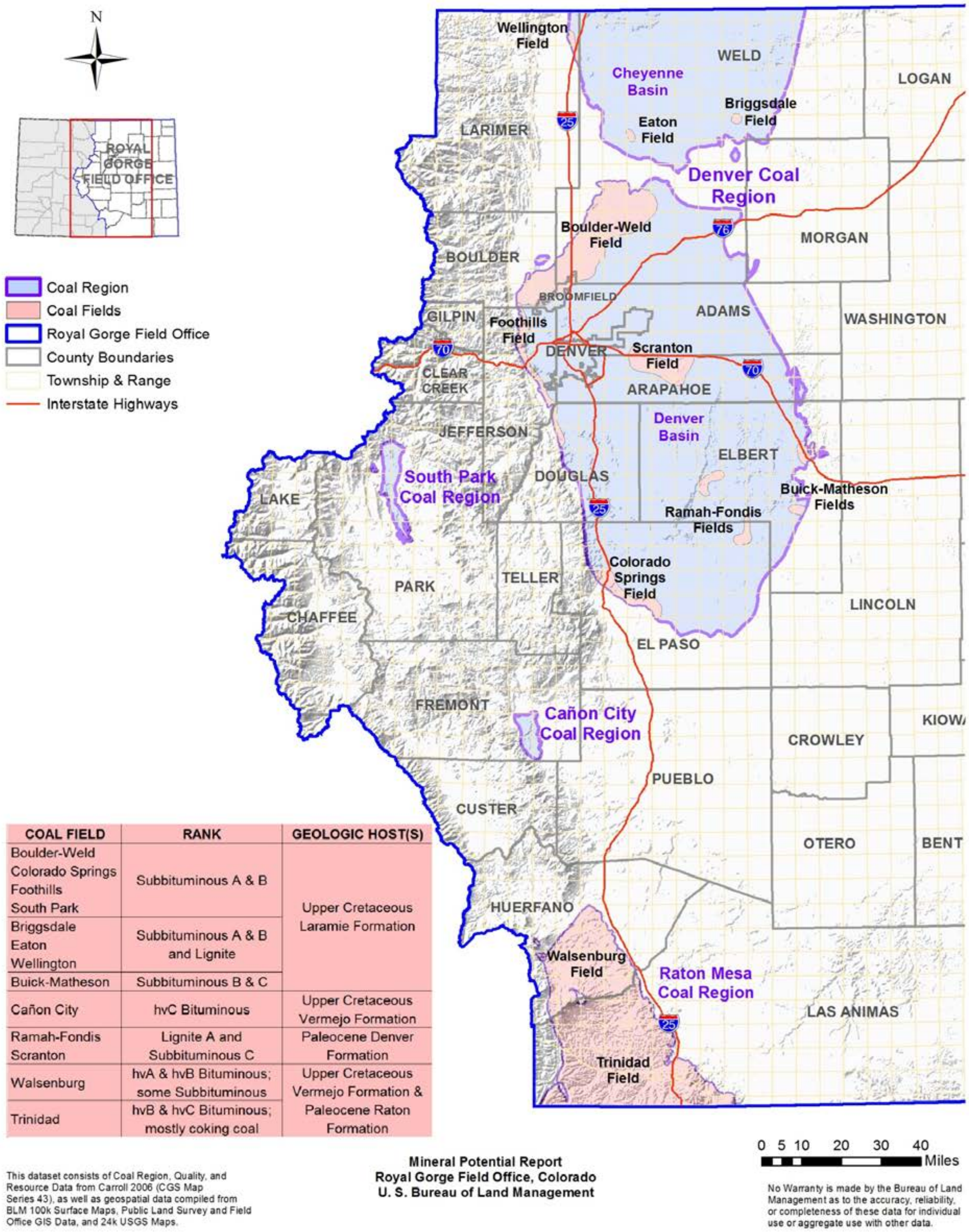
All areas within the Denver Basin area of the Denver Coal Region, as well as the Raton Mesa and Cañon City Coal Regions, are assigned a high occurrence potential. As described in the following section (3.1.1), reconnaissance-level studies by the CGS involving widely spaced drill holes demonstrate that parts of the Denver Basin have significant localized coal resources, but additional drilling is needed to confirm the existence of laterally extensive mineable coal.

The intrusive rocks at Spanish Peaks in the west-central part of the Raton Mesa Coal Region have replaced the coal in that area, and small dikes and sills within this coal region have also locally replaced the coal. The area with replaced coal at Spanish Peaks is large enough to show on Figure 3-1 and is excluded from the coal region; however, areas where dikes and sills have replaced coal are too small to depict on the map.

Available data on the occurrence of coal in the coal regions within the RGFO area are summarized in the following sections (3.1.1–3.1.4). Coal regions and fields are shown on Figure 3-1, as well as on the coal occurrence potential map (Map 7-1 in section 7).

3.1.1 Denver Coal Region

The Denver Coal Region, where coal is preserved within two large, asymmetrical, structural basins (Denver and Cheyenne Basins), is host to over 400 historic coal mines that produced 135.2 million tons of coal between 1950 and 2002 (Carroll and Bauer, 2002; Kirkham and Ladwig, 1979). The Denver Basin, in the southern part of the coal region, is separated from the Cheyenne Basin to the north by a structural high called the Greeley Arch, although the exact nature of this structure is not well understood (Kirkham and Ladwig, 1979). Coal-bearing strata have been removed by erosion across the Greeley Arch, resulting in two disconnected coal-bearing basins within the same coal region.



COAL FIELD	RANK	GEOLOGIC HOST(S)
Boulder-Weld Colorado Springs Foothills South Park	Subbituminous A & B	Upper Cretaceous Laramie Formation
Briggsdale Eaton Wellington	Subbituminous A & B and Lignite	
Buick-Matheson	Subbituminous B & C	
Cañon City	hvC Bituminous	Upper Cretaceous Vermejo Formation
Ramah-Fondis Scranton	Lignite A and Subbituminous C	Paleocene Denver Formation
Walsenburg	hvA & hvB Bituminous; some Subbituminous	Upper Cretaceous Vermejo Formation & Paleocene Raton Formation
Trinidad	hvB & hvC Bituminous; mostly coking coal	

Figure 3-1. Coal regions and fields in the Royal Gorge Field Office.

Axes of the synclinal basins trend north-south and are located near the mountain front. Coal beds dip moderately to very steeply east along the western margins of the basins and are gently west dipping in the broad eastern flanks of the synclines. Numerous faults disrupt the coal beds in the northwestern part of the Denver Basin, forming discrete segmented structural blocks that are either upthrown (horsts) or downthrown (grabens) (Roberts et al., 2001). The faults are thought to be listric and flatten with depth in strata well below the coal zones.

The Denver Basin extends from about Colorado Springs northward to Greeley, and from the foothills eastward nearly to Limon. Approximately 107 million tons of coal was recovered from mines in the Boulder-Weld coal field in the northwestern part of the Denver Basin (Kirkham and Ladwig, 1979; Carroll, 2006). Underground mines in the Boulder-Weld coal field used vertical shafts to access coal beds, in contrast to most other underground coal mines in the RGFO region that used adit, slope, or shaft portals constructed at or near coal outcrops (Kirkham and Ladwig, 1979). Production of 16.2 million tons of coal is reported from the Colorado Springs coal field between 1882 and 1957 (Kirkham and Ladwig, 1979). About 6.6 million tons of coal were mined in the Foothills coal field along the western edge of the Denver Basin (Kirkham and Ladwig, 1979). Relatively small tonnages of coal or lignite were recovered from mines in the Buick-Matheson coal field and Ramah-Fondis coal field in the southeastern part of the Denver Basin and the Scranton coal field east of the Denver metropolitan area.

The Cheyenne Basin occupies the northern part of the Denver Coal Region. Only the southern part of the Cheyenne Basin lies within Colorado; its northern part is within Wyoming. Less than 66,000 tons of coal were recovered from all the known mines in the Cheyenne Basin (Kirkham and Ladwig, 1979). Most mined coal in this basin (~57,000 tons) was produced from the Wellington coal field along the western margin of the Cheyenne Basin (Kirkham and Ladwig, 1979). The Eaton coal field north of Greeley and the Briggsdale coal field in the southeastern part of the basin accounted for the remainder of coal production.

Most of the coal mined in the Denver Basin and all of the coal produced in the Cheyenne Basin were recovered from the Upper Cretaceous Laramie Formation. In the Denver Basin, the economical coal seams are located within 300 feet of the base of the Laramie Formation, although the exact stratigraphic position of the lower Laramie coal zone varies. Numerous individual coal beds usually are present within the lower Laramie coal zone. They range up to about 25 feet in thickness, but typically are less than 10-feet thick. Relatively little is known about the lower Laramie coal zone in the Cheyenne Basin. Mined coal beds are as much as about 8-feet thick, but generally they are about 5-feet thick or less. Some mined beds were as thin as 2-feet 10-inches thick. A minor coal zone locally exists within the upper part of the Laramie Formation in the Cheyenne Basin in the vicinity of the towns of Nunn and Purcell. The maximum known thickness of these coal beds is only 1.5 feet (Kirkham, 1978a).

The Laramie coal beds crop out around the perimeters of both basins. They lie at depths suitable for surface mining in a zone of varying width on the northern, eastern, and southern sides of the

Denver Basin. Because of current mining technology, surface mining has not yet occurred along the western side of the Denver Basin, most likely due to the steep dips of strata in that area. The coal beds also occur at depths suitable for surface mining in a zone of varying width around the Cheyenne Basin. The coal beds gradually deepen towards the axis of the basins. They are as much as 2,900 feet deep in the Denver Basin and are over 1,500 feet deep in the Cheyenne Basin (Kirkham and Ladwig, 1979).

In the Denver Basin, coal is also found in Paleocene-age lignite beds of the Denver Formation, some attaining thicknesses in excess of 50 feet (Soister, 1972, 1974; Kirkham and Ladwig, 1979; Brand and Eakins, 1980). The Denver Formation is younger than the Laramie Formation and is separated from it, at least locally, by the Arapahoe Formation. Denver Formation lignite beds are present only in the central and eastern parts of the basin. The lignite beds are at depths suitable for surface mining in several areas, and most of the lignite resources are less than 1000-feet deep. Recent studies have resulted in modifications to the stratigraphic nomenclature of the Denver Formation and other strata above and below it (e.g., Raynolds, 2002; Thorson, 2011). This research may result in new formation names being applied to the strata within the Denver Formation.

Coal in the Laramie Formation typically is classified as low-sulfur, subbituminous B coal to lignite A (Kirkham and Ladwig, 1979). Laramie coal with higher heat values (~8,500 to 9,700 Btu/pound) is found along the western side of the Denver Basin (Kirkham and Ladwig, 1979). Coal with the highest heat values are found in the southwestern part of the Boulder-Weld coal field near the mountain front (Kirkham, 1978a). Along the eastern margin of the Denver Basin some Laramie coal is subbituminous C or even lignite, having heat values averaging about 6,100 to 7,000 Btu/pound (Kirkham, 1978a). Laramie coal in the Cheyenne Basin apparently contains slightly lower heat values than most Laramie coal in the Denver Basin. For example, in the Wellington coal field along the western side of the Cheyenne Basin the heat values average about 7500 Btu/pound. Sulfur concentrations in the Wellington coal field were high relative to other areas in both basins (1.7 percent versus less than 1 percent elsewhere) (Kirkham, 1978a). No analyses are available for Laramie coal in the deeper parts of either the Denver or Cheyenne Basins.

Lignite in the Denver Formation ranges from about 4,000 to 7,000 Btu/pound, has 8 to 30 percent ash, and low sulfur concentrations ranging from 0.2 to 0.6 percent (Kirkham and Ladwig, 1979). Carroll (2006) indicates some of the highest quality Denver lignite beds may classify as subbituminous C coal. No trace element analyses, including mercury, were found for coal in the Denver Coal Region.

According to the online DRMS database (CDRMS, 2016), there is one active coal mine permit in the Denver Coal Region: the Keenesburg Strip mine, operated by Coors Energy Company (Permit No. C1981-028). This mine is located in the northeastern part of the Denver Basin. It produced coal from the Laramie Formation during the 1980s, but currently is undergoing reclamation. Ash from the coal-fired Trigen Colorado Steam & Electric Plant at the Coors Brewery in Golden, Colorado is being hauled to the mine and used to backfill the strip mine pit.

The Federal Government owns the coal in numerous tracts scattered across the Denver Coal Region. Most of the tracts within the Denver Basin are concentrated along the eastern and southeastern part of the basin in areas underlain by Laramie coal, or they are in the central part of the basin in areas where Denver lignite is at relatively shallow depths. Other tracts with Federal coal lie in the southwestern and northeastern part of the Denver Basin. Within the Cheyenne Basin, the tracts with Federal coal are concentrated along the eastern margin and central part of the basin.

Landis (1959) estimated coal reserves at 5.3 billion tons in only 836 square miles of the Denver Coal Region; he also reported prior estimates from Hills (1893), Campbell and Clark (1916), Vanderwilt (1947), and Spencer and Erwin (1953). Boreck and Murray (1979) estimated original demonstrated resources at about 4 billion tons, with a total reserve base depletion at the end of 1976 of 0.26 billion tons (depletion includes both mined coal production and coal wasted in pillars or beneath permanent roads and structures), yielding a remaining reserve resource base of about 3.75 billion tons. Tremain et al. (1996) estimated reserves of 38 billion tons of subbituminous Laramie coal and 34 billion tons of Denver lignite.

Carroll (2006) described the original coal resources in the Denver Coal Region as 5.3 billion tons and the remaining coal reserves at 5.1 billion tons. Additional published literature on coal in the Denver Coal Region include Brand (1980); Brand and Caine (1980); Colton and Lowrie (1973); Eakins and Ballenski (1983); Goldman (1910); Kirkham (1978b, 1978c); Kirkham and Ladwig (1980); Martin (1910); Richardson (1917); Sanchez (1976); Sanchez and Hobbs (1977); and Weimer (1976, 1977).

Detailed coal resource information is available for selected areas in the Denver Basin. For the Denver East ½º x 1º quadrangle, refer to Brand and Eakins (1980); for the Castle Rock ½º x 1º quadrangle refer to Eakins and Ellis (1987); and for the Colorado Springs ½º x 1º quadrangle refer to Eakins (1986). For more detailed information on the coal resources of the Denver Coal Region, please refer to the following publications:

CGS Resource Series 5, "*Coal resources of the Denver and Cheyenne Basins, Colorado*" by Kirkham and Ladwig (1979), which contains the following plates:

Plate 1, Figure 1:	Depth to the top of the Laramie Formation coal zone (scale = 1:500,000)
Plate 1, Figure 2:	Areas known to be underlain by Laramie coal beds five feet thick or greater (1:500,000)
Plate 2, Figure 1:	Maximum individual lignite bed thickness in the Denver Formation (1:250,000)

Plate 2, Figure 2: Total lignite bed thickness in the Denver Formation (1:250,000)

Plate 3, Figure 1: Isopach map of the E lignite bed, Watkins area (1:50,000)

Plate 3, Figure 2: Extent of the alluvial valley floor and overburden thickness above the E lignite bed, Watkins area (1:50,000)

Plate 4, Figure 1: Isopach map of the Comanche bed, Station Creek area (1:50,000)

Plate 4, Figure 2: Extent of the alluvial valley floor and overburden thickness above the Comanche bed, Station Creek area (1:50,000)

Plate 4, Figure 3: Total thickness of lignite beds in the Denver Formation, Station Creek area (1:50,000)

Plate 5: Cross sections of the Denver Formation lignite beds, Denver Basin, Colorado

CGS Resource Series 13, "*Coal resources of the Denver East ½º x 1º quadrangle, Colorado*" by Brand and Eakins (1980), which contains the following plates:

Plate 1: Report text and stratigraphic columns

Plate 2: Index map of Laramie Formation drill holes and cross sections, and outline of the Antelope Flats-Deer Trail study area (scale = 1:100,000)

Plate 3: Map of the Laramie Formation coals suitable for stripping and in situ gasification (1:100,000)

Plate 4: Total coal thickness map of the Laramie Formation coal zone (1:100,000)

Plate 5: Structure map of the Laramie Formation coal zone (1:100,000)

Plate 6: Isopach map of the upper "A" coal bed, Laramie Formation, Antelope Flats-Deer Trail area (1:50,000)

Plate 7: Structure map of the upper "A" coal bed, Laramie Formation, Antelope Flats-Deer Trail area (1:50,000)

Plate 8: Isopach map of the "B" coal bed, Laramie Formation, Antelope Flats-Deer Trail area (1:50,000)

Plate 9: Structure map of the "B" coal bed, Laramie Formation, Antelope Flats-Deer Trail area (1:50,000)

Plate 22: Cross-sections of the Denver Formation, Watkins-Lowry area (J-J' to M-M')

Plate 23: Table I. Drill hole points of the Laramie Formation coal zone

Table II. Drill hole points of the Denver Formation coal zone

Plate 24: Table III. Coal resource estimates

Plate 25: Table III. Coal resource estimates (continued)

CGS Resource Series 25, "*Coal resources of the Castle Rock ½º x 1º quadrangle and adjacent area, Colorado*" by Eakins and Ellis (1987), which contains the following plates:

Plate 1: Isopach map of total coal in the Laramie Formation coal zone, west of the Buick-Matheson area (scale = 1:100,000)

Plate 2: Structure contour and overburden isopach map on the Laramie Formation coal zone, west of the Buick-Matheson area (1:100,000)

Plate 3A: Structure contour map on the A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 3B: Isopach map of the A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 3C: Overburden isopach map of the A coal bed/Upper A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 4A: Structure contour map on the Upper A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 4B: Isopach map of the Upper A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 5A: Structure contour map on the Lower A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 5B: Isopach map of the Lower A coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 6A: Structure contour map on the B coal bed, Laramie Formation, Buick-Matheson area (1:100,000)

Plate 16: Cross sections F-F' through H-H' showing the coal bearing interval of the Denver Formation, Ramah-Fondis area

Plate 17: Cross sections I-I' through K-K' showing the coal bearing interval of the Denver Formation, Ramah-Fondis area

CGS Resource Series 27, "*Coal resources of the Colorado Springs ½º x 1º quadrangle, Colorado*" by Eakins (1986), which contains the following plates:

Plate 1: Index map of data points compiled at a scale of 1:100,000 and index of quadrangles with data compiled at a scale of 1:24,000

Plate 2: Index map of drill hole and mine data points, Colorado Springs 7.5' quadrangle (1:24,000)

Plate 3: Index map of drill hole and mine data points, Corral Bluffs 7.5' quadrangle (1:24,000)

Plate 4: Index map of drill hole and mine data points, Hanover NE 7.5' quadrangle (1:24,000)

Plate 5: Index map of drill hole and mine data points, Hanover NW 7.5' quadrangle (1:24,000)

Plate 6: Index map of drill hole and mine data points, Pikeview 7.5' quadrangle (1:24,000)

Plate 7: Index map of drill hole and mine data points, Yoder 7.5' quadrangle (1:24,000)

Plate 8: Isopach map of the A coal bed, Laramie Formation (1:100,000)

Plate 9: Structure contour map on the A coal bed, Laramie Formation (1:100,000)

Plate 10: Overburden isopach map of the A coal bed, Laramie Formation (1:100,000)

3.1.2 Raton Mesa Coal Region

The RGFO portion of the Raton Mesa Coal Region, which straddles the Colorado-New Mexico border and coincides with the asymmetrical synclinal Raton Basin, is host to over 380 historic coal mines (Boreck and Murray, 1979; Carroll and Bauer, 2002; Landis, 1959a; Flores and Bader, 1999; Tremain et al., 1996). Carroll (2006) reports production of 264 million tons of coal from the RGFO portion of the Raton Mesa Coal Region, which falls entirely within Huerfano and Las Animas Counties. The region lies east of the Sangre de Cristo Mountains and extends eastward to Trinidad and Walsenburg. Carroll (2006) shows a narrow finger of the coal region extending from near the town of La Veta northwestward for several miles.

The arcuate axis of the Raton Basin generally trends north-south and lies near the mountain front. Along the western side of the basin, the coal beds dip very steeply to the east or are overturned, and they are cut by faults. Local anticlines (e.g., Tercio Anticline) and synclines (e.g., Cuatro Syncline) also deform the coal strata on the western side of the basin (Johnson, 1961; Fridrich and Kirkham, 2008). In contrast, on the eastern side of the basin, the coal beds dip gently to the west and are seldom disrupted by faults and folds.

Two formations host coal in the Raton Mesa Coal Region: the Upper Cretaceous Vermejo Formation and the overlying Upper Cretaceous to Paleocene Raton Formation. These formations are genetically similar to the Laramie Formation and Denver Formation in the Denver Coal Region. Coal was first discovered in the Raton Mesa Coal Region in 1821 by an exploration party led by S.H. Long (Lee, 1917). Landis (1959) subdivided the Colorado part of the Raton Mesa Coal Region into the Walsenburg coal field and the Trinidad coal field. Coal mines within Huerfano County were included in the Walsenburg coal field, and the mines in Las Animas County were included in the Trinidad coal field. Justification for the subdivision was that the Las Animas County mines produced coal suitable for coking, whereas those in Huerfano County, except for a few located near the county line, did not. In contrast, Johnson (1958, 1961) included most coal mines in Las Animas and Huerfano Counties in the Trinidad coal field.

Late Tertiary mafic to intermediate composition stocks, sills, and dikes intrude the coal-bearing strata across much of the Raton Mesa Coal Region (Miggins, 2002; Wallace, 2004). The major stocks include those at Spanish Peaks and Mount Mestas; prominent dikes radiate from stocks at the Spanish Peaks; and sills are pervasive throughout much of the coal region (Vanderbilt, 1947). The metamorphic effects of heat from the igneous stocks locally increased the coal rank and in places even coked the coal, whereas the dikes caused little to no alteration of the coal beds. (Vanderbilt, 1947). The sills, which often intruded along coal bedding planes, resulted in alteration, assimilation, and local destruction of the coal beds (Flores and Bader, 1999). Hundreds of millions of tons of coal may have been destroyed by the sills, and heat associated with the sills locally metamorphosed the coal into coke (Pillmore, 1969). The Morley Dome is a result of an intrusion of a large sill or igneous plug that caused overlying strata to be up-arched, causing the Morley mine to be gassy with methane (Johnson, 1961; Wood et al., 1957).

Most mines in the Walsenburg coal field were located either along the eastern or northern rim of the Raton Basin in the vicinity of the town of Walsenburg, or along the western margin of the basin near the town of La Veta. Most coal produced in the Walsenburg coal field came from the Vermejo Formation. Mines were widespread across the Trinidad coal field, and they produced from both the Vermejo and Raton Formations. The Colorado Fuel and Iron Corporation operated many of the mines in the Raton Mesa Coal Region.

The USGS undertook the first regional studies of coal in the RGFO portion of the Raton Mesa Coal Region. Lee (1917) and D. A. Carter (1956) described the geology and coal deposits of the region. Subsequent detailed USGS investigations of selected areas include the Stonewall-Tercio area by Wood et al. (1951); the La Veta area by Johnson and Stephens (1954a; 1954b); the Gulnare, Cuchara Pass, and Stonewall area by Wood et al. (1956); the Starkville-Weston area by Wood et al. (1957); the Walsenburg area by Johnson (1958); and the Trinidad-Aguilar area by Harbour and Dixon (1959). Johnson (1961) summarized these studies.

The Vermejo Formation typically contains more coal beds than the Raton Formation, and they are thicker and laterally more extensive than the Raton coals (Johnson, 1961). Johnson (1961) describes the Vermejo Formation coal zone as having 3 to 14 coal beds over 14-inches thick, the most extensive beds occurring near the base of the unit. The most widely worked seams include the Sopris, Cameron, Cokedale, Robinson, Robinson No. 2, Alamo, Starkville, Walsen, and Berwind. The Raton Formation also contains numerous coal beds, but most mines have produced from four main coal seams that are sufficiently thick and laterally extensive: the Ciruela, Frederick, Primero, and Delagua No. 2. Maximum thickness of coal beds in both formations is about 14 feet (Boreck and Murray, 1979). Much of the mined coal has come from relatively shallow depths, but the coal beds are over 3,000 feet deep along the axis of the basin and in the troughs of some synclines (Johnson, 1961). The Vermejo Formation coals are over 500 feet deep across much of the entire region (Carroll, 2006).

Vermejo and Raton coals are higher in coal rank than those in the Denver Coal Region. Coal rank is determined by carbon content (i.e., higher energy content); the higher the carbon content, the higher the rank. In Huerfano County, both Vermejo and Raton coals typically rank as high volatile B and C bituminous coal and are non-agglomerating and unsuitable for coking (Carroll, 2006; Johnson, 1961; Tremain et al., 1996). In Las Animas County, the coal rank is high volatile A and B bituminous, and the coal is agglomerating and suitable for coking (Carroll, 2006; Johnson, 1961; Tremain et al., 1996). Historically, the Trinidad coal field was the most important coking coal area in the western United States (Goolsby et al., 1979). High volatile bituminous coal from both the Vermejo and Raton Formations in the Trinidad coal field has been coked. Coking coal also was produced locally from a few mines in the southern part of the Walsenburg coal field, near the Huerfano-Las Animas county line.

Limited trace element analyses are available for coal in the Raton Mesa Coal Region (Hatch et al., 2006). On a dry basis, run-of-the-mine samples from the M seam at the Lorencito Canyon mine contained 0.04 ppm of mercury, and samples from the N-A seam contained 0.03 ppm of mercury; mercury content on an as-received, remnant moisture basis was the same. Tewalt et al. (2001) provide summary data for mercury in coal in the Raton Mesa Coal Region, including a median value of 0.05 ppm mercury and a mean value of 0.09 ppm based on 40 as-received whole coal samples.

According to the online DRMS database (CDRMS, 2016), there is one active coal mine permit within the RGFO part of the Raton Mesa Coal Region: the New Elk mine (Permit No. C1981-012), operated by the New Elk Coal Company, LLC and producing coal from the Raton Formation. The New Elk mine, formerly called the Allen mine, is located on the south side of the Purgatoire River between the towns of Weston and Stonewall. Historically, this underground slope mine was a major coal producer. The mine resumed coal production in May 2011 but ceased production in June 2012. About 350,000 tons of coal were produced during this time period. At the end of 2016, the mine was reported as idle (CDRMS, 2016).

The Raton Mesa Coal Region is now one of the major coalbed-methane producing areas in the United States. This MPR does not address coalbed methane or the New Mexico portion of the Raton Mesa Coal Region.

The Federal Government owns the rights to coal in numerous tracts scattered across the RGFO portion of the Raton Mesa Coal Region that is outside of the Maxwell Land Grant (a.k.a. Beaubien and Miranda Land Grant).

Landis (1959) estimated the coal reserves at 12.7 billion tons for 1,044 square miles of the Raton Mesa Coal Region; he also reported prior estimates by Hills (1893), Campbell and Clark (1916), Vanderwilt (1947), and Spencer and Erwin (1953). Hornbaker et al. (1976) and Tremain et al. (1996) estimated the original in-place resource to be 13.2 billion tons. Finally, Carroll (2006) estimated original resources of 12.7 billion tons of coal with 12.4 billion tons of reserves remaining. Other published reports relevant to the coal resources of the RGFO portion of the Raton Mesa Coal Region are D. A. Carter (1956), Flores (1987), Flores and Pillmore (1987), Flores et al. (1985), Goolsby et al. (1980), Johnson and Wood (1956), Jurich and Adams (1984), and Roehler and Danilchik (1980).

3.1.3 South Park Coal Region

The South Park Coal Region, host to an estimated dozen historic coal mines, is a narrow, north-south-trending elongate area in the northeastern and east-central parts of Park County (Carroll and Bauer, 2002). The coal is preserved in a structurally complex area in the foreland footwall of the Laramide-age Elkhorn Thrust Fault, which is a major west-vergent fault that bounds the western side of the Laramide Front Range Uplift at this latitude. The coal-bearing rocks are correlated with the Laramie Formation in the Denver Basin (Washburne, 1910; Barker and Wyant, 1976). According to Washburne (1910), Landis, (1959), and Carroll (2006), the South Park Coal Region extends from north of the town of Jefferson southward nearly to the town of Hartsel, a distance of about 24 miles.

The coal-bearing strata are only locally exposed around the perimeter of the coal region, with the best exposures limited to the northern part of the region (Landis, 1959a). In many places, alluvium and other surficial deposits conceal the Laramie strata (Washburne, 1910). Also, a major period of erosion carved an unconformity across Laramie and older rocks, locally removing the Laramie prior to deposition of the overlying South Park Formation (Boreck and Murray, 1979; Washburne, 1910). Furthermore, the Laramie Formation is locally cut by faulting and Laramie strata may occur in the subsurface beneath or adjacent to the faults, all of which complicates determination of the extent of the coal-bearing strata.

The northernmost outcrop of South Park coal occurs on Jefferson Hill at the Jefferson mine, about 1 mile north of Jefferson; no production was reported for this mine, and coal thickness was only about 1 foot (Carroll and Bauer, 2002; Washburne, 1910). This block of coal-bearing strata is wedged between two strands of the Elkhorn Thrust Fault and dips steeply west (Barker and Wyant, 1976). U.S. Highway 285 crosses another small outcrop of Laramie strata about midway between the town of Jefferson and the junction with County Road 33, which goes to the town of Como. The Laramie strata locally crop out southward from the highway for a distance of about 4 miles to near the confluence of Park Gulch and the South Branch of Park Gulch. Eight of the 13 known mines in the South Park Coal Region, including the productive King Cole mine complex, are located along Park Gulch in this outcrop belt (Carroll and Bauer, 2002).

Three coal beds were worked by the King mine complex, which includes the Como Nos. 1, 2, 4 and 5, Lechner, America, Thompson and Wagon mines; nearly all South Park Coal Region production reported was recovered from these mines (Washburne, 1910; Carroll and Bauer, 2002). The upper two beds at the King mine complex reportedly varied from 4 to 6 feet and the lower bed from 7 to 40 feet (Washburne, 1910). The beds dip moderately to very steeply east or northeast, ranging from about 30° to as much as 90° and the thickest coal is likely a result of shearing and folding (Washburne, 1910).

Further north, the Old Como mine and nearby prospects were developed in two coal beds in a narrow, north-northwest-trending zone on the northwestern and western sides of the town of Como (Washburne, 1910). The Old Como mine was abandoned in 1883, and when visited by Washburne in 1908 it had caved in, filled with water, and was not available for inspection, but several local residents described the mine as having produced from a 5- to 6-foot-thick coal bed. Stark et al. (1949) confirmed the presence of coal strata at and near this location. However, no outcrops of Laramie strata were detected by Widmann et al. (2005) while mapping these areas at a scale of 1:24,000, although waste dumps from the Old Como mine and nearby prospects still contained coal fragments and pieces of Laramie sandstone. Widmann et al. (2005) interpreted the block containing the Laramie coal as a narrow, isolated, fault-bounded block that is not physically connected to the coal beds at the King mine complex.

Washburne (1910) described Laramie strata north of Hartsel, between Threemile and Sevenmile Creeks, which contained a coal bed less than 1-foot thick. He described evidence of a coal prospect on a 1-foot-thick bed in this area, and Carroll (2006) described two mines here. Clement and Dolton (1970) also report the presence of coal in the Laramie Formation in this area.

Carroll (2006) and Boreck and Murray (1979) report total coal production of nearly 725,000 tons in the South Park Coal Region. Limited analytical data from coal samples collected and analyzed when the mines were operating in the late 1800s and early 1900s suggest the Laramie coal in this region is subbituminous A or B coal, containing 9,780 Btu/pound, 6.3 to 15.5 percent moisture, 1.3 to 6.4 percent ash, and 0.47 to 0.53 percent sulfur (Washburne, 1910; Hornbaker et al., 1976; Carroll and Bauer, 2002).

The Federal Government owns the coal resources in numerous tracts that make up a significant part of the South Park Coal Region.

Landis (1959) estimated at least 92 million tons of coal reserves in the South Park Coal Region. Boreck and Murray (1979) reported the remaining reserve base at 23.9 million tons. Carroll (2006) estimated remaining resources at 91.3 million tons of coal. Based on reserves of 91.3 million tons and a realistic recovery rate of 35 percent, 30 million tons of coal remain (Brandt, 2015). Due to the complex structure, the erosional removal of the Laramie Formation from parts of the coal region, and the relatively few reliable sources on the extent and thickness of the coal beds, all estimates of the coal reserves should be considered approximate.

3.1.4 Cañon City Coal Region

Nearly 200 historic mines have produced 48 million tons of high-volatile C bituminous coal from the Upper Cretaceous Vermejo Formation (identified as and essentially correlated with the Laramie Formation by Washburne, 1910b) in the Cañon City Coal Region between 1864 and 2002 (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959).

Hatch et al. (2006) analyzed four coal samples from the Southfield mine for ultimate, proximate, and trace-element chemistry, on both an as-received, remnant moisture basis and a dry basis. Raw coal delivered to the coal preparation plant contained 0.58 ppm mercury on a dry basis, whereas the product from the preparation plant contained <0.03 ppm mercury on a dry basis (Hatch et al., 2006). A channel sample collected from the mined seam, which excluded a parting, contained 0.19 ppm of mercury on a dry basis and 0.18 ppm on an as-received, remnant moisture basis (Hatch et al., 2006).

There is one mine in the region with an active "Awaiting Warranty Package" permit from the DRMS, the Northfield mine (Permit No. C2006085). It is an underground mine that has yet to initiate mining as of mid-2018, presumably because the DRMS is awaiting receipt of the financial warranty (CDRMS, 2018). No Federal mineral ownership was identified in the Cañon City Coal Region.

An estimated original coal resource of 247 million tons and realistic recoverability of 35 percent implies reserves of 90 million tons (Brandt, 2015). Boreck and Murray (1979) estimated reserves at 107 million tons.

3.2 Geothermal

Geothermal energy exists everywhere beneath the RGFO management area, as it is a product of the interior heat of the Earth. Geothermal heat can become an energy resource if the heat can be harnessed, usually dependent on its temperature, depth, and available technology (CGS, 2013). Geothermal systems are usually classified as high temperature (>~300°F), moderate temperature (<~300°F but >~195°F), or low temperature (<~195°F) (Williams et al., 2008). Williams and DeAngelo (2008) described the basic requirements of a geothermal reservoir as having high temperature and high permeability, and generally also some type of cap or seal that reduces the mixing of the geothermal fluids with adjacent or overlying cooler groundwater. These types of geothermal systems are commonly referred to as *hydrothermal systems*. The types of applications geothermal energy can be used for are determined mainly by the temperature of the system, although depth to the desired temperature also plays a role. Harnessing geothermal resources is a dynamic and constantly evolving field of study, but there are four major categories of geothermal energy use: electricity production, enhanced geothermal systems, direct use, and low temperature/co-produced.

Electricity production is typically done with traditional hydrothermal resources, those that involve high temperature geothermal systems that naturally have water available at accessible depths (U.S. EERE, 2016). They may or may not have surface manifestations of the geothermal system. The heat of these systems is directly converted to electricity, usually via a steam turbine. Steam may be taken directly from the ground (dry steam) or may be separated as very hot water boils as it approaches the surface (flash steaming) (NREL, 2016). Binary plants use geothermal fluids that fall in the temperature range between high and low temperature systems (225-360°F). These plants produce vapor by using the geothermal fluid to boil a secondary (working) fluid with a lower boiling point; the vapor of the working fluid is then used to drive the turbine (NREL, 2016).

If a moderate or high temperature geothermal resource exists at drillable depths, but natural geothermal fluids cannot be recovered from the rocks due to lack of availability or permeability, then heat will somehow need to be transferred from the subsurface to the surface to use the resource. Heat can be extracted from these hot rocks using a method called hydraulic stimulation or hydro-fracturing, a technology which involves injection of fluids deep into the subsurface and the creation of fracture systems in the hot dry rock (U.S. EERE, 2016). These types of hot dry rock geothermal systems are called enhanced geothermal systems (EGS) and may provide the opportunity to access large amounts of currently untapped geothermal resources. The estimated potential for this type of technology is about 10 percent of the overall electric capacity of the U.S. (U.S. EERE, 2016).

Uses of geothermal resources that don’t involve an energy or temperature conversion are classified as direct use (CGS, 2013). Direct use generally involves low temperature geothermal systems that are naturally available at the surface. Direct use is efficient because the resource is being used as-is, but the heat cannot generally be transported very far. Therefore direct use applications are limited to locations with surficial geothermal resources (CGS, 2013). Space heating and domestic hot water provision are common direct uses; hot springs and pools are also considered direct use (CGS, 2013). Several fish farms in Colorado use geothermal resources for warm-water aquaculture, and Pagosa Springs has a direct use geothermal district-heating system (U.S. DOE, 2005). There are many industrial applications for direct use geothermal energy, including greenhouse heating, food dehydration, cement curing, and evaporation (CGS, 2013).

Low temperature geothermal applications are those that use geothermal fluids with temperatures <300°F in non-direct uses. The U.S. EERE (2016) is investigating energy generation via novel technologies based off of mid-temperature binary electric plants (discussed above) as a major low temperature use; they are also investigating mineral production from saturated geothermal fluids during energy generation as a way to make low temperature system more economic. "Co-produced geothermal resources" generally refers to the hot water produced as a byproduct of oil and gas wells (NREL, 2016). Co-produced fluids are being considered as a potential energy generation source, via low temperature technologies discussed above.

Extension and thinning of the earth's crust associated with the Rio Grande Rift (see section 2.2.10), as well as related igneous activity, have been thought by many to be the primary controlling factors of the geothermal systems in the management area. However, the low dissolved solids content and absence of other indicators of interactions with magmatic fluids suggest magmatic activity may not play a significant role in the geothermal systems in the RGFO management area (Morgan, 2013a). The specific mechanism or mechanisms that control the geothermal systems in the management area are as yet not well understood. Additionally, the exact characteristics and potential of the geothermal systems in most of the management area are the subject of considerable debate among scientists, mostly due to the relatively limited amount of reliable subsurface information. This limitation should always be remembered when examining derivative maps showing geothermal gradients, heat flow, and geothermal potential.

Methods for assessing geothermal resources depend on the type of resource being explored. Several methods are used to assess high and moderate temperature traditional or EGS resources, including bottom-hole temperature and temperature-depth logs of drill holes. Bottom-hole temperatures come from geophysical logs run in petroleum wells. In Colorado, most petroleum wells typically have the bottom-hole temperature reported, and this is generally the only publically available data for estimating geothermal resources throughout the State. Reliability of bottom-hole temperatures for use in geothermal assessments is affected by drilling fluid and other factors. Dixon (2002) summarizes the bottom-hole temperatures in the Denver Basin. Dixon (2004) provides data for the Raton Basin and Cañon City Embayment. Morgan (2009) also discusses the Raton Basin. Morgan and Sares (2011) cover the Denver and Raton Basins.

Although bottom-hole temperatures can be and are used to calculate geothermal gradients, they are not the most accurate data source for gradient determination. Temperature-depth logs provide a continuous measurement of the temperature at depth in drill holes. This makes them more reliable and thorough data than bottom-hole only temperatures. They can indicate whether temperatures change gradually or abruptly with depth, and can detect the presence of cooler zones beneath warmer zones. Temperature logs are available at the COGCC for some petroleum wells, which can be very useful for estimating geothermal resources. Holes specifically drilled for running temperature logs for geothermal purposes and holes that have not been pumped for long periods of time can provide reliable estimates of geothermal gradients. Ringrose (1980) ran temperature logs in 11 holes in the Cañon City area that were drilled specifically for temperature-depth logging. The geothermal gradients in these holes ranged from 21.8 to 89.7°C/km. Paul Morgan (CGS) has an ongoing temperature-logging program that currently includes several drill holes in the management area, and it may be possible to contact him directly for his as-yet-unpublished data.

Bottom-hole temperatures and temperature-depth logs can be used to create several geothermal assessment tools like geothermal gradient and heat flow maps. Geothermal gradient maps are used to characterize the geothermal resources of an area by indicating temperature change with depth. An interpretive geothermal gradient map by Berkman and Watterson (2010) shows geothermal gradients range from less than 20°C/km in the southeastern part of the RGFO management area to as much as 167°C/km near Buena Vista in the Upper Arkansas Valley. Gradients were locally as high as 141°C/km in the Raton Basin. The most significant high-gradient areas in the RGFO management area include the Mount Princeton-Chalk Cliffs area (Chaffee County) and an area in the Raton Basin west and southwest of Trinidad, where gradients are >100°C/km; the Poncha Springs area with a gradient >90°C/km; and the Florence area with a gradient of >80°C/km.

A larger geothermal gradient means that higher temperature resources would exist at shallower (and therefore more accessible) depths. Heat flow maps show how much heat moves from the Earth's interior to its surface. Heat flow depends on temperatures and rock type. The CGS produced a heat flow map for Colorado (Berkman and Carroll, 2008) that shows generally increasing heat flow values from east to west across the RGFO region and high heat flow areas in the Upper Arkansas Valley and Raton Basin. It also depicts an area of relatively high heat flow extending from near Florence eastward beyond Pueblo, as well as small local areas of moderately high heat flow (>100 mW/m^2) at Denver, east of Fort Collins, and in western Boulder County. Areas of high heat flow can be indicators of potential geothermal resources (either traditional or EGS, depending on fluid availability and rock permeability).

Raw data and derivative products are synthesized to produce maps of geothermal potential, such as that in Figure 1-5 of the *Final Programmatic Environmental Impact Statement for Geothermal Leasing in the Western United States* (BLM and USFS, 2008). This figure suggests that the western half of the RGFO management area and an area along the Arkansas River Valley in the Great Plains have geothermal potential. The figure was prepared as part of a study by the BLM and USFS in partnership with the DOE and USGS. It attempts to depict areas where either hydrothermal systems or deep enhanced geothermal systems may exist, and where the BLM and USFS would likely receive geothermal lease nominations and applications in the near future. Geothermal potential may also be assessed by type. Traditional hydrothermal systems are generally associated with active or geologically recent volcanism, but the USGS (2008) did predict some areas of high favorability for undiscovered high- to moderate-temperature traditional geothermal resources in the western part of the RGFO region. Augustine (2011) provides a map of identified hydrothermal sites and the favorability of deep enhanced geothermal systems. Two of the identified hydrothermal sites are within the RGFO management area: the Mount Princeton-Chalk Cliffs area and the Poncha Springs area. Nearly all of the management area is rated as having moderate to most favorability for deep enhanced geothermal systems.

Direct-use and low temperature geothermal resources are generally easier to estimate, as they are usually manifested at the surface. Thermal springs and wells are found in several parts of the RGFO management area (see Figure 3-2). Barrett and Pearl (1976, 1978) completed the first comprehensive studies of the geothermal wells and springs in the management area. They described the geology, temperatures, flow, and chemistry of these geothermal systems, and made some of the first estimations of reservoir temperatures at depth using geothermometry models. Cappa and Hemborg (1995) revisited many of the same geothermal springs and wells as Barrett and Pearl, and also reported on many others.

Most of these hot or warm springs and wells are either in or near to the mountainous areas in the western part of the RGFO management area (similarly to areas of high potential for other types of geothermal resources). Any areas with noted “hot springs” have a high potential for direct or low temperature geothermal resources. Co-produced geothermal resources are associated with areas of oil and gas drilling. A final consideration for low temperature resources is “deep direct use.” The U.S. EERE (2016) identifies these resources as those between ~100-300°F (40-150°C) and deeper than traditional direct use but shallower than traditional hydrothermal resources. These resources are an area of investigation in current geothermal resource analysis, although they are considered to be widespread, especially in the western U.S.

Geothermal occurrence potential for this report is broken into two broad categories: traditional/EGS and direct-use/low temperature (see Maps 7.2.1 and 7.2.2 in section 7 for geothermal occurrence potential in the RGFO management area). Potential for traditional/EGS geothermal resources in the RGFO region is based off of wider estimates performed by the USGS (2008) and Augustine (2011). These estimates take into account known hydrothermal occurrences, as well as the potential for high temperatures. High temperatures are required, but a lack of fluids or permeability may be overcome with EGS. Although there are no developed

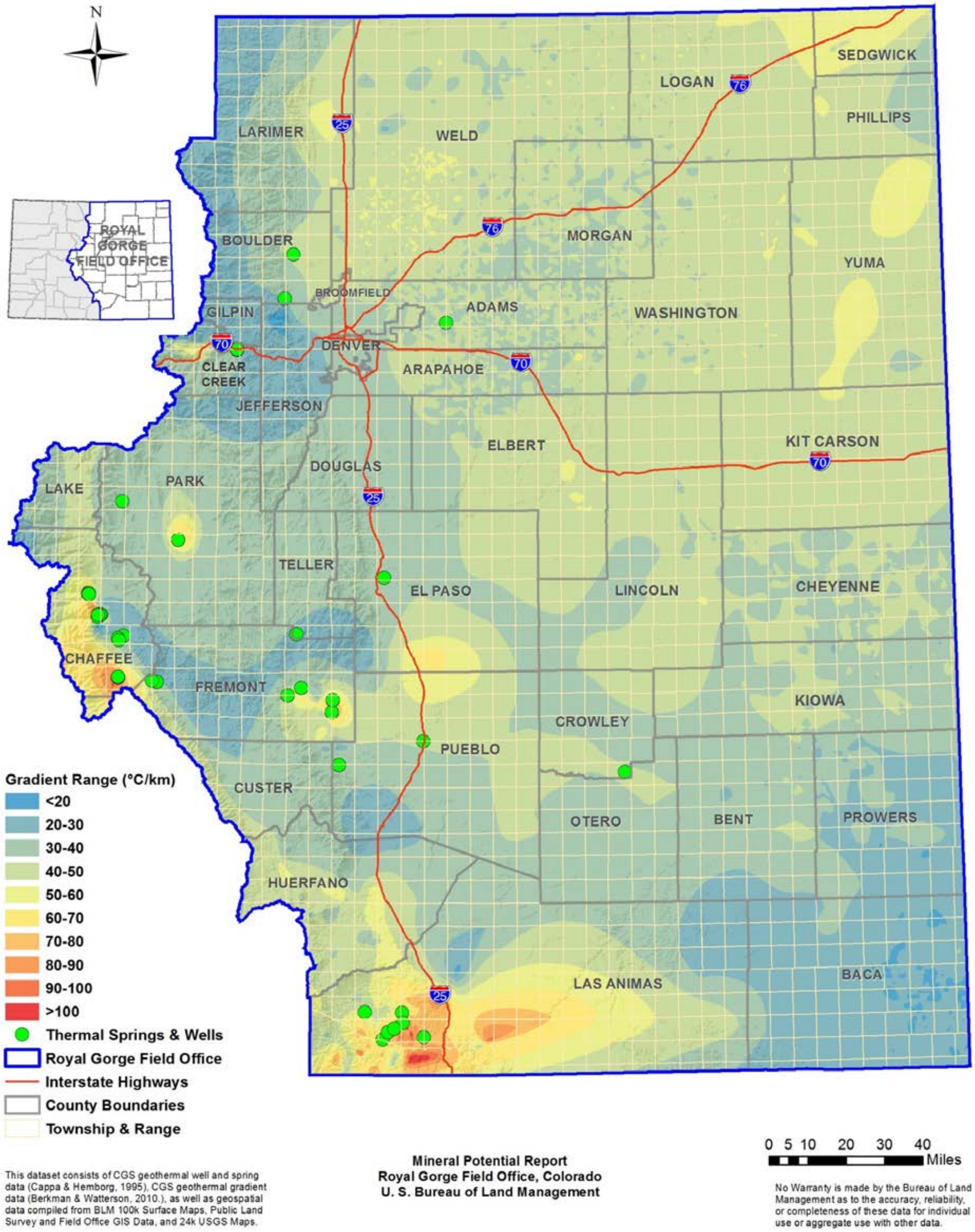


Figure 3-2. Geothermal gradient, springs, and wells in the Royal Gorge Field Office.

geothermal electrical energy systems in Colorado to date, it has the 4th highest thermal heat/acre in the U.S. (Held and Henderson, 2012). The USGS (2008) estimated the identified hydrothermal resource potential for electrical power generation on all lands in Colorado during the next 30 years at 30 megawatts (MW), with a range of 8 to 67 MW. Two of the four identified electrical power resource areas used for this calculation are within the RGFO region: the Mount Princeton-Chalk Cliffs and Poncha Springs areas.

A third area within the RGFO management area also may be suitable for generating electricity: the central Raton Basin west of Trinidad (Macartney, 2011). Due to lack of currently developed resources of these types and the general lack of geothermal exploration data, no areas in the RGFO region are designated as a "D" level of certainty. Areas that have the highest potential from both the USGS (2008) and Augustine (2011) analyses are designated as H/C. Areas with a high potential from one report and high to moderate potential from the other report are designated as H/B. Areas with moderate potential from both reports are designated as M/C. Areas with moderate potential from one report and low to moderate potential from the other report are designated as M/B. Areas with low potential from both reports are designated as L/B. Areas with moderate or low potential from only one report are designated as L/A.

Potential for direct-use/low temperature geothermal resources in the RGFO region is based in part off of the existence of hot springs and wells noted by Cappa and Hemborg (1995) and the Oregon Institute of Technology (via NREL, 2016; used for locations). The temperature of the water is not considered, as direct-use applications can employ a wide range of temperatures (CGS, 2013), and all wells or springs are considered points of H/D potential for direct use. Current direct-use applications are considered to be evidence of H/D potential, with point location data sourced from the Oregon Institute of Technology via NREL (2016). For wells or springs with temperatures over ~122°F (50°C), geothermal fluids can be transported up to 5 miles (8 km) for district heating and other direct uses (NREL, 2016; U.S. EERE, 2004); therefore a buffer of 5 miles around such wells in the RGFO region is designated as H/D. Co-produced geothermal resource potential depends on the amount and temperature of water produced from oil and gas wells.

Using data from the Colorado Oil and Gas Conservation Commission (COGCC, 2017), the average maximum depth of wells drilled in the RGFO region was used to estimate the average depth of the producing formation. That was multiplied by the geothermal gradient (Berkman and Watterson, 2010) to get the change in temperature at the bottom of the hole. Finally, that change in temperature was added to the mean surface temperature (Hijmans et al., 2005) to get an absolute temperature at the bottom of the hole, which is a proxy for the temperature of the formation water being produced. Low-temperature geothermal resources are considered to be those between ~100-300°F (40-150°C) (U.S. EERE, 2016), and those temperatures are therefore also considered an appropriate range for co-produced resources (given that the technology for both is likely to be similar). Areas that fall within the temperature range and within named oil and gas fields (COGCC, 2017) are designated as H/C due to the potential concentration of producing wells mitigated by the fact that technologies are still in development. Areas that fall within the temperature range but not within named oil and gas fields (COGCC, 2017) are designated as H/B due to the potential lack of concentration of producing wells and developing technologies. All other areas in the State are considered M/B for low temperature and/or co-produced geothermal resources, given the growing amount of research and development in those areas, including “deep direct use.”

Due to large data gaps, there could be significant areas with undiscovered hydrothermal potential. For example, the USGS (2008) estimates the undiscovered hydrothermal electrical power generation potential in Colorado at 1,105 MW, well above the potential of the identified resources. Also, they estimate the enhanced geothermal systems in Colorado are capable of producing 52,600 MW of electricity. A significant part of this undiscovered hydrothermal system and enhanced geothermal system capability is likely within the RGFO management area.

As pointed out by Morgan (2009), deep sedimentary basins may be the most under-developed geothermal resource potentially capable of electrical generation. The potential of the central Raton Basin has been discussed by Macartney (2011) and Morgan (2009). The Cañon City Embayment also has significant geothermal potential (Zacharakis and Pearl, 1982), as does the Denver Basin (Dixon, 2002). These deep sedimentary basins probably would be developed as enhanced geothermal systems.

3.3 Precious Metals

The following subsections provide a brief discussion of known types of precious metal resources in the RGFO region as well as general strategies for assigning potential designations. Some of the larger and most notable historic mining districts mapped by the CGS in the RGFO region are depicted in Figure 3-3. These districts were important for assessing occurrence potential and provided general boundaries for areas of mineral potential for some commodities.

3.3.1 Gold

Gold was a major influence on the early economic development of Colorado, having been produced in the State since the 1859 discovery near the confluence of Cherry Creek and the South Platte River (Davis and Streufert, 2011). As of 2014, Colorado ranked fourth in production among 10 gold-producing States, with the majority of production coming from the Cripple Creek & Victor Gold mine in Teller County (USGS MYB, 2014). Gold is generally found in two types of deposits: lode (hard rock) and placer.

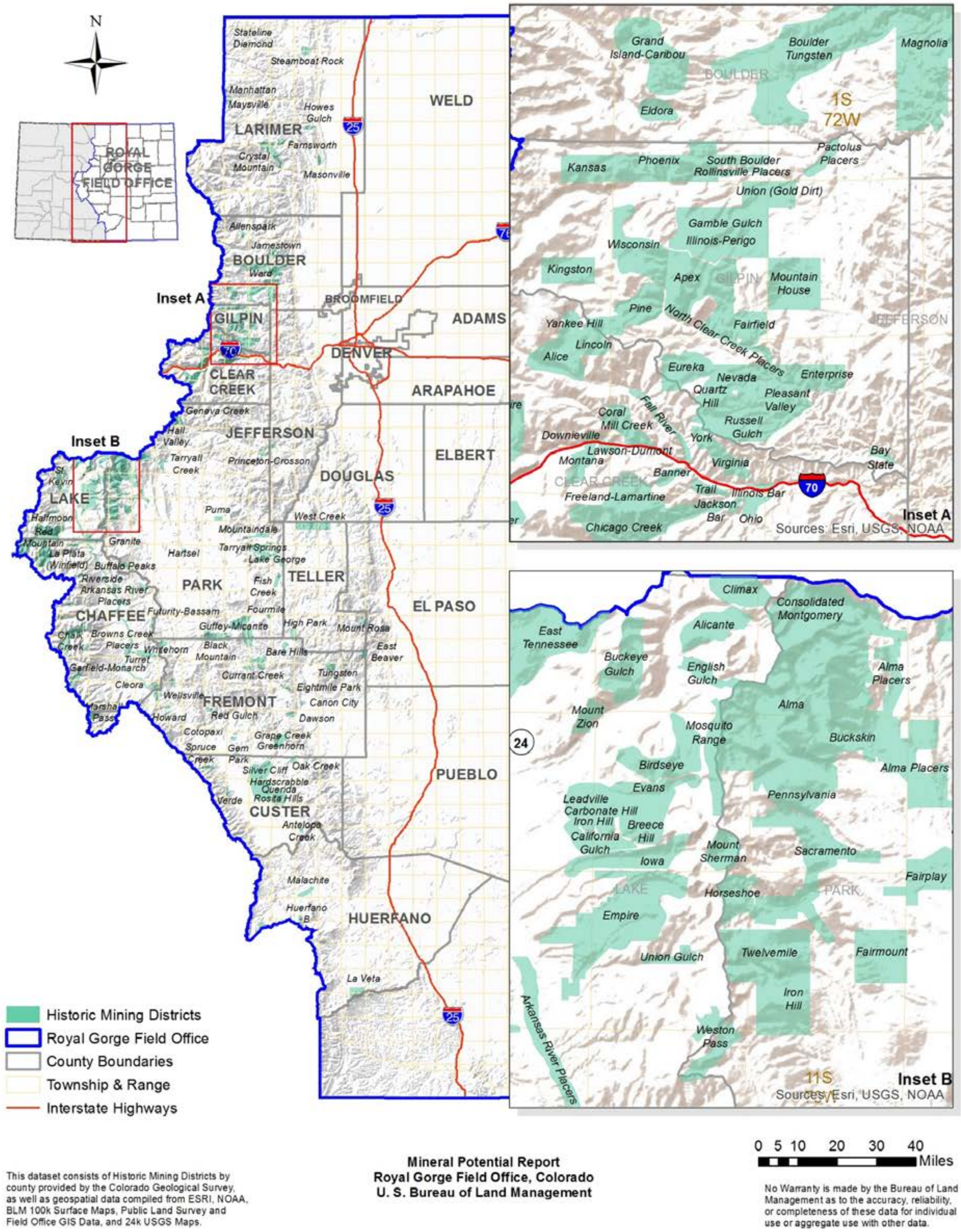


Figure 3-3. Historic mining districts in the Royal Gorge Field Office.

Lode deposits occur within in-place, hard rock material, which is mined by open pit or underground techniques. Hard rock deposits within Colorado include those with native (free) gold and those with gold alloys (e.g., electrum). Hard rock gold mineralization is associated with four main types of deposits in Colorado: vein, replacement, and sulfide deposits, as well as deposits in alkali volcanic rocks (Cappa, 2003). Gold is known to occur in Precambrian stratabound exhalative deposits (Sheridan and Raymond, 1984a; Sheridan et al., 1990). These types of deposits were generally overlooked historically as sources of economical ores due to low gold content; Precambrian sulfide ores generally contain less than 0.3 ounces per ton of gold (Sheridan and Raymond, 1984a). All lode deposits in Colorado occur in Precambrian or Laramide-Tertiary rocks, and a large number are found within the CMB (Davis and Streufert, 1990). The most productive alkalic gold deposit in North America, and the largest source of gold in Colorado, is within the RGFO management area in the Cripple Creek district (Cappa, 1998).

Placer deposits are those in which the gold has migrated from its original source and been concentrated by a mechanism such as water sorting and/or gravity. Placer deposits are usually found in river or stream gravels, ancient river terrace gravel deposits, alluvial fans, and glacial moraines and till (Cappa, 2003). Placer deposits contain free gold or gold alloys that can be separated with methods such as panning, sluicing, and dredging; gold panning remains a popular recreational activity in several parts of Colorado, especially along the Arkansas River and its tributaries in Chaffee and Fremont Counties. In the RGFO region, the most productive placer gold deposits occur in Lake, Park, Gilpin, and Chaffee Counties (Davis and Streufert, 1990).

Lode and placer gold occurrence potential in the RGFO region are grouped together and depicted on Map 7.3.1 in section 7. High potential for concentrated occurrences of hard rock deposits are associated with the CMB, the unique alkalic rocks of Cripple Creek, the Pikes Peak Batholith, Tertiary intrusives, and Precambrian exhalative sulfide deposits. High potential areas for placer deposits occur in areas of alluvial or glacial material that can be traced to a known hard rock source or mining district. Assignment of certainty level was performed based on available geologic reports, historic production, mine locations, general geologic knowledge, and mapped geologic units.

3.3.2 Platinum-Group Metals

Six elements make up the platinum-group metals (PGMs): iridium, osmium, palladium, platinum, rhodium, and ruthenium. PGMs are rare, comprising only 0.0005 parts per million of the Earth's crust (Zientek and Loferski, 2014). PGM deposits are most often associated with mafic to ultramafic layered intrusive igneous rocks, although they can also occur in alkaline igneous rocks (Keller, 2001). PGMs are sometimes recovered from copper-nickel sulfide ores of ultrabasic igneous rocks (USGS, 1968). Like gold, PGMs can occur as in-place hard rock or placer deposits. There are no historic PGM mines in Colorado, but there are several mafic intrusive complexes that have similar characteristics to other known PGM occurrences; these occur in the Elkhorn gabbro in Routt and Jackson Counties on the Wyoming border and in Cambrian intrusive complexes in the Wet Mountains between Fremont and Custer Counties (Keller, 2001). Occurrences of lode platinum in the RGFO region have been noted in the Caribou district in Boulder County, the Georgetown district in Clear Creek County, the Granite district in Lake County, and Mosquito Gulch in Park County (Eckel, 1997). PGMs have been found in several placer deposits in Colorado, including around Aspen, Buena Vista, Como, Telluride, and in Saguache County (Peterson, 1994).

Because no known historic mining districts or deposits of PGMs were identified in the RGFO management area, the certainty levels assigned are lower than for other, better studied commodities. PGM occurrence potential is depicted on Map 7.3.2 in section 7. PGM occurrence potential was assigned based on geologic environment, rock type, known deposit types, and any chemical analyses available.

3.3.3 Silver

Colorado has been a silver (Ag) producing State since the 1860s, with the Leadville district being the most productive district historically in the RGFO region (Pings and Mellor, 1974). Silver is currently produced in the RGFO area only as a byproduct of gold mining at the Cripple Creek and Victor mine in Teller County. The value of silver production is very small compared to that of gold because of the price differential between the two metals. Silver in Colorado generally occurs within the same types of deposits as gold, although it can also occur in base-metal deposits. Carbonate replacement deposits are the host of Leadville-type silver occurrences (Romberger, 1980). Silver is also known to occur in Precambrian stratabound exhalative deposits (Sheridan and Raymond, 1984a; Sheridan et al., 1990). Historically, these types of deposits were generally overlooked as sources of economical ores due to low silver content; Precambrian sulfide ores generally contain less than 2 ounces per ton of silver (Sheridan and Raymond, 1984a). Silver may occur as a native element or alloyed with other metals; silver-bearing sulfide minerals are the most common type of silver ore in Colorado (Pings and Mellor, 1974). Silver-bearing minerals found in the RGFO region include argentite (Ag_2S), cerargyrite ($AgCl$), polybasite ($Ag_{16}Sb_2S_{11}$), proustite (Ag_3AsS_3), the tetrahedrite-tennantite series ($(CuFeAg)Sb_4S_{13}$), hessite (Ag_2Te), empressite ($AgTe$), and native silver.

Silver occurrence potential within the RGFO management area was generally assessed on a mining district scale and is depicted on Map 7.3.3 in section 7. Each district has a unique geology, structural setting, and history that affect occurrence potential. High potential areas are associated with the CMB mining districts and the unique alkalic rocks of Cripple Creek. Deposits show a general trend along the CMB from veins in Precambrian rocks in the northeast to sedimentary replacement deposits in the central portion to veins in volcanic rocks in the southwest, and each type of deposit affects the silver occurrence potential designation (Romberger, 1980). Assignment of certainty level was performed based on available geologic reports, historic production, mine locations, general geologic knowledge, and mapped geologic units.

3.4 Base Metals

3.4.1 Copper-Lead-Zinc

Copper (Cu), lead (Pb), and zinc (Zn) are treated together as base metals for the purposes of this MPR.

Historically, Colorado was a major producer of lead and zinc, but only moderate production of copper is reported in the RGFO management area or even Colorado. Del Rio (1960) reports that 585 million pounds of copper, 5.46 billion pounds of lead, and 3.71 billion pounds of zinc were produced in Colorado between 1867 and 1958 (in terms of recoverable metals). There are currently no primary base-metal mines operating in the State, although some active operations report copper and/or lead and/or zinc as secondary commodities (CDRMS, 2016).

Base-metal mineralization occurs in a variety of geologic and structural settings. Lovering and Goddard (1950) describe numerous base-metal deposit types observed in the Front Range of Colorado, including: magmatic segregations and disseminations, hypothermal replacement veins, pegmatitic quartz veins, intrusion breccias, mantos, silver-lead veins, pyritic quartz veins, and supergene enrichment deposits, among others. Deposits within the RGFO area occur primarily in Precambrian igneous and metamorphic, Tertiary igneous, and Paleozoic sedimentary rocks. Faults, igneous intrusions, and igneous-metamorphic contacts often control the location and concentration of deposits.

Polymetallic replacement of carbonates forming stratiform deposits (mantos) in the Leadville district (Lake County) made it the most productive base-metal mining area in Colorado. Leadville is home to the Black Cloud mine, which was the most recently producing base-metal mine in the State, shutting down in 1999 (Cappa et al., 2007). Base-metal replacement of carbonates is also described in Park County. The most noted sedimentary units hosting carbonate replacement deposits include the Mississippian Leadville Dolomite, the Devonian-Mississippian Dyer Dolomite, and the Ordovician Manitou Limestone.

Base metals are also known to occur in Precambrian stratabound exhalative deposits (Sheridan and Raymond, 1984a; Sheridan et al., 1990). Historically, these types of deposits were generally overlooked as sources of economical ores due to low gold and silver content; Precambrian sulfide ores generally contain less than 0.3 ounces per ton of gold and less than 2 ounces per ton of silver (Sheridan and Raymond, 1984a). Sheridan et al. (1990) characterized five types of Precambrian massive sulfide deposits and identified numerous mines and prospects within the western RGFO region: Type 1 stratabound sulfide deposits, which are metamorphosed to the upper amphibolite facies and typically host sphalerite, chalcopyrite, galena, and frequently gahnite; Type 3 stratabound deposits, which contain tungsten with copper disseminated in lenses in calc-silicate gneiss; Type 4 deposits, which occur as pre-metamorphic copper- and/or tungsten-bearing quartz veins, primarily in the Cleora district (Chaffee County); Type 5 deposits, which are massive sulfides that occur as lenticular layers in amphibolite at the Copper King mine (Boulder County); and Type 6 deposits, which occur as copper-bearing pegmatites in Fremont County and point to concealed Type 1 occurrences.

Copper, copper-zinc, and tungsten-copper skarns are found in the RGFO region and are hosted primarily by Precambrian amphibolites (Heinrich, 1981); these may overlap in part with the stratabound exhalative and massive sulfide occurrences identified by Sheridan and Raymond (1984a) and Sheridan et al. (1990). Heinrich (1981) notes occurrences of base-metal-bearing skarns in Chaffee, Custer, Fremont, and Park Counties.

Anomalous copper concentrations in Pennsylvanian and Permian redbeds throughout the western RGFO region have been reported by several authors (Fay, 1983; Henderson, 1926; Johnson, 1984; Kues and Lucas, 1987; Lindsey and Clark, 1995; Lovering and Goddard, 1950; McLaughlin, 1954; Nelson-Moore et al., 1978; U.S. Bureau of Mines, 1989; Vanderwilt, 1947). Sediment-hosted copper ore occurs in the Paleozoic upper Minturn, Belden, lower Sangre de Cristo, and Lyons Formations. Base-metal deposits are also described in the Triassic Sheep Pen Sandstone (Dockum Group), the Jurassic Entrada (Exeter) Sandstone, the (possibly) Morrison Formation, and the basal member of the Cretaceous Purgatoire Formation.

The occurrence potentials of copper, lead, and zinc within the RGFO management area are considered together and depicted on Map 7.4.1 in section 7. Each district has a unique geology, structural setting, and history that affect occurrence potential. Due to the prevalence of base metals in mineralized systems, medium potential areas are associated with the CMB generally; high potential areas within the Belt are restricted to known areas of historic production or areas with ideal geologic setting. Assignment of certainty level was done after consideration of available geologic reports, historic production, mine locations, major known deposit types, general geologic knowledge, and mapped geologic units.

3.4.2 Iron

Iron (Fe) is a ubiquitous element in mineralized environments throughout Colorado. Thirty Colorado counties produced an estimated 6 million tons of iron ore between 1870 and 1956 (Harrer and Tesch, 1959). Common iron minerals include magnetite (Fe_3O_4), hematite (Fe_2O_3), limonite ($Fe_2O_3 \cdot nH_2O$), siderite ($FeCO_3$), and pyrite (FeS_2). Magnetite, hematite, and limonite occur in contact metamorphic and replacement deposits within carbonate rocks, such as at the Calumet mine near Salida in Chaffee County (Brown and Reeves, 1968). Limonite and hematite are also common weathering (oxidation) products of other iron-bearing minerals, often occurring in oxidation zones at or near the surface of polymetallic deposits; the Leadville district in Lake

County contained a significant oxide zone that was the first to be mined out (Cappa and Bartos, 2007).

Siderite, limonite, and hematite concretions are often found in shale, clay, and coal sedimentary rocks, as in the Rusty zone of the Pierre shale, the Vermejo Formation (Raton Basin), and Laramie Formation (Denver Basin) (Harrer and Tesch, 1959; Reade, 1979; Scott, 1969). Magnetite may be associated with mafic veins and intrusions like those in the Caribou district in Boulder County (Brown and Reeves, 1968). Pyrite is generally not mined for its iron due to the byproduct, sulfur, which is created. The Rico district in Dolores County, however, produced primary sulfuric acid from pyrite deposits, leaving significant hematite byproduct (Brown and Reeves, 1968). In 1959, the Bureau of Mines analyzed 100 known iron mines or deposits in Colorado; of these, the Wahl mine in Custer County was one of the last to operate, closing in 1924 (Harrer and Tesch, 1959). There are currently no active primary iron mines in the RGFO region.

Iron occurrence potential within the RGFO management area was assessed on a mining district scale and is depicted on Map 7.4.2 in section 7. Each mine has a unique geology, structural setting, and history that affect occurrence potential. Due to the abundance of iron in rock forming minerals and particularly mineralized systems, medium potential areas are associated with known concentrations of iron minerals or with areas in ideal geologic settings. High potential areas are those with known historic production. Assignment of certainty level was performed based on available geologic reports, historic production, mine locations, general geologic knowledge, and mapped geologic units.

3.4.3 Manganese

Manganese (Mn) occurs in several small, higher-grade deposits and a few larger, lower-grade deposits in Colorado (Crittenden, 1968). Manganese carbonate ($MnCO_3$), also known as rhodochrosite, is Colorado’s state mineral and is found in 18 counties where gold, silver, lead, zinc, and molybdenum ores are found (Arbogast et al., 2011). Manganese occurs in primary minerals (those that are original to the mineralized system) like rhodochrosite and rhodonite ($MnSiO_3$), or in manganiferous iron minerals like magnetite, siderite, or hematite; these minerals are not generally considered ore minerals as the concentration of manganese is too low. However, once these minerals weather into one of the manganese oxides, they may have a more economical concentration. Common manganese oxide ore minerals are pyrolusite (MnO_2), the psilomelane group (KMn_8O_{16}, or $BaMn_9O_{18}\cdot 2H_2O$, etc.), and wad. Wad refers to a hydrous non-crystalline mix of manganese and iron oxides (Crittenden, 1968). From 1891 to 1959, production in Colorado of high-grade (>35 percent) manganese ore amounted to 71 million pounds and low-grade (10-35 percent) ore totaled about 2 billion pounds (Crittenden, 1968).

Primary manganese occurs in vein, replacement, and bedded deposits (Jones, 1920). The vein and replacement deposits are the same as those discussed in the gold and silver sections (3.3.1

and 3.3.2, respectively) above. The Leadville replacement deposits are noted as the largest primary deposits of manganese in Colorado (Crittenden, 1968). Oxidized primary vein and replacement deposits are found in the Salida/Wellsville area, in the Westcliffe/Silver Cliff districts, and in the Cripple Creek district within the RGFO region, as well as throughout Gunnison County (Muilenburg, 1919). Bedded deposits are those in which manganese is found within sedimentary rocks, sometimes as nodules or concretions, or as manganiferous iron minerals (Crittenden, 1968; Wells et al., 1952). Any primary manganese deposit may weather and oxidize into a secondary deposit. These deposits tend to be more concentrated with manganese, although their character depends on the size and grade of the original deposit from which they were derived (Crittenden, 1968). Manganese is widespread in the RGFO region, but nearly all the deposits are too small, too disseminated, or too inaccessible for exploitation (Vanderwilt, 1947). Manganese is also found in volcanics and associated rocks or as cement in breccias and arkoses.

Manganese occurrence potential in the RGFO region (depicted on Map 7.4.3 in section 7) is frequently associated with iron, where it occurs as a secondary concentration of manganese oxides; high potential is also associated with the other metallic deposits of the CMB. Concentrations from weathering of bedded deposits occur on the Front Range and east of Denver (Wells et al., 1952). Although manganese is common as a weathering product, significant occurrences of manganese oxides in high-grade deposits are uncommon; therefore medium potential areas are associated with concentrations of known primary minerals that may lead to secondary concentrations. Assignment of certainty level was performed based on available geologic reports, historic production, mine locations, general geologic knowledge, and mapped geologic units.

3.4.4 Molybdenum

In North America, most large molybdenum deposits are associated with Tertiary calc-alkalic porphyritic intrusions, with some smaller deposits found within other alkalic rocks (Cappa, 1998). Four types of molybdenum deposits occur in the RGFO region, including: porphyry or disseminated deposits, contact metamorphic deposits, quartz veins, and pegmatites (King, 1968). Most occurrences in Colorado are within the CMB and are associated with porphyries (most commonly granite and rhyolite porphyries) (Keller, 2001). The three largest molybdenum deposits in Colorado- Henderson, Climax, and Mt. Emmons- were formed during the mid-Tertiary Period (Keller, 2001). Colorado is the top molybdenum-producing State and has the only primary-producing molybdenum mines in the U.S. (USGS MYB, 2015).

Molybdenum does not occur as a native element but most commonly as molybdenite (MoS_2), which is the chief ore, powellite ($CaMoO_4$), or wulfenite ($PbMoO_4$) (King, 1964). Molybdenum, as an accessory mineral, is widespread in the crystalline rocks of the CMB. Greisen-hosted beryllium deposits, tungsten- and tungsten-copper skarns, and Tertiary polymetallic veins in Precambrian igneous and metamorphic rocks are all known to host minor amounts of molybdenum, either as molybdenite or powellite (Scarbrough, 2001). Molybdenum occurrence potential in the RGFO region is depicted on Map 7.4.4 in section 7.

3.4.5 Nickel

Economic nickel ores occur primarily in sulfide deposits as pentlandite or in laterites as nickeliferous limonite (Cornwall, 1966). Laterite ores account for 40 percent of world production and were formed by the large-scale weathering of mafic and ultramafic rocks, especially peridotite, in subtropical to tropical conditions, most commonly during the Tertiary Period (Cornwall, 1966). Nickel-bearing sulfide deposits account for 60 percent of world production and are found primarily in proximity to peridotite or norite intrusions (Cornwall, 1966). Economical ores have a minimum average concentration of about 1.2 percent nickel, depending on world prices (Cornwall, 1966). Nickel occurs mainly as an accessory mineral in the RGFO management area, associated with Precambrian sulfide deposits of either metasedimentary/metavolcanic origin or as hypothermal replacements bodies (Lovering and Goddard, 1950; Sheridan and Raymond, 1984a). The only noteworthy nickel deposit in the RGFO area is the Copper King mine in the Gold Hill district of Boulder County, where Goddard and Lovering (1942) estimated reserves at 44 million pounds of 0.5 to 3.0 percent nickel ore.

Nickel occurrence potential in the RGFO region (depicted on Map 7.4.5 in section 7) is frequently associated with copper, where it occurs as a substitution element in sulfide minerals. High potential is associated with areas of documented production. Medium potential areas are associated with Precambrian exhalative sulfides and documented hypothermal replacement bodies in rocks of Proterozoic age. Generally, nickel is not associated with the Tertiary ore deposits.

3.4.6 Tungsten

During the search for gold in Boulder County, tungsten was identified in 1899 and first mined in 1900. The value of the metal increased greatly with the onset of World War I. The U.S. military recognized the superiority of German armor-plating and armor-piercing projectiles and learned the secret to their hardened steel was tungsten. In fact, the Krupp Steel Corporation of Germany was heavily invested in Boulder County tungsten mines at the beginning of the 20^{th} century (Sharps, 1965). Boulder County soon became the leading tungsten producer in the country and remained so until larger deposits were discovered in Nevada and California (Voynick, 1994). Tungsten production peaked during the World War I and World War II periods, and from 1900 to 1962, Colorado produced 35,724 tons of 60 percent tungsten concentrate (USGS, 1968).

Commercially important mineral ores of tungsten are scheelite (calcium tungstate: $CaWO_4$) and the wolframite solid solution series (iron and/or manganese tungstate: $(FeMn)WO_4$), including endmembers ferberite ($FeWO_4$) and hübnerite ($MnWO_4$) (Hobbs, 1968). Scheelite or wolframite most commonly occur in hypothermal veins and pegmatites in all rock types and sometimes concentrated along shear zones or stockworks (Hobbs, 1968). The most prevalent tungstate hosts in the RGFO region are veins and skarns in the Precambrian Boulder Creek-aged granite and metamorphic gneisses (Idaho Springs Formation biotite or calc-silicate gneisses). Northeast-striking fissures are common in the Boulder County Tungsten Belt, where quartz veins containing ferberite are up to 3 feet wide (Lovering and Goddard, 1950).

Precambrian tungsten or tungsten-copper skarns, formed by recrystallization and metasomatism of calc-silicate gneisses, are reported in Chaffee and Park Counties by Heinrich (1981). In these skarns, scheelite occurs as specks or euhedral crystals weighing as much as 20 to 45 pounds (Heinrich, 1981). Sheridan et al. (1990) identify two types of tungsten-bearing exhalative deposits: Type 3, which occur as stratabound deposits containing tungsten, +/- copper, and +/- molybdenum in calc-silicate gneiss; and Type 4, which occur as tungsten-copper veins possibly in association with feeder systems for stratabound deposits. Exhalative-related, tungsten-bearing deposits have been identified in Chaffee, Fremont, Gilpin, and Park Counties by Sheridan et al. (1990). There is some overlap of the classification of deposits as skarns by Heinrich (1981) and exhalative-related deposits by Sheridan et al. (1990).

Tungsten also occurs in the powellite-scheelite ($CaMoO_4$-$CaWO_4$) solid solution series, which is typically found in oxidation zones of molybdenum-bearing hydrothermal deposits, in contact-metasomatic (tactite) zones, and pegmatites (Hsu and Galli, 1973). Deposits of this type are found primarily in Larimer County (Lemmon and Tweto, 1962). Other districts in the CMB may contain tungstates as byproducts, e.g., the Climax deposit (Lake County) produced tungsten (hübnerite) during processing of molybdenite (Hobbs, 1968).

Tungsten occurrence potential in the RGFO management area is depicted on Map 7.4.6 in section 7. Economical concentrations of tungsten ore may occur in the Boulder Tungsten district; high occurrence potential is associated with the Idaho Springs biotite gneiss and the Boulder Creek batholith. Low to medium potential is associated with the same rocks, but where no tungsten occurrences are currently reported.

3.5 Minor Metals

3.5.1 Beryllium

Beryllium is most commonly found and commercially produced from beryl ($Al_2Be_3Si_6O_{18}$); it can also be obtained from the minerals bertrandite ($Be_4Si_2O_7(OH)_2$), chrysoberyl ($BeAl_2O_4$), and euclase ($BeAlSiO_4(OH)$) (Galbraith, 1960; MEC, 2016). In the RGFO region, beryllium occurs primarily in pegmatites, granites, and hypothermal (high temperature) veins (Galbraith, 1960; Griffitts, 1968). Beryllium-bearing pegmatites occur most commonly where Precambrian igneous (especially the Boulder Creek granodiorite and Silver Plume-aged granite) contact metamorphic rocks throughout the Rocky Mountains and are generally granitic in composition (Hanley et al., 1950). Zoned pegmatites account for all beryllium pegmatites in Colorado.

Beryllium minerals are most commonly found in the intermediate zone, though they also occur in the border, wall, and core of the zoned pegmatites (Hanley et al., 1950). Beryllium is generally not associated with fluorite-rich pegmatites, such as those in the South Platte Pegmatite district (Griffitts, 1968; Simmons and Heinrich, 1980).

Although most beryllium in the world is currently produced from one bertrandite deposit in Utah, Colorado was historically a major producer of beryl from pegmatites, having produced 2.3 million pounds of 10 to 12 percent BeO through 1963 (Del Rio, 1960; Hanley et al., 1950; Meeves et al., 1966). Meeves et al. (1966) attributes significant historic production of beryllium to nine counties within the RGFO region. These are as follows (in pounds produced of the mineral beryl through 1963):

- Boulder—2,925
- Chaffee—49,805
- Clear Creek—8,796
- Douglas—“some”
- El Paso—“some”
- Fremont—1,086,946
- Jefferson—108,152
- Lake—311
- Park—61,566

Non-pegmatite beryllium can occur in several settings: granitic rocks, tactite zones, volcanic extrusives that contain fluorite, deposits of manganese and zinc, and areas of intense faulting and alteration (Meeves, 1966). Mt. Antero, famous for its aquamarine (a variety of beryl), hosts beryl crystals and bertrandite in disseminated pods, small quartz veins, and vugs in a Tertiary quartz monzonite stock associated with the Princeton batholith (Heinrich, 1957; Meeves, 1966). Beryllium minerals occur with tin and tungsten in greisens associated with the Precambrian Redskin potassic pluton near Badger Flats, where pods, shoots, and veins contain beryl, bertrandite, and occasionally euclase (Hawley, 1969; Wallace, 2010). The Boomer mine in this area was the first commercial source of non-pegmatite beryllium ore and was intensely studied by the U.S. Bureau of Mines (Meeves, 1966).

Beryllium occurrence potential in the RGFO region is depicted on Map 7.5.1 in section 7. Beryllium is found in most types of vein and hydrothermal deposits, primarily as an accessory mineral; likewise it can occur to some degree in most pegmatites, which are widely distributed in Colorado (Griffitts, 1968). Primary concentrations occur mainly in major pegmatite districts and in the Badger Flats area; high occurrence potential is associated with pegmatite-bearing areas and areas of greisen alteration. Medium potential may be associated with other hydrothermal or vein deposits or areas with geochemical or nuclear beryllium detections.

3.5.2 Gallium-Germanium-Indium

Gallium (Ga), germanium (Ge), and indium (In) are present as minor constituents in other mineral deposits and recovered when economic to do so. All three of these metals occur as trace elements in the main ore mineral of zinc, sphalerite (ZnS). Gallium is mainly recovered from bauxite deposits processed for aluminum, as it substitutes in low amounts for other elements of similar size and charge, like aluminum (Foley and Jaskula, 2013). Germanium and indium are more commonly recovered as byproducts of zinc processing, with 60 percent of germanium and the majority of indium being produced this way (Bleiwas, 2010). Germanium is also recovered from leaching coal fly ash (a leftover product from coal burning) which provides about 30 percent of germanium supply (Bleiwas, 2010). Germanium occurs natively in coal, with concentrations in the resulting ash varying by type of coal (higher in woody coal), location within a coal bed (top and/or bottom higher than middle), and regionally (generally higher in the eastern vs. western U.S.) (Stadnichenko et al., 1953). None of the Colorado coals within the RGFO management area analyzed by Stadnichenko et al. (1953) had a value of germanium in ash higher than 0.005 percent (the highest value in their study was 0.04 percent from ash in Routt County).

The occurrence potentials of gallium, germanium, and indium in the RGFO management area are considered together and depicted on Map 7.5.2 in section 7. There is no known historic production of these three commodities in the RGFO region; however, it is possible that recoverable quantities exist in zinc deposits. Any zinc deposits in the RGFO region are considered potential sources for gallium, germanium, and/or indium. Likewise, coal deposits are also a potential source of germanium. Areas assigned a high potential for occurrence of zinc (see section 3.4.1 above) are assigned M/B for gallium, germanium, and/or indium occurrence potential. Additionally, the occurrence potential for germanium in coal is assigned L/B for all known coal regions in the RGFO region.

3.5.3 Rare Earth Elements

The rare-earth elements (REEs) comprise the lanthanide series of the periodic table of the elements, from lanthanum (#57) to lutetium (#71), plus yttrium (#39) (Long et al., 2010). REEs are divided into two groups based on atomic weight, light rare-earth elements (LREEs), including lanthanum through gadolinium, and heavy rare-earth elements (HREEs), comprising terbium through lutetium plus yttrium. Mineralized deposits are typically enriched in either "lights" or "heavies", although any REEs can occur together (USGS MYB, 2014). Although the presence of REEs within the earth's crust is actually not rare (average crustal concentrations range from 150 to 220 ppm compared to 55 ppm for copper or 70 ppm for zinc), REEs are not commonly concentrated by geologic processes into economically exploitable deposits (Long et al., 2010; Van Gosen et al., 2014). Economically viable concentrations of REEs (a minimum of 0.3 to 2.6 percent total REE oxides) occur in four types of geologic settings: carbonatites, alkaline igneous systems, ion-absorption clays, and monazite-xenotime-bearing placer deposits

(Van Gosen et al., 2014). Also, pegmatites, as products of residual magmatic crystallization, often contain REEs, although concentrations are mostly limited to zoned pegmatites (Adams, 1968b; Long et al., 2010). Of these deposit types, carbonatites, alkaline igneous systems, and pegmatites occur in Colorado.

Of note outside the RGFO area, the Iron Hill carbonatite complex in Gunnison County is enriched in REEs and contains an estimated 2.8 million tons of rare-earth oxide reserves (Van Gosen, 2009). Within the RGFO region, REE deposits exist in the Wet Mountain Alkalic Province around the McClure Mountain, Gem Park, and Democrat Creek intrusive complexes, which host carbonatite dikes (Long et al., 2010). Rare-earth minerals occur with thorium in carbonatites and in veins and mineralized shear zones in surrounding pyroxenite and gabbro (Adams, 1968b).

There are numerous REE-bearing pegmatites throughout the RGFO mountain region. Usually, rare-earth minerals are dispersed in the quartz-microcline pegmatite core zone in small quantities (Hanley et al., 1950). Also, rare-earth minerals may be disseminated as trace elements in alkali and granitic igneous rocks, and metamorphic rocks derived from such, since REEs crystallize at a late stage in magmas. In the RGFO region, Precambrian plutons, such as the Boulder Creek, Silver Plume, Sherman, and Pikes Peak Granites, host one or more trace rare-earth minerals, including, monazite ($(Ce,La)PO_4$), allanite $(Ce,Ca,Y,La)_2(Al,Fe^{+3})_3(SiO_4)_3(OH)$, bastnaesite ($(REE)CO_3F$), fergusonite ($(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$), xenotime ($YPO_4$), euxenite ($(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$), gadolinite ($(Ce,La,Nd,Y)_2FeBe_2Si_2O_{10}$), and samarskite ($(Y,Er,Ce,U,Fe,Th)(Nb,Ta)_4O_6$); rarely are they economically concentrated (Gross and Heinrich, 1965). Trace rare-earth elements (up to 1050 ppm total REE oxide) are also known from some Tertiary dikes and stocks in the CMB, although no production is reported (Gable, 1984).

REE occurrence potential in the RGFO management area is depicted on Map 7.5.3 in section 7. Small-scale historic production of REEs is noted from pegmatites and other deposits in the RGFO region (Del Rio, 1960). High occurrence potential is associated with areas of demonstrated production and with pegmatites, carbonatites, or alkaline, granitic, and metamorphic rocks that have a demonstrated REE concentration. Medium to low potential is associated with the same rock types in areas without geochemical testing or confirmation or areas where the occurrence may be sporadic or widely disseminated.

3.5.4 Niobium-Tantalum

Niobium (previously known as columbium) and tantalum share many physical and chemical properties and are most often found together in oxide minerals, but not as free metals (Parker, 1968; Schulz and Papp, 2014). They are found as end members in several solid solution series, including: columbite-tantalite (orthorhombic crystallization; $(Fe,Mn)(Nb,Ta)_2O_6$); tapiolite-mossite (tetragonal crystallization; $(Fe,Mn)(Nb,Ta)_2O_6$); pyrochlore-microlite ($(Na,Ca)_2(Nb,Ta)_2O_6(O,OH,F)$); fergusonite-formanite ($(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$); and euxenite-polycrase ($(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$) (Parker, 1963). Niobium and tantalum also occur in samarskite ($(Y,Er,Ce,U,Fe,Th)(Nb,Ta)_4O_6$) and as accessory or trace elements in brookite, ilmenorutile, perovskite, ilmenite, and sphene (Parker, 1963). As can be seen from these chemical formulas, niobium and tantalum are often associated with REEs and other incompatible lithophilic elements (those elements that are the last to crystalize from a silicate melt). Niobium and tantalum occur in many of the same deposit types as REEs, including pegmatites, disseminations in granitic, alkalic and carbonatite hosts, and placers of heavy mineral sands (Parker, 1968).

In carbonatites and related alkali igneous rocks, niobium often occurs in disseminated pyrochlore minerals (Cappa, 1998; Parker, 1968). Outside the RGFO region, the Iron Hill carbonatite stock in Gunnison County contains pyrochlore with a majority niobium composition, and is considered one of the largest niobium deposits in the U.S. with an estimated 412,000 tons of Nb_2O_5 (Van Gosen, 2009). In the RGFO region, the Wet Mountains and DeWeese Plateau of Fremont and Custer Counties contain niobium disseminated in carbonatite dikes (both primary and replacement), as well as in veins and fracture zones related to the McClure Mountain, Democrat Creek, and Gem Park alkalic intrusions (Armbrustmacher, 1988).

Niobium-tantalum minerals have been produced in several pegmatite provinces within the RGFO region. Though pegmatites are numerous along a north-south belt from Custer to Larimer Counties, niobium-tantalum concentrations are small and disseminated, and they can be economically recovered only as a byproduct (Parker, 1963). Columbite-tantalite is associated with beryl-bearing pegmatites, although microlite, euxenite, fergusonite, and samarskite also occur (Parker, 1968). Generally, the tantalum content increases towards the core, and one sample from Colorado contained 70-80 percent tantalite (Hanley et al., 1950). Pegmatites were mainly mined for quartz and feldspar, but niobium-tantalum was produced as a byproduct in the following RGFO region counties, according to Meeves et al. (1966) (in pounds of niobium-tantalum minerals):

- Chaffee—1,093
- Clear Creek—188
- Fremont—3,574
- Jefferson—4,327
- Larimer—102
- Park—2,020

Although an estimated 150,000 tonnes (metric tons) of niobium and 1,500 tonnes of tantalum are identified as reserves from carbonatites and pegmatites in the United States, including Colorado, commercial production is not economic at current prices (Schulz et al., 2017).

Niobium and tantalum occurrence potentials in the RGFO management area are considered together and depicted on Map 7.5.4 in section 7. High occurrence potential is associated with areas of demonstrated production or favorable geology, e.g., areas containing pegmatites, carbonatite, or other alkaline rocks with a demonstrated niobium-tantalum content. Medium to low potential is associated with the same rocks types in areas without geochemical testing or confirmation or areas where the occurrence may be sporadic.

3.5.5 Tellurium

Tellurium, like gallium, indium, and germanium, is not mined as a primary commodity. It is recovered as a byproduct of base-metal and sometimes gold or silver smelting. There are a wide variety of tellurium minerals, eighteen of which are recognized in Colorado (most in conjunction with gold and silver deposits): sylvanite ($(Ag,Au)Te_2$), petzite (Ag_3AuTe_2), krennerite ($AuTe_2$ to Au_3AgTe_8), calaverite ($AuTe_2$), hessite (Ag_2Te), and tetradymite (Bi_2Te_2S) are the most common tellurium minerals (Dasch, 1968). Commercially produced tellurium today mostly comes from processing large-tonnage, low-grade copper and copper-gold deposits, with the processing of volcanogenic massive sulfide deposits also constituting a significant portion (Goldfarb, 2015).

In the RGFO region, tellurium is chiefly found in association with gold deposits, most notably in the Cripple Creek mining district of Teller County and several districts in Boulder County. Principal ore minerals are calaverite, krennerite, and sylvanite, with an absence of native tellurium (Dasch, 1968). A portion of the Cripple Creek district investigated by Gott et al. (1969) showed enrichment of gold 1,000 times that of average crustal abundance and enrichment of tellurium 5,350 times that of average crustal abundance. In Boulder County, the Magnolia and Jamestown districts contain native tellurium and tellurides, with the Eldora, Ward, east Boulder Tungsten, and Gold Hill districts also noted for their gold-tellurium mineralization (Lovering and Goddard, 1950).

Tellurium occurrence potential in the RGFO management area is depicted on Map 7.5.5 in section 7. There is no known historic production of tellurium in the RGFO management area, but the presence of tellurium is highly associated with certain types of gold deposits and occurrence potential follows that of gold. High occurrence potential is associated with areas of documented gold-tellurium mineralization, such as at Cripple Creek. Medium potential is associated with Precambrian rocks that host significant gold and copper mineralized occurrences, but with no or minimal reports of tellurides. Precambrian rocks without gold or copper occurrences throughout the RGFO management area are assigned a minimal potential since the same rocks host gold and copper elsewhere.

3.5.6 Titanium

Titanium is most commonly found in the form of ilmenite ($FeTiO_3$), titaniferous magnetite $(Fe,Ti)_2O_4$, rutile (TiO_2), and titanite (sphene) ($CaTiSiO_5$). Titanium occurs mainly in two deposit types: magmatic segregation from titanium- and iron-rich magmas related to mafic rocks and heavy mineral sands placers (Woodruff and Bedinger, 2013). Average abundance in the continental crust ranges from 0.75 to 0.88 TiO_2; economical concentrations are usually associated with alkalic or mafic rocks (Force, 1976a; Schwochow and Hornbaker, 1985). Titanium may occur in common rock-forming minerals like garnet, titanite, and clinopyroxene, and consequently most alkalic igneous rocks are enriched in titanium (Cappa, 1998).

Titanium concentrations are also known from granitic to syenitic metalliferous veins and pegmatites and alumina-rich metamorphic rocks (Schwochow and Hornbaker, 1985). There are fossil mineral sands placer deposits in Mesa and Montezuma Counties (USGS, 1968) and in Elbert County near Limon (Pirkle et al., 2012). Eckel (1961) describes ilmenite as “one of the most common accessory minerals in igneous and metamorphic rocks; hence, small quantities are widespread in such rocks and the detrital material derived from them.” Concentrations of ilmenite are associated with titaniferous iron ores (magnetite and hematite), especially in gabbros and amphibolites (Schwochow and Hornbaker, 1985).

Concentrations of titanium-bearing minerals occur in the Iron Hill complex in Gunnison County, in the Caribou-Grand Island district in Boulder County, and at Iron Mountain in Fremont County (USGS, 1968). Outside the RGFO region, pyroxenite at the Gunnison County Iron Hill complex hosts titanium from perovskite, ilmenite, magnetite, and titanite, and carbonatites host accessory magnetite and ilmenite; one estimate states there are 46 million tons of material grading 13.2 percent TiO_2 (Van Gosen, 2009). The Caribou stock contains masses of titaniferous magnetite up to 4.5 percent TiO_2, the largest of which is nearly 1,500 feet long (Lovering and Goddard, 1950). Located in the McClure Mountain alkalic complex, Iron Mountain is a collection of mafic and ultramafic rocks that hosts concentrated titaniferous magnetite (Shawe and Parker, 1967). Titanium-bearing minerals occur as accessories in many of the CMB metalliferous deposits, especially those in proximity to volcanic centers, like the Cripple Creek complex in Teller County (Lovering and Goddard, 1950; Schwochow and Hornbaker, 1985).

Titanium occurrence potential within the RGFO management area, depicted on Map 7.5.6 in section 7, was assessed based mainly on geology and documented occurrences. Due to the abundance of titanium in rock forming minerals, medium potential areas are associated with mafic rock units that host known occurrences. High potential areas are assigned to areas of documented concentrations or production. Assignment of certainty level is based on available geologic reports, historic production, mine locations, general geologic knowledge, and mapped geologic units.

3.6 Uranium

Uranium occurs in an incredible variety of geologic settings and deposits, generally narrowed down to 15 main types based on geologic or genetic features as described by the International Atomic Energy Agency (Bruneton et al., 2014; World Nuclear Association, 2016):

1. Intrusive
2. Granite-related
3. Polymetallic hematite breccia complex
4. Volcanic-related
5. Metasomatite
6. Metamorphite
7. Proterozoic unconformity
8. Collapse breccia pipes
9. Sandstone
10. Paleo quartz-pebble conglomerate
11. Surficial
12. Coal-lignite
13. Carbonate
14. Phosphate
15. Black shales

The deposit types are listed in order by primary magmatic high temperature deposits to sedimentary and surficial low temperature deposits, but the majority of global mines are found in sandstones and granite- or volcanic-related geologic settings (Bruneton et al., 2014). Within the 15 categories, there are primary deposits, where uranium is deposited at the same time as its host rock, and secondary deposits, where uranium is leached out of primary minerals and subsequently re-deposited (CGS, 2006). Leaching is possible since uranium becomes soluble in oxidizing aqueous solutions and is therefore easily weathered (CGS, 2006). Of the 15 deposit types, two broad categories are important in the RGFO region: sedimentary/sandstone (peneconcordant) deposits and veins/fractures/breccia zones/stockworks (Butler, 1968). In secondary sandstone deposits, uranium is deposited in reducing conditions in pods, “rolls”, or tabular forms (World Nuclear Association, 2016). The second type (veins, etc.) may cut rocks of almost any age and type across Colorado, but the mineralization is thought to be mainly related to Tertiary emplacement of the CMB; these are primary deposits (Butler, 1968). Pitchblende (uraninite; UO_2) is the primary uranium ore; other common uranium minerals include coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), autunite (hydrous $Ca(UO_2)_2(PO_4)_2$), and carnotite (hydrous $K_2(UO_2)_2(VO_4)_2$). An extensive amount of research has been performed on uranium deposits of Colorado, including: Vanderwilt (1947), who briefly described Colorado uranium resources; King et al. (1953), who provided a more complete description of the uranium mining districts in Colorado; Wright and Everhart (1960) who describes uranium production history and key occurrences in Colorado; Nelson-Moore et al. (1978), who produced an extensive catalog that briefly described all the known radioactive mineral occurrences in the State; and Chenoweth (1980), who further summarized the uranium deposits in Colorado.

The sedimentary uranium deposits, primarily in the Colorado Plateau, have historically been the most commercially productive in Colorado, with 90 percent of ore mined in the State coming from them as of 1968 (Butler, 1968). The Hansen orebody of the Tallahassee Creek area in Fremont County, the Avery Ranch deposit in Pueblo County, the Denver Basin in Weld County, and the High Park area in Teller County are some of the larger sedimentary occurrences, with secondary occurrences also noted in Huerfano, Park, and El Paso Counties (Chenoweth, 1980). These deposits are mainly hosted by Tertiary sandstones and conglomerates, as well as the Cretaceous Dakota Sandstone.

Primary uranium deposits in the RGFO are found in alkalic igneous rocks, mainly as disseminated mineralization in intrusive and extrusive rocks, in pegmatites, and in hydrothermal deposits (Cappa, 1998). The central part of the Front Range contains most of the significant uranium deposits and producing mines, many of which are associated with mineralization. The uranium deposits of the Front Range are generally veins that contain pitchblende (uraninite) and coffinite, occurring chiefly in complex fault zones or "breccia reefs" within Precambrian crystalline rock of the CMB and adjacent foothills to the southeast (Sims and Sheridan, 1964). The Schwartzwalder mine of Jefferson County accounted for one-seventh of the total production in Colorado in 1977 (Nelson-Moore et al., 1978). A few deposits occur in the sedimentary rocks, as stratiform, fracture-controlled deposits (Chenoweth, 1980). Uranium-bearing pegmatites commonly occur throughout the Front Range; however, the uranium minerals are disseminated in small amounts and hence more likely to be recovered as byproducts than as primary ore (Sims and Sheridan, 1964). Vein deposits in Boulder, Clear Creek, Gilpin, and Jefferson Counties accounted for nearly all uranium production in the Front Range region through 1960, having yielded about 106,400 tons of crude ore (Sims and Sheridan, 1964).

The occurrence potential for primary and secondary uranium deposits is considered together in this report and depicted on Map 7.6 in section 7. Sedimentary-hosted potential was assessed on a district scale by examining historic production, reported occurrences, favorable host and primary lithologic units, and favorable paleo-groundwater conditions. Areas meeting all these requirements have a high potential, whereas those that have favorable geologic conditions but no demonstrated production were considered to have medium or low potential. For vein-type deposits, geologic conditions, historic production, and location relative to mineralization were considered. Areas with documented historic production were designated high potential, whereas those with favorable geologic settings but no production were designated medium or low potential.

3.7 Thorium

Thorium, a naturally radioactive element, occurs most commonly in monazite ($(Ce,La,Y,Th)PO_4$); concentrations of 3 to 10 percent thoria (ThO_2) in monazite ore are considered economically viable (Staatz, 1968). In Colorado, thorium is also found in thorite ($ThSiO_4$), thorianite (ThO_2), and thorogummite ($(Th,U)(SiO_4)_{1-x}(OH)_{4x}$), a thorite alteration product. Thorium commonly occurs with REEs or uranium, but unlike uranium, it is more disseminated than concentrated and is stable in weathering environments (Staatz, 1968). Like REEs, titanium, and niobium-tantalum, thorium is often found in veins associated with alkalic igneous rocks and/or primary magmatic carbonatites, and mineralized veins are the most economical source of thorium in Colorado (Nelson-Moore et al., 1978; Van Gosen et al., 2009). The largest historical source worldwide is alluvial or heavy-mineral beach sands where monazite is recovered along with rutile, ilmenite, zircon, and cassiterite (Schwochow and Hornbaker, 1985). Pegmatites, syenites, granites, fossil heavy-mineral sands placers, metamorphic rocks, and disseminated minerals in Tertiary igneous rocks are known sources of thorium in Colorado (Staatz, 1968).

Outside the RGFO region, the Iron Hill carbonatite complex in Gunnison County hosts thorium in veins, carbonatite dikes, and disseminated in a massive carbonatite stock; this is the largest estimated reserve, 31,000 tons of ThO_2, in a carbonatite stock in the country (Van Gosen et al., 2009). Within the RGFO management area, one of the largest known thorium vein reserves in the U.S. occurs in the composite Wet Mountains Alkalic Province; this area contains an estimated 46 percent of U.S. thorium vein resources (Schwochow and Hornbaker, 1985). Within the Province, thorium occurs in veins, syenite dikes, fracture zones, and carbonatite dikes associated with the Cambrian McClure Mountain, Gem Park, and Democrat Creek alkalic intrusions (Van Gosen et al., 2009). Parker and Sharp (1970) theorize that there is an unexposed massive carbonatite under the Gem Park complex, which may host disseminated thorium.

Twenty-eight known pegmatite areas in Colorado host thorium, where it usually occurs in the core zone as scattered, sparse minerals like monazite, euxenite, and samarskite (Staatz, 1968). Thorite was noted in pegmatites in Chaffee, Fremont, Larimer, Custer, El Paso, Douglas, and Jefferson Counties (Meeves et al., 1966). Monazite is also produced as a byproduct of molybdenum mining at Climax (Lake County) from ore grading 0.005 percent thorium (Staatz, 1968).

Occurrence potential for all thorium deposit types is considered together in this report and depicted on Map 7.7 in section 7. Thorium occurrence potential was assessed mainly by rock type, geologic conditions, historic production, and location relative to mineralization. Areas possessing all these characteristics have a high potential, whereas those that have favorable geologic conditions but no demonstrated production were considered to have low to moderate potential.

3.8 Vanadium

Colorado has historically been an important producer of vanadium. From 1900 to 1906, Colorado was the only producing State, and Colorado produced 74 percent of domestic recoverable vanadium (46 percent of the world's recoverable vanadium) between 1946 and 1968, the majority of which came from the Colorado Plateau (Schwochow, 1985). Schwochow and

Hornbaker (1985) report production of 274.5 million pounds of V_2O_5 between 1900 and 1968 in Colorado. Since then, vanadium has primarily been recovered as a byproduct of uranium mining (Wichmann, 1960).

Vanadium is depleted in highly siliceous igneous rocks and more abundant in mafic rocks (Fischer, 1962; Hillebrand, 1900). Principal vanadium ore minerals include the vanadium mica, roscoelite ($(Al,V)_2(AlSi_3)(K,Na)O_{10}(OH,Fe)_2$) and the hydrous vanadates, carnotite ($K(UO_2)_2(VO_4)_2$), hewettite (CaV_6O_{15}), and tyuyamunite ($Ca(UO_2)_2(VO_4)_2$) (Schwochow and Hornbaker, 1985). In Colorado, vanadium was recovered chiefly from Mesozoic sedimentary deposits in association with uranium, especially from the Salt Wash Member of the Jurassic Morrison Formation, as well as the Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). Vanadium also occurs in iron ores, particularly titaniferous magnetite, as well as telluride gold deposits (Fischer, 1968; Schwochow and Hornbaker, 1985). In the RGFO region, sandstone-related deposits of vanadium are generally minor but are noted in Fremont, Jefferson, Larimer, Park, and Weld Counties (Schwochow and Hornbaker, 1985). Titaniferous magnetite occurs at Caribou, Iron Mountain, and Iron Hill; Iron Hill has a demonstrated vanadium enrichment of 255 ppm in pyroxenite (Schwochow and Hornbaker, 1985; Van Gosen, 2009). Vanadium associated with telluride gold deposits occurs in Boulder and Teller Counties, generally as roscoelite (Fischer, 1968).

Occurrence potential for all vanadium deposit types in the RGFO management area is considered together in this report and depicted on Map 7.8 in section 7. Areas with mines where vanadium has been produced in the past or that have geochemically confirmed enrichments are considered to have a high occurrence potential. Nearby areas with a similar geologic setting but lacking production or geochemical testing are generally considered low to medium potential, as are areas that may not be near mines but do have the proper rock types. Occurrence potential for sedimentary-type vanadium follows that of uranium.

3.9 Nonmetallic Minerals / Industrial Minerals

3.9.1 Fluorspar

Fluorspar is an industrial aggregate generally composed of at least 30 percent CaF_2 in addition to quartz, chalcedony, and other minerals; it is sold in three grades, based on the fluorite content (Brady, 1975). The highest grade (class 1 or acid-grade) is white or colorless and comprises at least 97 percent CaF_2 and less than 1.5 percent silica. Ceramic-grade (class 2) has 85 to 96 percent CaF_2 and a maximum of 3 percent silica. The lowest grade (class 3 or metallurgical-grade) is commonly colored a shade of red, blue, purple, or green due to impurities, and is characterized by 60 to 85 percent CaF_2, usually with over 4 percent silica (Brady, 1975; Van Alstine, 1968). The bulk of Colorado fluorspar is classified as metallurgical-grade, coming in shades of gray, brown, green, and purple, but only rarely colorless (Aurand, 1920).

Fluorite occurs in many types of mineral deposits and can be a rock-forming mineral, but large deposits of fluorspar in Colorado were generally produced by low temperature and pressure hydrothermal processes in silicic Precambrian granitic or Tertiary volcanic rocks (Aurand, 1920; Van Alstine, 1968). Colorado fluorspar deposits are found predominantly in fissure veins and sometimes in pipes, all of epithermal origin, having been formed by waters ranging from 50 to 200°C flowing through fractures, faults, and breccia zones at shallow depths during Tertiary times (Arbogast et al., 2011; Van Alstine, 1968). Average crustal abundance of fluorine is 650 ppm, and anomalously high fluorine abundances were documented for Central Colorado crystalline rocks (Wallace, 2010). Precambrian igneous rocks averaged 1,750 to 2,500 ppm with outliers up to 260,000 ppm; Paleozoic alkalic diatremes averaged 2,070 ppm; Tertiary intrusives averaged 1,220 ppm with highs of 33,900 ppm; and Precambrian metamorphic rocks averaged 1,180 ppm with outliers up to 81,000 ppm (Wallace, 2010). Fluorspar also occurs in pegmatites, as gangue minerals in metalliferous deposits, and in association with modern hot springs (Brady, 1975). Several hot springs in the RGFO region host fluorine as a trace element (Wallace, 2010). The major fluorspar-producing areas in Colorado are Northgate in Jackson County; Jamestown in Boulder County; St. Peters Dome in El Paso County; Browns Canyon and Poncha Springs in Chaffee County; and Wagon Wheel Gap in Mineral County (Van Alstine, 1968).

Fluorspar occurrence potential in the RGFO management area is depicted on Map 7.9.1 in section 7. Fluorspar has been documented in at least 16 counties in the RGFO region, but large deposits are restricted to the veins and pipes mentioned above (Van Alstine, 1968). High occurrence potential is associated with known vein or breccia deposits and the surrounding areas, as well as Precambrian igneous rocks. Medium potential is associated with Precambrian metamorphic rocks that commonly host veins or pegmatites and alkalic intrusives.

3.9.2 Diamond and Gemstones

Gemstones are varieties of minerals that are valued for their color, clarity, durability, suitability for faceting, and ornamental nature (Arbogast et al., 2011). Diamonds are perhaps the most well-known and sought after variety, but Colorado hosts myriad gemstone types including alabaster, aquamarine, rhodochrosite, amazonite, fluorite, garnet, topaz, several quartz varieties, tourmaline, turquoise, peridot and zircon (Cappa et al., 2007; USGS MRDS, 2013). Diamonds are discussed separately from other gemstones in this section due to their unique method of formation, although other minerals such as garnet can be associated with diamond-bearing rocks.

Diamonds occur as primary or placer deposits; they accumulate in placers with concentrations of heavy minerals due to their density and hardness (they are the hardest, naturally occurring substance known). Primary diamonds occur in igneous rocks called kimberlites and lamproites; these rocks occur in pipe- or carrot-shaped bodies that form when xenolith-bearing magma is transported from great depths (Arbogast et al., 2011). Diamonds crystallize at depths of 150 to 200 kilometers under extreme heat and pressure within upper mantle rocks like peridotite and eclogite; these rocks are then transported to the surface as xenoliths in molten material that rises at high velocities (CGS, 1999).

In the State Line district of Larimer County, about 40 Early Devonian diamondiferous kimberlite diatremes (pipe-like bodies of rock) are found within a north-south-trending region near the Colorado-Wyoming State line; isolated dikes and pipes also occur at Green Mountain near Boulder and south of Estes Park (Cappa, 1998; Hausel, 1998; McCallum and Mabarak, 1976). State Line district kimberlites are ellipsoidal to irregular in shape and range from a few to 1,800 feet in diameter (CGS, 1999; Hausel and McCallum, 1980). About 65 percent of all diamonds recovered from State Line district kimberlites were classified as gem-quality diamonds (the remainder were classified as industrial); production of 130,000 total diamonds through 1997 is reported (Hausel, 1998). Non-gem-quality diamonds are discussed in the Industrial Abrasives section of this report (see section 3.9.4).

In addition to diamond, Colorado has more than 30 known varieties of gemstone (Pearl, 1972). The State's official gemstone is aquamarine, which is primarily found around 13,000 feet above sea level on Mount Antero and Mount White in Chaffee County (CGS, 2013). Most of Colorado's gemstones are found in or associated with pegmatites, although some are found in hydrothermal vein systems (Murphy and Modreski, 2002). The following is a partial listing of gemstones and where they can be found in the RGFO management area, as compiled from Cappa et al. (2007), Pearl (1972), and Arbogast et al. (2011):

- Alabaster—a fine-grained, compact variety of gypsum used to make elegant vases and other ornamental items. One of the largest alabaster quarries in the country lies in the foothills northwest of Fort Collins (Larimer County).
- Amazonite—a variety of microcline that is green to blue-green in color and is usually sold as mineral specimens, although it is hard to facet. Abundant in the Crystal Peak area (Park and Teller Counties); Harris Park (Park County); and Cameron Cone, Specimen Rock and Crystal Park (El Paso County).
- Aquamarine—a pale blue to blue-green variety of the mineral beryl. The most famous occurrences are at Mt. Antero and Mt. White in Chaffee County.
- Garnet—a group of silicate minerals with variable composition and color from red to brown. Gem-quality spessartine is deep red and found on Ruby Mountain in Chaffee County; almandine crystals are found at the Sedalia mine, Chaffee County. Garnets also occur in some Precambrian schists.
- Peridot—a gem-quality variety of the mineral olivine. Peridot occurs in vesicular basalt near Badger and Herring Creeks of Park and Fremont Counties.

- Quartz—many varieties of quartz are considered gemstones: rock (colorless), amethyst (purple), citrine (yellow), rose (pink), smoky (brown to black), milky (white), and rutilated (contains needle-like crystals of rutile). Gem-quality amethyst is found in Fremont County and around the Pikes Peak batholith, whereas the Crystal Peak area of Park and Teller Counties is famous for smoky quartz. Cryptocrystalline varieties of quartz like jasper, carnelian, and agate are found in petrified wood and fossilized dinosaur bones.

- Rhodochrosite—the State mineral of Colorado; a manganese carbonate mineral that varies from pale pink to deep red. Colorado is famous for gem-quality dark red specimens, although with a hardness of only 3.5-4, it is difficult to facet for jewelry. The most famous occurrence is at the Sweet Home mine (Park County), but it also occurs in the Moose mine (Gilpin County) and the Urad mine (Clear Creek County). Rhodochrosite occurs in hydrothermal systems, rather than pegmatites, often in association with silver-lead-zinc deposits.

- Topaz—a colorless, yellow, brown, red, bluish, or pink aluminum silicate; colored specimens may fade to clear if exposed to sunlight. The Devil's Head area in Douglas County has produced some of the largest specimens in the RGFO region. Topaz occurrences are also noted at the Spruce Grove campground area (Jefferson County); Crystal Park and Specimen Rock (El Paso County); Crystal Peak and Glen Cove areas (Teller County); Ruby Mountain and Mount Antero (Chaffee County); and Pilot Peak (Park County).

- Turquoise—a hydrated copper aluminum phosphate that forms as a secondary mineral associated with weathering of porphyry copper deposits or aluminous igneous or sedimentary rocks; it occurs as vein or fault fillings, nuggets, nodules, films, and as impregnations of the wall rock. The Cripple Creek area (Teller County) and the Turquoise Chief mine (Lake County) are some of the more well-known occurrences.

Occurrence potential for diamonds and gemstones in the RGFO management area, depicted on Map 7.9.2 in section 7, is based on geology and historic production. In the RGFO region, diamonds have been extracted only in Larimer County, and there are no reported occurrences of kimberlites outside the areas discussed above. High potential for diamonds is associated with kimberlite or lamproite diatreme complexes, which have very small surface expressions and weather thoroughly, thus making them difficult exploration targets (McCallum and Mabarak, 1976). At the scale of this report, identifying individual kimberlites was not practical, and high potential was assigned to areas that contain swarms of these bodies. Medium potential is associated with the generalized area of known kimberlite occurrence. Gemstone potential, outside of that associated with diamonds, generally follows pegmatite occurrence potential. Other areas of high potential are those hydrothermally mineralized areas with documented historic production of gemstones. Medium potential for gemstones is associated with rock types that are known to host gems in other areas.

3.9.3 Pegmatite Minerals

In the RGFO region, beryllium, tantalum, niobium, REEs, thorium, fluorspar, and gemstones can all be found in pegmatites, but are also found in other mineral deposits; therefore, they are treated separately in other sections of this report. In addition to the minerals containing those commodities, industrial minerals such as feldspar and mica are mined from pegmatite deposits. These will be the focus of this section, but the occurrence potentials, geologic analysis, and references for this section also apply to the other commodities found in pegmatites. Coarse-grained, lenticular intrusions of non-granitic rocks, which may be referred to as pegmatites due to their texture, are not considered in this section.

Pegmatites are very coarse-grained, tabular, lenticular, or pipe-like bodies generally intruded within Precambrian gneisses, schists, and granitoids; in Colorado, the majority are of Precambrian age (Hanley et al., 1950). They are of granitic composition (contain an abundance of quartz, feldspar, and mica), and are associated with large granitic intrusions (Hanley et al., 1950). Most pegmatites are steeply dipping to vertical, cutting across any foliation, but earlier pegmatites are more likely to intrude along foliation and local folds; however, all pegmatites can be affected by local structure (Lovering and Goddard, 1950; Hanley et al., 1950). They may be zoned, i.e., made up of concentric shells with differing mineralogies and textures; the zones are (from outside in) the border zone, the wall zone, the intermediate zone, and the core (Hanley et al., 1950).

These zones may contain different concentrations of important minerals and be highly variable to non-existent, but most pegmatites that have appreciable concentrations of minerals of interest are zoned (Adams, 1968a). Pegmatites form during the water-rich, late-stage crystallization of large igneous bodies as segregations of the magma or as bodies that intrude from these magmas into surrounding rock (Arbogast et al., 2011; Hanley et al., 1950). They are likely to contain incompatible lithophilic elements (those that are last to be crystalized out of a melt or first to partition into melt during partial melting), many of which are of strategic importance (e.g., Linnen et al., 2014).

Adams (1968a) divides Colorado pegmatites into two large groups: feldspar-rich with accessory fluorite, topaz, REEs, and thorium; and fluorine-poor with common beryl, mica, niobium-tantalum minerals, tourmaline, garnet, and rare lithium and plagioclase feldspar. Hanley et al. (1950) further divide pegmatites by their most prevalent economic commodity: beryllium, lithium, muscovite, columbium-tantalum, potash feldspar, or rare earth elements (although they note that most pegmatites contain more than one). Pegmatites of all types are generally small, from a few feet wide and long up to 500 feet wide and a mile long; the average size is less than 50 feet wide and 500 feet long (Hanley et al., 1950). Pegmatites occur in the Precambrian igneous and metamorphic rocks, as well as some Tertiary intrusives, of the Front Range, mostly within a zone about 155 miles long by 40 miles wide that extends from Cañon City to the Cache le Poudre River (Baillie, 1962). Those pegmatites with the highest economic potential are zoned and located along the contacts of Boulder Creek-aged plutons and Precambrian metamorphic rocks (Lovering and Goddard, 1950; Taylor et al., 1984).

Feldspar, a group of common, aluminum silicate, rock-forming minerals, occurs in the vast majority of Colorado pegmatites; however, economic concentrations are primarily found in the intermediate zone and core of zoned pegmatites (Baillie, 1962). Historically, feldspar has been chiefly recovered from mines in Jefferson, Douglas, Fremont, and Chaffee Counties (Adams, 1968a). An estimated 560 million pounds of feldspar was mined prior to 1945, with an estimated annual average production of 100 million pounds between 1945 and 1957 (Adams, 1968a; Vanderwilt, 1947).

Mica is a term for a family of phyllosilicate minerals. Muscovite, a common mica mineral in pegmatites, may be classed as “sheet” (large, impurity-free crystals), or “scrap” (mica that falls short of sheet quality) (Adams, 1968a). Sheet mica is found in the wall and intermediate zones of some pegmatites, whereas scrap mica tends to occur in the intermediate zone and core (Hanley et al., 1950). Sheet mica has been commercially mined primarily from Park, Clear Creek, Larimer, and Jefferson Counties (Adams, 1968a). Prior to 1945, about 56 million pounds of scrap mica was produced in Colorado (Vanderwilt, 1947). Another important mica mineral is lithium-bearing lepidolite, which has been mined in Fremont County (Adams, 1968a). This mineral is found in the intermediate zone and core, although only core deposits generally contain mineable concentrations (Adams, 1968a). Arbogast et al. (2011) report that industrial feldspar and mica are not currently mined in Colorado.

Pegmatites are widespread in the RGFO region and all contain the industrial minerals quartz, feldspar, and mica. Pegmatite occurrence potential in the RGFO region is depicted on Map 7.9.3 in section 7. Known pegmatite districts are designated as having high mineral occurrence potential. Pegmatite bodies are discreet units and are not large enough to be represented at the scale of this MPR; therefore, buffer zones surrounding pegmatite swarms are considered to have high potential. Although pegmatites are associated with Precambrian batholiths, they are predominantly found in the metamorphic rocks marginal to plutons, and more commonly in the felsic facies (Lovering and Goddard, 1950). Outside of pegmatite districts, Precambrian felsic metamorphic rocks in proximity to plutons have a high potential for pegmatite mineral occurrence whereas biotite gneisses and schists have moderate potential. Precambrian plutonic rocks have lower potential.

3.9.4 Industrial Abrasives

Industrial abrasives include non-gem-quality diamond, garnet, and corundum. These minerals have the same chemical formula as their gemstone counterparts, but lack the quality and clarity to be used for jewelry. Diamond (C) is one of the hardest known substances, with a Mohs rating of 10. Garnet is a name for a group of minerals with the general chemical structure $A_3B_2(SiO_4)$ where A is Ca, Fe^{2+}, Mg, or Mn, and B is Al, Cr, Fe^{3+}, or Ti (USGS MYB, 2013). The varying chemical components dictate the hardness of garnets, which ranges from 6.5 to 7.5 on the Mohs scale. Corundum (Al_2O_3) has a hardness of 9.0 on the Mohs scale. The hardness of diamond, garnet, and corundum make them ideal for cutting and polishing in a wide range of industrial settings. Industrial abrasives occurrence potential in the RGFO management area is depicted on Map 7.9.4 in section 7.

Diamonds are known to occur in kimberlites of the State Line district of Larimer County, as well as in isolated kimberlites near Estes Park (e.g., Hausel, 1998). Worldwide, about 80 percent of mined diamonds are relegated for industrial purposes, although at some State Line district kimberlites, 65 percent of all crystals recovered were classified as gem-quality diamonds (Arbogast et al., 2011; Hausel, 1998). The diamond deposits of Colorado, along with some in Arkansas, are the only occurrences of diamonds in the U.S. to be mined commercially (Arbogast et al., 2011). The State Line district contains many kimberlites that have been sampled for diamonds or that possess a similar geochemical signature to known diamond-bearing rocks, making the whole district a high potential area for industrial diamonds (Hausel, 1998).

Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites and kimberlites, in Colorado (Eckel, 1961; Hausel, 1998; McCallum and Mabarak, 1976). In the RGFO management area, garnet occurs as an accessory mineral with diamonds in kimberlites, as well as in Precambrian schists, gneisses, and pegmatites of the Front Range (Hausel, 1998; Meeves et al., 1966). High potential for garnets is associated with kimberlites and pegmatite districts, as well as with metamorphic rocks around Clear Creek County; elsewhere in the RGFO region, metamorphic rocks have medium to high potential.

Industrial corundum is known from Chaffee, Clear Creek, Fremont, and Jefferson Counties, although production has only been reported from Chaffee County (Schwochow, 1981). Corundum occurs in metamorphic mica schists and gneisses, pegmatites, and some igneous rocks (e.g., syenite and ultramafic rocks). High potential for corundum is associated with the Calumet mine in the Turret district of Chaffee County; moderate potential is noted for the other counties with occurrences.

3.9.5 Limestone and Dolomite

This section describes the resource potential of limestone and dolomite for industrial uses other than aggregate and dimension stone, which are discussed in section 3.10. Limestone is a carbonate sedimentary rock composed chiefly of calcite (calcium carbonate, $CaCO_3$); dolomite (or dolostone) is a carbonate rock containing magnesium in addition to calcium ($CaMg(CO_3)_2$) that can be used in similar applications (Freas et al., 2006). Both limestone and dolomite contain variable amounts of clastic grains such as quartz, clay, and other minerals that may affect the purity and suitability of the rock for industrial uses. The industrial uses of limestone and dolomite include manufacture of cement and lime; agricultural uses include soil conditioner or poultry feed; and specialty uses include mine dusting or water treatment (Freas et al., 2006). Each application requires a specific grade of stone, which is determined by physical and chemical testing (Freas et al., 2006).

Limestone is formed in marine environments from the accumulation of sea shells (both macroscopic and microscopic), precipitated calcium carbonate, and fine sediment (Keller and Widmann, 2002). Dolomite can be directly precipitated from sea water, but is most often the result of the alteration of limestone by hypersaline brines (Freas et al., 2006). Many limestone formations are locally or partially dolomitized into dolomite or dolomitic limestone, and units mapped as dolomite may contain unaltered limestone. Limestone and dolomite deposits occur in areas that once hosted warm, shallow marine environments. Colorado hosted such seas during the Lower to Middle Paleozoic (see section 2.2.4) and Cretaceous (see section 2.2.7) periods.

The main Paleozoic carbonate rocks include the Manitou, Fremont, and Leadville Limestones (all of which are dolomitized in places). These Paleozoic rocks were used as sources of flux material for the Colorado Fuel and Iron Corporation steel plant in Pueblo (D. A. Carter, 1968). The Leadville Limestone crops out in the mountains and the un-dolomitized portions may be suitable for local cement production (Wolfe, 1968). Quarried in Fremont, El Paso, and Chaffee Counties, the Leadville Limestone was also used in the sugar refining process (Schwochow, 1981). The Williams Canyon, Hardscrabble, Forelle, and Beulah Limestones, as well as the Belden Shale, Dyer Dolomite, and the Minturn and Maroon Formations, are minor Paleozoic carbonates, although some of these rocks are correlative to the major units discussed above (see section 2.4.2). Carbonate rocks of Cretaceous age occur in the Colorado Group and overlying Niobrara Formation (see section 2.4.5).

The Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; it crops out along the Front Range and is extensively exposed in southeastern Colorado (Wolfe, 1968). Rock units containing limestone and dolomite are widely distributed across all but the northeastern and east-central parts of the RGFO management area; they are especially widespread in the southeastern part of the region and prevalent in the eastern foothills of the Front Range, as well as in the Mosquito Range and in western South Park (Tweto, 1979a).

The occurrence potentials of limestone and dolomite in the RGFO region are considered together and depicted on Map 7.9.5 in section 7. The scale of mapping, the fact that limestone and dolomite are often interlayered within a formation, and the occurrence of limestone beds within units mapped as primarily shales or other sedimentary rocks prohibits capture of local variability. Although certain units may not maintain a continuous specific potential along their entire outcrop extent due to changes in mineralogy/chemistry/etc., the scale of this MPR and the level of existing mapping detail make it most efficient to identify potential by geologic unit. Areas near historic or current production are considered high potential, as production indicates the presence of desirable qualities in the limestone or dolomite. Rock units hosting historic prospects are considered high or medium potential depending on their proximity to known production and geologic/mineralogic/chemical similarity to producing areas. Medium potential units are noted for carbonate content, but may not have any production or record of quality testing.

3.9.6 Industrial Sand

Industrial sand refers to sands used for specialized purposes other than construction aggregate, especially high-silica sands that meet specific size, purity, color, inertness, hardness, and thermal resistance requirements (Herron, 2006). Industrial sand generally contains a high proportion of silica, as the mineral quartz (SiO_2), and has much fewer contaminants (clay, feldspar, iron oxides, etc.) than common sand (Arbogast et al., 2011). Quartz is highly resistant to weathering and is therefore a common remnant following extensive weathering and erosion of silicate rocks. Silica sand may collect naturally in high concentrations, or deposits may need to be washed, screened, floated, blended, dried, or otherwise processed to obtain the necessary properties (Arbogast et al., 2011).

After weathering out of rocks, quartz is transported by water or wind, collecting in stream channels, terraces, alluvial fans, and other environments. Geologic environments where sand is sorted, such as beaches and sand dunes, are ideal depositional settings for industrial sand (Arbogast et al., 2011). The highest quality industrial sands in the U.S. occur in the Midcontinent region, where the deposits have undergone many weathering and erosion cycles resulting in better sorting and roundness (Herron, 2006). In Colorado, the eastern plains host Quaternary eolian deposits of well-sorted and well-rounded sand used for filtration and water well packing (Builinger and Keller, 2015). These eolian deposits were also mined near Colorado Springs for use as hydrofracturing sand (Schwochow, 1981). The eolian deposits cover extensive portions of the eastern RGFO area, although the content of silica sand throughout is unknown (Tweto, 1979). These deposits are unconsolidated and may be mined using front-end loaders, scrapers, bulldozers, and other earth-moving equipment; this is an advantage over consolidated deposits (Herron, 2006). Consolidated deposits consist of a high proportion of quartz sand grains cemented together.

Geologic formations that preserve ancient beaches and dunes are likely to contain quartz sand. The most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica in the Dakota Sandstone and 96.7 percent silica in the Lykins Formation. Best quality sands average over 99 percent silica (Vanderwilt, 1947). The industrial sand produced from these formations is largely used for foundry and glass applications (W. D.

Carter, 1968). The formations crop out in the foothills of the Front Range; however, these exposures have highly variable composition and are relatively thin (W. D. Carter, 1968). The Dakota Sandstone is widely exposed in southeastern Colorado, although reports of industrial sands production from this area are lacking (Tweto, 1979a).

Previous and current DRMS mining permits listing silica sand as a commodity are recorded in Quaternary alluvium, eolian sand, the Tertiary Ogallala Formation and Dawson Arkose, as well as the Dakota Sandstone and Lykins Formation. Many other units have reportedly been sporadically mined on a small scale: the Cambrian Sawatch Quartzite; Ordovician Harding Sandstone; Devonian Parting Quartzite Member of the Chaffee Formation; certain layers of the Pennsylvanian Fountain Formation; Permian Lyons Sandstone; Jurassic Morrison Formation; and the Cretaceous Lytle Sandstone Member of the Purgatoire Formation, Codell Sandstone Member of the Carlile Shale, Trinidad Sandstone, Fox Hills Sandstone, and Laramie Formation (Arbogast et al., 2011; W. D. Carter, 1968; Schwochow, 1981).

The occurrence potential of industrial sand in the RGFO management area was assigned based on geologic unit and is depicted on Map 7.9.6 in section 7. Resource maps from Schwochow et al. (1974b) and Schwochow (1981), as well as lithologic descriptions from Tweto (1979a), helped to delineate appropriate rock types. Generally, high and medium potential areas have sand that has been demonstrated as suitable for industrial use through previous or current production. Highly sorted sand dunes and beach- or dune-derived sandstones are the most likely deposit types to have high potential.

3.9.7 Gypsum

Gypsum ($CaSO_4 \cdot H_2O$) is a marine evaporite mineral (Keller and Widmann, 2002). Massive gypsum is the most common variety, with anhydrite (anhydrous calcium sulfate), alabaster, satin spar, selenite, and gypsite being other varieties (Arbogast et al., 2011). All of these varieties are considered together in this MPR due to the scale of geologic mapping used for potential assignment. Gypsum is quite soft (2 on the Mohs scale) and is colorless in pure form, although it may be tinted yellow, red, or brown; it is in the monoclinic crystal system with twinning being fairly common (Sharpe and Cork, 2006). Gypsite is an earthy mass of impure gypsum that usually forms above gypsum deposits. Selenite, alabaster, and satin spar are fine-grained, compact varieties used for ornamental and/or sculptural purposes (Withington, 1968).

Evaporites form when marine waters become oversaturated with minerals, prompting gypsum and other salts to precipitate out; this tends to occur in warm, shallow seas and can create significant deposits if the evaporitic basins are stable for long periods of geologic time (Keller and Widmann, 2002). The conditions required for gypsum formation prevailed in the Late Paleozoic (see section 2.2.5) and Jurassic (see section 2.2.6) periods. The Permian-Triassic Lykins Formation (especially the correlative Blaine Gypsum and Day Creek anhydrite units) and the Jurassic Ralston Creek Formation produced the earliest recorded gypsum deposits in

Colorado (Schwochow, 1981). Discontinuous lenses and nodules of gypsum and anhydrite occur irregularly in the Jurassic Morrison Formation and Lower Cretaceous Colorado Group (correlative with the Benton Formation and including the Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) along the east flank of the Front Range between Larimer and Fremont Counties (Withington, 1968). The gypsum mined from these areas was used as cement retardant and in plaster products (Schwochow, 1981). In southeastern Colorado, the Morrison Formation is exposed along the Purgatoire River and Muddy Creek and contains beds and lenses of gypsum, the most substantial of which is a 17-foot-thick bed at the base of the formation which likely corresponds to the Ralston Creek Formation (Withington, 1968).

Ornamental alabaster has been produced from the Lykins Formation near Livermore in Larimer County and the Niobrara-Colorado Group near La Junta in Otero County (Vanderwilt, 1947; Eckel, 1961). The transition from clastic to evaporite deposition was irregular, and some evaporite beds occur in the Pennsylvanian Minturn and Maroon Formations (Arbogast et al., 2011). These gypsum beds are exposed along the Arkansas River from Salida to Coaldale in Chaffee and Fremont Counties, and a deposit was mined near Howard for use as cement retardant (Withington, 1968).

Gypsum occurrence potential in the RGFO management area is depicted on Map 7.9.7 in section 7. Gypsum potential was assessed by geologic map unit largely based on Tweto's (1979a) 1:500,000 scale map; however, in many areas gypsum-bearing formations are lumped with other formations into a combined geologic unit. For instance, the Lykins Formation averages 800 feet thick, but along the Front Range gypsum occurs near the top of the formation in lenses up to about 50 feet thick (Withington, 1968), and the Lykins itself may be mapped with other units on the Tweto (1979a) map. All of this geologic information was used as a basis for potential assignment, and the assignment map therefore shows, in most cases, the maximum extent of gypsum-bearing formations. High potential areas are those with appropriate geologic setting, as well as evidence of current or past production or the presence of commercial gypsum deposits. Units generally designated as high potential are the Lykins, Morrison, and Ralston Creek Formations. Medium potential was assigned based on presence of a known gypsum-bearing unit and documentation of gypsum presence, especially in the Minturn Formation.

3.9.8 Helium

Helium is the second lightest element and a noble gas. It is inert (chemically nonreactive) and lighter than air. It also has the lowest boiling point of any element, –452.7°F. These unique chemical properties make it an indispensable cooling agent, levitation aid, and chemical insulator. It is vital to physics research, the operation of MRIs, and to making silicon computer chips.

Helium is naturally emitted by the earth's crust and exists in the atmosphere at a concentration of ~5.2 parts per million (Cima, 2015). This concentration is not economic, and it wasn't until

1903 that natural gas high in helium was found in a Kansas oil well that helium became a commercial commodity (Cima, 2015). Helium is generally produced as a byproduct of natural gas, with gas in the Mid-Continent U.S. averaging between 0.3 and 2.7 percent (U.S. BLM Helium Program, 2016). By the 1960s, the U.S. had designated a partially depleted gas field near Amarillo, TX as a storage facility and spent the next decades building up a national reserve (Cho, 2015).

In 1996, the U.S. Congress passed the Helium Privatization Act (Public Law 104–273) in order to repay the $1.3 billion debt creating the helium reserve had cost and to transition the helium industry to private control (Cho, 2013). The helium was to be sold off at equal annual volumes and a formula-driven price; this lead to helium being sold at below market value (Cima, 2015). The erasure of the Federal Helium Reserve's debt was projected to take place in 2015, but by early 2013 it appeared that sales would stop on September 30, 2013, as the BLM would break even on the reserve (Cho, 2013). There had been little investment by private business due to low prices, so a helium shortage was feared.

In order to provide a continued helium supply, the U.S. Congress passed the Helium Stewardship Act of 2013 (HSA) on October 2, 2013 (Public Law 113-40). The purpose of the HSA was to assure continued operation of the Federal helium program but with operational changes that would continue to transfer the helium industry to private control with minimal market disruption (USGS MYB, 2014). The HSA is to be carried out in four phases:

> *"-Phase A, Allocation Transition.—This phase began upon passage of the HSA and ended on September 30, 2014. This phase was a continuation of the Helium Privatization Act's sales volumes and conditions.*
>
> *-Phase B, Auction Implementation.—This phase began on October 1, 2014, and will end when the crude helium stored in the Federal Helium Reserve reaches 3 billion cubic feet. During this phase, the Bureau of Land Management (BLM) was to implement auctions beginning in fiscal year (FY) 2015. In FY 2015, the BLM was to auction 10% of the total volume available for sale from the Federal Helium Reserve. The auction was open to all qualified bidders as defined in 50 U.S.C. 167d(b). The remainder each year is sold to refiners with connections to the crude helium pipeline. Each subsequent year, the percent auctioned is to increase by at least 15% from that of the previous year until 100% is achieved.*
>
> *-Phase C, Continued Access for Federal Users.—This phase will begin when the remaining crude helium stored in the Federal Helium Reserve reaches 3 billion cubic feet. The BLM would continue to provide crude helium for sale to Federal users. There would be no sale or auction of helium to private entities, but deliveries to private entities of helium sold in Phase B may continue. Current projections show that this phase will*

begin on October 1, 2018, after helium sold for FY 2019 delivery is transferred to private accounts.

-Phase D, Disposal of Assets.—In this phase, the Secretary of the Interior is required to dispose of assets by no later than September 30, 2021. These assets include all underground natural resources and the United States' rights to those assets. Unlike the 1996 legislation, the BLM was no longer required to sell helium from the reserve in equal annual volumes. Under the HSA, sales can match the amount available for production from the reserve" (USGS MYB, 2014)

As noted in Phase C above, the Federal Helium Reserve is projected to stop private sales sometime in late 2018. After this, it will be up to private businesses to fill the helium demand in the U.S., unless there is additional legislation by Congress. The helium market is complicated and unique among minerals in the RGFO.

Helium is present in the RGFO in several natural gas fields. The BLM (2008) reported the average helium concentration in Rocky Mountain Region gas fields as 0.1173 percent. Noted occurrences of helium in the RGFO are in Las Animas, Baca, Bent, Prowers, Kiowa, Cheyenne, and Kit Carson Counties. Two major structures, the Model Dome anticline (Clair and Bradish, 1956) and the Las Animas Arch (e.g., BLM, 2008), are responsible for most of the helium potential in the RGFO. The arch is a broad anticline that extends north-northeast from southwestern Bent County through eastern Cheyenne County and into northwestern Kansas (Merewether, 1987). The Las Animas Arch averages 0.0642 percent helium (BLM, 2008), although smaller fields within the structure have been found to have much higher concentrations. Map 7.9.8 in section 7 depicts helium occurrence potential in the RGFO management area.

3.10 Construction Materials

This category includes both nonmetallic and several industrial minerals (sand and gravel, aggregate, clay, dimension stone, gypsum, industrial sand, etc.), generally falling under the purview of the Materials Act of 1947 and the Multiple Surface Use Mining Act of 1955. These materials generally fall into the salable category, but in certain circumstances can be locatable (see the introduction of section 3 for definitions). Construction materials are widespread throughout the RGFO, primarily in surficial deposits. Due to the expense of transporting heavy materials long distances, the economic feasibility of saleable minerals is very dependent upon the proximity of their location to their final destination. Sand, gravel, and crushed stone aggregate deposits are generally developed in areas close to their end destination, often near major cities and urban centers.

This report uses map units (as mapped by Ogden Tweto (1979a) at a 1:500,000 scale), the USGS MRDS (2013) database of operating facilities, and operator data from CDRMS (2016) to delineate units favorable for sand and gravel, crushed stone aggregate, lightweight aggregate, clay, building and dimension stone, limestone, industrial sand, and gypsum. The potential for each geologic unit has been given a blanket assignment with the geologic information available (average composition, grain size, sorting, etc.). However, just because a unit is suitable (contains the proper geologic characteristics), it may not be favorable if it's not within close proximity to where it will be used. For example, in eastern Colorado, a certain unit may not be mined due to less suitable characteristics, but within Jefferson and Douglas Counties, where development is happening faster, that same unit may be used, despite it not having ideal specifications, because it is available nearby. Also, some construction materials occur as small deposits within a larger body. For instance, clay can occur in small seams or veins, or only certain pockets of limestone are of the proper chemical composition; therefore, occurrence potential is assigned to the entire unit that could bear those veins or pockets, but the actual deposits are small portions of the overall unit. Occurrence potential and confidence level are based on the best overall information available.

3.10.1 Sand and Gravel

Sand and gravel aggregates form as a consequence of the weathering and erosion of rocks and are typically composed of resistant rock and mineral types. On the Wentworth scale, sand grains are smaller than 2 mm but larger than 1/16 mm; gravel is generally composed of pebbles (2-64 mm) and cobbles (64-250 mm), although sometimes the determination is by what remains between the No. 4 (4.75 mm) and No. 200 (.075 mm) sieves (Arbogast et al., 2011). Not all sand and gravel deposits have equal potential for use as aggregate. Coatings of clay, calcium carbonate, or iron and manganese oxide, as well as clasts of chert or clay-altered minerals, contaminate the aggregate making it unsuited for use in concrete (Lindsey, 1997). Clast roundness, hardness, sorting, and toughness affect the suitability of a deposit for use as aggregate. An ideal mix for sand and gravel deposits is 60 percent gravel and 40 percent sand, which is enough gravel for use as roadbase and enough sand for use in concrete (Arbogast et al., 2011). Natural deposits may be refined by screening out fine materials, or supplemented with crushed rock to increase the gravel fraction. Note that "construction aggregates" refers to the combination of sand and gravel and crushed stone. This can result in some ambiguity between sand and gravel and crushed stone deposits.

Sand and gravel resources are common in alluvial fans, terraces, and floodplains and are locally present along rivers and perennial or ephemeral streams (Arbogast et al., 2011; Lindsey et al., 2005). Alluvial material is produced in the headwaters of rivers and streams by physical and chemical weathering of the country rock and/or incorporation of pre-existing surficial deposits; the material is moved downstream by gravity, with increased sorting, roundness, and variability of grain size occurring with increased distance from the source (Schwochow et al., 1974a). Major streams that drained the mountains during the Quaternary Period developed floodplains and multi-level terraces. Undissected terraces and floodplains are the primary source of high-quality sand and gravel, as older gravels on dissected and usually higher terraces are more weathered, and alluvial fans often contain excess fines and boulders (Arbogast et al., 2011).

In Colorado, some late Tertiary conglomerates contain unconsolidated or weakly consolidated alluvium that may be suitable as a sand and gravel deposit after mechanical crushing (Arbogast et al., 2011). Late Tertiary formations potentially suitable as sand and gravel deposits include the Ogallala Formation in the Great Plains, Santa Fe Formation in the Wet Mountain Valley, Dry Union and Santa Fe Formations in the Upper Arkansas Valley, and Wagontongue Formation in South Park (W. D. Carter, 1968; Scarbrough, 2001; Schwochow, 1981; Voegeli and Hershey, 1965). Glacial till (mapped as glacial drift on the 1:500,000-scale map by Tweto, 1979a) may also contain material suitable to be crushed and sieved for use as a sand and gravel resource (Schwochow, 1981).

The occurrence potential for sand and gravel in the RGFO management area was assessed based on geologic unit and is depicted on Map 7.10.1 in section 7. Resource maps from Schwochow et al. (1974b), as well as lithologic descriptions from Tweto (1979a), helped to delineate appropriate rock types. Reports by Langer et al. (1997) and Knepper et al. (1999) were used to help assess the quality of units for use as construction aggregate. Generally, high potential areas have sand and gravel suitable for most uses and contain little deleterious materials; materials from lowland and floodplain deposits would mostly fall in this category. Deposits that meet the standards for most uses or require minimal processing are designated as medium potential; alluvial fans and weakly consolidated materials may fall under this designation.

3.10.2 Crushed Stone Aggregate

Crushed stone aggregate is derived by blasting and crushing bedrock, rather than processing alluvial material. Many bedrock formations in the RGFO management area are suitable for crushed stone aggregate. Any igneous, metamorphic, or sedimentary rock can be used for crushed stone if it has the correct physical properties, including abrasion resistance, soundness, grain size, low deleterious chemical constituents, and color. (Arbogast et al., 2011). Favorable rock types include fine-grained granite and gneiss, basalt, rhyolite, quartzite, dolomite, and limestone; unfavorable types include schist, loosely consolidated sandstones, shale, coarse-grained granite, and highly weathered, friable, or weak rocks (Langer and Knepper, 1995; Schwochow et al., 1974a). Crushed stone is increasingly a replacement for sand and gravel because the quarries generally have a smaller footprint and can be located farther from urban areas, both advantages that direct land use away from alluvial operations near populated areas. (Arbogast, 2011; Carroll et al., 2001).

Crushed stone is used in a wide variety of applications, and each one requires source rocks with different ideal properties, hence there is no one deposit model for crushed stone resources. Instead, potential rock units are assessed based on physical and chemical properties, which are observed in the field or tested for in a lab. These properties are then compared to the requirements for a specific purpose, and the rock is deemed to have satisfactory, fair, or poor physical qualities and innocuous or deleterious chemical qualities (Langer and Knepper, 1995).

Mafic igneous rocks may be referred to as traprock or black granite within the aggregate industry, and the low quartz content and insensitivity to chemicals make it suitable for use in cement, as long as there are no large vugs or pores (Langer and Knepper, 1995). Mafic rocks are found as Tertiary-aged extrusive volcanics within the RGFO region, such as in the North and South Table Mountain area near Golden (Arbogast et al., 2011). Granite is a term generally used to refer to any light-colored, coarse-grained rock in the aggregates industry; this may include granite, coarse-grained gneiss, and other felsic to intermediate igneous rocks (Langer and Knepper, 1995). In the RGFO area, the Silver Plume, Boulder Creek, and Pikes Peak batholiths, plus the metamorphosed Precambrian basement rocks, have been quarried and used as crushed stone (Arbogast, 2011). Felsic volcanics and micaceous metamorphics cannot be used to make concrete aggregate, but may make appropriate road base (Langer and Knepper, 1995). There are several instances of Tertiary felsic volcanic outcrops in the RGFO area, and schist is found exposed as part of the metamorphosed Precambrian basement of the Front Range.

Sedimentary rocks such as limestone, dolomite, well-cemented sandstone and siltstone, breccia, and conglomerate can be suitable for crushed stone aggregate, whereas many shales, poorly cemented siltstones, and arkosic sandstones are too soft to be used. Limestone and dolomite are the most common source of crushed stone nationwide, making up 70 percent of crushed stone aggregate in the U.S. in 2015 (Schwochow, 1981; USGS MCS, 2016). Within the RGFO region, sedimentary rocks are found on the eastern plains, along the east edge of the Front Range uplift, and west of the mountains in intermontane basins like South Park (CGS, 2013).

The occurrence potential for crushed stone in the RGFO region was assigned based on geologic unit and is depicted on Map 7.10.2 in section 7. Resource maps from Schwochow et al. (1974b), as well as lithologic descriptions from Tweto (1979a), helped to delineate appropriate rock types. Reports by Langer and Knepper (1995) and Knepper et al. (1999) were used to help assess the quality of units for use as construction aggregate. Generally, high potential areas have rock units that are known to have satisfactory physical qualities and few or no deleterious constituents. Dense limestones, well-cemented sandstones, and unweathered igneous and non-schist metamorphic rocks qualify for this potential. Consideration is also given to past or current production. Deposits that have physical limitations or contaminants, such as abundant fractures or high clay content, are designated medium or low potential.

3.10.3 Lightweight Aggregate

Lightweight aggregates are a group of geologic materials that generally weigh 6 to 70 pounds per cubic foot and are used as substitutes for traditional aggregates in order to reduce the weight or increase the insulation factor of concrete, among other applications (Bush, 1968). Lightweight aggregates may be natural, such as volcanic rocks like scoria, pumice, tuff, breccia, and cinders, or they may be manufactured, such as heat-treated shales, clays, slates, vermiculite, and perlite (Bush et al., 2006).

The terms scoria and volcanic cinder are often used interchangeably and refer to the same material, although “cinder” may be used to indicate material finer than 1 inch (Bush et al., 2006). Scoria is a generally dark-colored, mafic extrusive igneous rock with a low-density vesicular structure and thick vesicle walls, whereas pumice is lighter-colored, felsic, and can have a more open/sponge-like texture with thin, glassy vesicle walls (Arbogast et al., 2011). The typical bulk density of pumice is 500 to 700 kg/m^3, whereas scoria ranges from 700 to 900 kg/m^3 (Presley, 2006). The glass comprising the matrix of pumice has a hardness of 5 to 5.5 (Mohs scale), although the rock is easily crushed; scoria is generally heavier with a tougher matrix (Presley, 2006). Fine-grained pumice is called pumicite (volcanic ash), and grain size is typically less than 3 mm (Arbogast et al., 2011).

Expanded perlite and vermiculite are generally considered ultra-lightweight manufactured aggregates, formed from the thermal expansion of naturally occurring constituents. Perlite is any volcanic glass with 2 to 5 weight-percent trapped water; perlite mainly occurs in rhyolitic, glassy, siliceous rocks; however, hydrated obsidian or rhyolite may also be termed “perlite” by industry (Arbogast et al., 2011; Barker and Santini, 2006). Vermiculite refers to a group of minerals that are formed by the weathering of biotite and iron-bearing phlogopite but retaining the micaceous, sheet-like structure of their progenitor minerals (Hindman, 2006).

Many clays, shales, and slates can be heated to expand them forming lightweight expandable clay aggregate (Leca) (Bush et al., 2006). This process evolves gas out of the rocks, which is then trapped in the partially melted matrix; the result is an expanded product with many pores contained in a ceramic or vitrified matrix (ESCSI, 2016). The chemical composition of suitable clay, shale, and slate varies widely but is generally very similar to rocks that expand little or not at all; suitable rocks are generally argillaceous, but otherwise lab testing is required to determine if rocks meet manufacturing requirements (Bush et al., 2006). The most suitable rocks for producing Leca are dominated by illite and montmorillonite, which is also favorable for structural clay products; kaolinite is less favorable (Bush, 1968; Hansen and Crosby, 1982).

Pumice, scoria, and perlite occur in extrusive volcanic rocks, generally of Tertiary age and associated with major volcanic centers in the RGFO area, especially the middle Tertiary volcanic field and the Rio Grande Rift (see sections 2.2.9-2.2.10). Extrusive volcanic rocks containing pumice, scoria, or perlite are found in the Nathrop volcanics on Ruby Mountain in Chaffee County; south of Coaldale and southeast of Howard in Fremont County; near Florissant and Cripple Creek in Teller County; on the eastern plains in the Ogallala Formation; and near Walsenburg, Delcarbon, and Muddy and Turkey Creeks in Huerfano County (Arbogast et al., 2011; Argall, 1949; Del Rio, 1960; Williamson and Burgin, 1960). Large deposits also occur in association with the Thirtynine Mile Volcanic Field of Park and Fremont Counties (Argall, 1949; Scarbrough, 2001). Scoria is found near mapped cinder cones and mafic extrusive volcanic rocks. Perlite can be found with pumice or scoria, depending on the water content of the original melt.

Vermiculite forms from the weathering of micas especially in Precambrian granitic igneous and metamorphic rocks, which are abundant in the mountains of Colorado (Arbogast et al., 2011). Vermiculite is also associated with weathered pegmatites and syenite dikes that are found in Precambrian igneous and metamorphic rocks (Bush, 1968; Heinrich, 1957). Vermiculite has been identified in several locations including the Turret district in Chaffee County; the Royal Gorge, west Texas Creek, east Howard, and Wet Mountain areas of Fremont County; the Gem Park and Hardscrabble districts in Custer County; west of Lake George in Park County; and south of San Isabel in Pueblo County (Del Rio, 1960; Vanderwilt, 1947).

Raw materials for manufactured expanded clay, shale, and slate lightweight aggregates are found in many sedimentary deposits. These include the shales deposited by the Western Interior Seaway along the Front Range, the sedimentary rocks of intermountain basins, and the sedimentary deposits of the eastern plains. There is no exploration model based on composition, as rocks of similar compositions may expand suitably or not at all (Bush et al., 2006).

Occurrence potential for lightweight aggregates in the RGFO region, depicted on Map 7.10.3 in section 7, is based on geologic map units, reported occurrences, and past production. Potential is considered high in areas with reported occurrences and/or past production, and medium in areas with exposed rocks of the appropriate progenitor type. The occurrences for clay, shale, and slate were mapped based on geologic map units. Rock units with past or current production are considered high potential, but considerable lateral variation in some rock units prevents that potential from being extended everywhere (Bush et al., 2006). All mapped clay or shale units are considered to have at least low potential for producing manufactured lightweight aggregates.

3.10.4 Clay

The term “clay” denotes both size (grains with a diameter less than 1/256 millimeter or 4 microns) and chemical composition (rich in alumina [Al_2O_3], silica [SiO_2], and water) (Arbogast et al., 2011). When referring to the material for industrial purposes, “clay” generally means a material composed of clay minerals and clay-sized particles of other minerals like quartz, carbonates, and iron oxides (Foley, 1999). Common clay minerals in Colorado include kaolinite, halloysite, montmorillonite, and illite (Patterson, 1968). Clay minerals are characterized by an affinity for water, with some minerals able to swell when wet, and most also have the ability to adsorb ions from solution or desorb ions if conditions change (Foley, 1999). Clay minerals are formed from sheet-like arrangements of silicon tetrahedra and aluminum octahedra, the various minerals created by differing patterns (Harvery and Murray, 2006). Generally, six groups of clay are recognized for their specific uses: ball (pottery) clay, bentonite, fire (refractory) clay, fuller’s earth (absorbent, natural bleach), kaolin (china clay), and common clay and shale (USGS MYB, 2014). For convenience, all clay groups are discussed under this general MPR heading.

Clay minerals are formed from the chemical alteration of other rocks and minerals, usually by interaction with water, and are found on or near the Earth's surface (Foley, 1999). Broadly, clays form either from chemical weathering of aluminum-silicate rocks at Earth's surface or from the hydrothermal alteration of rocks in the subsurface (Arbogast et al., 2011). Some clays, like bentonite, are formed during the diagenesis of volcanic ash or other source rocks (Foley, 1999). Once clay minerals form, they are eroded, transported, and may collect in soil horizons or in continental and marine sedimentary deposits; clays may also be eroded from older sedimentary rocks and re-deposited (Foley, 1999). Most clay deposits mined in Colorado are from sedimentary rocks, although some hydrothermal clays obtain enough volume to be mined (Arbogast et al., 2011).

All of the clay-producing formations are shales or sandstones with clay lenses; most are common clay, although some have the proper refractoriness for specialized uses. The pyrometric cone equivalent (PCE) measures refractoriness of clays: a PCE greater than 30 is deemed high-grade refractory clay, a PCE between 27 and 29 is considered semirefractory clay, and a PCE below 27 is a low-grade clay (Golson, 1980; Waagé, 1953). The highest-grade refractory clays are composed of kaolinite and halloysite, with minimal impurities. Typical impurities found in clay include silica, ferric iron, lime, and alkalies (Golson, 1980; Waagé, 1953). Montmorillonite and illite are typically classified as low-refractory clays useful for brick making (Spence, 1980).

Clay deposits are common in the RGFO management area, primarily within the Late Paleozoic-Mesozoic sedimentary sequence of the Front Range in Arapahoe, Boulder, Jefferson, Elbert, Douglas, El Paso, Pueblo, Huerfano, Las Animas, and Fremont Counties (Patterson, 1968). In southern and eastern Colorado, clay is mined principally from two Cretaceous geologic units, the Glencairn Shale Member of the Purgatoire Formation and the Dry Creek Canyon Member of the Dakota Sandstone; the Laramie Formation and Pierre Shale have also been mined for clay (Arbogast, 2011; Waagé, 1953). Elsewhere in the State, clay deposits have been mined from within the Benton, Graneros, and Mancos Shales, the Fox Hills Sandstone, Dawson Arkose, and the Lykins, Mesaverde, Morrison, Niobrara, and Lewis Formations (Arbogast et al., 2011; Patterson, 1968; Spence, 1980). Numerous bentonite beds are mapped within the lower member of the Pierre Shale (Tweto, 1979a). Additionally, bentonite clay layers are found in altered volcanic ash in the Jurassic Morrison Formation, especially in Fremont County (Brady, 1969; Cappa et al., 2007). The highest grade refractory clays are primarily found in the Dry Creek Canyon Member of the Dakota Sandstone and occasionally in the Glencairn Shale Member of the Purgatoire Formation (Golson, 1980; Patterson, 1968; Spence, 1980; Waagé, 1953).

Clay deposits are formation-specific and local in nature. Although certain units do not maintain continuous potential for clay deposits along their entire outcrop extent due to changes in mineralogy, chemistry, etc., the scale of this MPR and the level of existing mapping detail make it most efficient to identify occurrence potential by geologic unit. Areas near historic or current production are considered high potential, as production indicates the presence of desirable qualities in the clay. Rock units associated with productive occurrences are considered high or medium potential depending on their proximity to known production and geologic, mineralogic, and chemical similarity to producing areas. Medium potential units are also those noted for concentrations of clay, but may not have any production or testing record. Clay occurrence potential in the RGFO management area is depicted on Map 7.10.4 in section 7.

3.10.5 Dimension and Building Stone

Dimension stone refers to rock that is quarried and cut/finished/dressed to specific sizes or shapes for use as decorative stone, facing/façade panels, flagstone, sculptures and monuments, or other projects requiring large, durable masses of stone (CGS, 2013). Building stone may refer to rock that is used in its natural state and has not been cut or sawed to size, such as flagstone or moss rock (Mead and Austin, 2006). When used for integral building elements, stone should meet the standards of the American Society for Testing and Materials (ASTM) for absorption, bulk specific gravity, modulus of rupture, compressive strength, and resistance to abrasion in order to ensure the proper durability (Arbogast et al., 2011).

Any stone may be used for dimension or building stone if it has the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). The most common types of building and dimension stone are granite, sandstone, limestone, marble, and slate (Mead and Austin, 2006). The same characteristics that make a good dimension stone are also favorable for crushed stone (see section 3.10.2), and some dimension stone quarries may also crush and market a portion of their product for landscaping purposes. In Colorado, the most prevalent dimension stone types are granite, marble, travertine, sandstone, limestone, and rhyolite (Arbogast et al., 2011).

Like crushed stone, dimension and building stones are used for a wide variety of applications, each one requiring rocks with different ideal properties; hence, there is no one deposit model for dimension and building stone deposits. Instead, potential rock units are assessed based on aesthetic, physical, and chemical properties, which are observed in the field or tested for in a lab. If a rock meets the requirements for a project, it will likely be produced; if the rock doesn’t meet the requirements for a specific project, it still may be mined at some point for a different use.

The dimension stone industry and the ASTM have standard definitions for different types of dimension stone that vary from the geologic definitions; commercial definitions stem from historical industry use, and may not always align with scientific terminology (Mead and Austin, 2006). For instance, “granite” in industry refers to any granular crystalline rock and may include gneiss, gabbro, syenite, and basalt (black granite) (Mead and Austin, 2006). Scientifically defined granitic rocks occur in the central mountains of Colorado in the Boulder Creek (granite), Pikes Peak (pink granite), and Silver Plume (grey to pink granite) batholiths (Arbogast et al., 2011). Other granitic intrusions of dimension quality occur in Fremont and Larimer Counties, but many granites in Colorado contain too many fractures, joints, or overly large crystals to be economically quarried (Lindvall, 1968). Basalts and other mafic rocks have not been documented as commercial dimension stone in the RGFO region.

Marble, as used in industry, refers to any crystalline rock composed mainly of calcite, dolomite, or serpentine which can take a polish; varieties include travertine, onyx marble, and verde antique (Mead and Austin, 2006). Colors range from white to grey to pink to green. Colorado is famous for the Yule Marble deposit, near the town of Marble in Gunnison County, which has been used in many national monuments due to its white color and fine crystallization. In the RGFO region, deposits exist near Wellsville, Cotopaxi, and Cañon City in Fremont County, northeast of Salida in Chaffee County, and near Beulah in Pueblo County (Lindvall, 1968).

The ASTM definition for sandstone is any sedimentary rock composed of mainly sand-sized grains and having >60 percent free silica; this definition may exclude arkoses that are marketed as sandstones (Mead and Austin, 2006). These sandstones crop out along the Front Range, in the intermountain basins to the west, and in the southeastern portion of the State (Tweto, 1979a). The buff- to red-colored Lyons Sandstone in Larimer and Boulder Counties is the most widely used dimension stone in Colorado. The Dakota and Harding Sandstones have also been used locally in buildings and vary from yellow to red in color (Arbogast et al., 2011).

Limestone, in addition to being a popular crushed stone, can also be used as dimension stone. Within ASTM definitions, limestone is a sedimentary rock primarily composed of $CaCO_3$, with special varieties including calcarenite, coquina, dolomite, microcrystalline limestone, oolitic limestone, and recrystallized limestone; calcarenite, coquina, and oolitic limestone are the only commonly used commercial terms (Mead and Austin, 2006). If any of the varieties takes a polish, they may be sold as "marble" as described above. Limestones are found in sedimentary deposits throughout the RGFO area, mostly cropping out along the Front Range, the upper Arkansas River Valley, along the western side of South Park, and extensively throughout southeastern Colorado (Tweto, 1979a). Limestone for building purposes has been quarried from several locations around Cañon City and used in local buildings as foundations and facings (Stiles Storm and Nelson, 2015).

Despite its aphnitic texture, rhyolite may be commercially sold as granite or rhyolite. Welded tuffs and volcanic ashes may also be sold as rhyolite and used as dimension stone. Rhyolite is a fine-grained extrusive igneous rock, formed from volcanic eruptions of aluminum- and silica-rich felsic lava (Arbogast et al., 2011). Rhyolites and welded ashes and tuffs are associated with Tertiary volcanism and occur near the volcanic centers of Guffey and the Sawatch Range, extending northeast through Teller and Douglas Counties, and south to Custer County (Tweto, 1979a). Blocks of Wall Mountain Tuff (known in the building industry as Castle Rock rhyolite) were quarried near Castle Rock and used for many structures in central Colorado, including the Trinity United Methodist Church in Denver (Arbogast et al., 2011). Other welded tuffs suitable for dimension stone occur west of I-25 near Castle Rock in the upper portion of the Dawson Arkose (Del Rio, 1960).

The occurrence potential for dimension and building stone was assigned based on geologic unit and is depicted on Map 7.10.5 in section 7. Lithologic descriptions from Tweto (1979a) helped to delineate appropriate rock types, and resource maps from Schwochow et al. (1974b) helped to identify units with potentially suitable characteristics. Because dimension stone requires many of the same physical and chemical qualities as crushed stone, reports by Langer and Knepper (1995) and Knepper et al. (1999) were used to help assess the quality of units. Generally, high potential areas have rock units with previous or current production and are known to have satisfactory physical qualities. Dense limestones, well-cemented sandstones, rhyolites, marbles, and unweathered igneous and metamorphic rocks are all considered to have potential. Deposits that have some physical limitations (such as fracturing or limited extent) or certain contaminants are designated as medium to low potential.

3.11 Other Minerals

Because the RGFO encompasses such a vast and geologically varied area, not all minerals and deposits have been specifically addressed in this MPR. This is largely a function of limited historical data, isolated, low grade or sub-economic deposits and resources, or ever-changing and emerging technologies for mineral extraction or commodity usage. Regardless, the possibility exists for the presence of other minerals and geologic materials in the RGFO management area, which need to be considered. This is an ongoing process, and this document will be updated to reflect additional mineral resource occurrence potentials.

Several additional minerals have recently been screened to determine the resource potential occurrence in the RGFO area: aluminum, anitmony, arsenic, barium, bismuth, cesium, chromium, cobalt, graphite, hafnium, lithium, magnesium, potash, rubidium, scandium, strontium, tin and zirconium. However, aluminum, cesium, chromium, hafnium, rubidium, scandium, and strontium do not appear to have much widespread potential occurrence as either sulfide, sulfate, oxide, semi-metal or salt deposits in the RGFO. Additional information will be forthcoming in future revisions of this document.

3.11.1 Rhenium

One important element of note is rhenium, a transition metal with atomic number 75 on the periodic table of the elements. Rhenium is a critical element in metal superalloys used in the construction of various jet aircraft engine parts, and it also makes an excellent catalyst in the production of high-octane gasoline (John, 2015; John et al., 2017). Due to its rare occurrence (as low as 0.4 ppb in Earth’s crust) and high demand for its exceptional properties (extremely high melting point), the price of rhenium reached a high of US$4,800 per troy ounce in 2009 (John et al., 2017). Rhenium substitutes for molybdenum in the mineral molybdenite and is recovered primarily as a by-product of copper mining from sediment-hosted stratabound or porphyry copper deposits (John et al., 2017). The RGFO region is home to numerous porphyry and stratabound copper deposits hosting molybdenum, but economical recovery of this rare element requires the processing of sizeable tonnages. The enormous Climax molybdenum mine in Lake County, as well as the Henderson-Urad molybdenum mine in Clear Creek County, may host economically viable rhenium resources. Please see section 3.4.1, Copper-Lead-Zinc, and section 3.4.4, Molybdenum, as well as the related sections in each county, for further information on the occurrence potential of rhenium in the RGFO region.

3.11.2 Pozzolan

Another mined substance of critical concern is pozzolan, a natural supplementary cementitious material (SCM) for concrete that has economic, environmental, and performance-enhancing benefits (Juenger et al., 2012). Pozzolan greatly improves the long-term strength and durability of the concrete product (Juenger et al., 2012; Snellings et al., 2012). Production of Portland cement is energy-intensive (high temperatures are needed during production), and vast amounts of CO_2 are released into the atmosphere during the processing of limestone for cement. Adding SCMs into the mixture reduces expense and emissions (Juenger et al., 2012; Snellings et al., 2012). For decades, the primary SCM has been fly ash, a coal combustion product generated by coal-fired power plants (Caltrans, 2016). Increased environmental regulations to mitigate greenhouse gas emissions (i.e., reduction of coal-generated power) has reduced the supply of fly ash for secondary markets (Caltrans, 2016). The reduced supply of fly ash and increased industry standards for the quality of concrete have amplified the demand for natural SCMs as a substitute for fly ash (Caltrans, 2016).

As a natural SCM, pozzolan includes volcanic rock such as ash, pumice, tuff, and perlite; however, not all pyroclastic materials meet the requisite standards for use as high-quality pozzolan (Juenger et al., 2012). Laboratory analysis is required to verify that the volcanic resource meets the physical and chemical requirements dictated by the ASTM to be deemed a suitable pozzolan. The RGFO region is home to numerous volcanic deposits, primarily in the mountainous areas. Large deposits are found in association with the Thirtynine Mile volcanic field along the border of Park and Fremont Counties, and countless smaller outcrops occur throughout the Front Range. Please see the Laramide and Tertiary rock subsections in section 2.4 (Rock Units), section 3.10.3 (Lightweight Aggregate), as well as the related lightweight aggregate sections in each county, for further information on the occurrence potential of volcanic extrusive rocks and pozzolan in the RGFO region.

4. MINERAL PRODUCTION AND OCCURRENCE POTENTIAL BY COUNTY

The methodology for assigning the occurrence potential of each mineral, as well as the certainty level, is described in section 1.3, MPR Methodology, and section 3.0, Description of Energy and Mineral Resources. Color-coded mineral occurrence potential maps are located in section 7.0, Maps of Mineral Occurrence Potential. These maps give a visual representation of the mineral resource occurrence potential on an RGFO region-wide scale and are meant to accompany the description in this section. These maps provide an intermediate level of detail of mineral resource occurrences for all lands within the RGFO region regardless of the surface ownership.

4.1 Adams County

4.1.1 Coal

The western three-quarters of Adams County lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). Carroll and Bauer (2002) report production of 36,210 tons of coal from the Cretaceous Laramie and Paleocene Denver Formations at two producing mines in Adams County between through 2001. Of an estimated 335.3 million tons of original coal resources under less than 3000 feet of overburden in the county, only 72.4 thousand tons are reportedly depleted, implying reserves of 335.2 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Adams County is designated H/C for coal occurrence potential. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.1.2 Geothermal

Traditional/EGS Geothermal

The entirety of Adams County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Adams County contains one known well at Lost Creek with a reported temperature of 81°F (NREL, 2016). This well is designated as H/D for direct use. The rest of Adams County is designated as a mix of H/C and H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields are considered to have more certainty because of the general higher density of drilling and therefore higher level of confidence.

4.1.3 Gold

Production of placer gold from along Clear Creek in Adams County was first reported in the mid-1850s (Parker, 1974). The gold source for the Clear Creek placers is most likely the lodes in Gregory and Russell Gulches near Central City in Gilpin County (Parker, 1974). Vanderwilt (1947) and Del Rio (1960) report production of 15,729 ounces of gold in the county between 1922 and 1958, the later years produced as byproducts of sand and gravel operations. Total production through 1990 is estimated at 31,000 troy ounces of gold (Davis and Streufert, 1990).

The history of mining activities indicates a potential for placer gold occurrence along Clear Creek and in the South Platte River gravels. From the confluence of Clear Creek and the South Platte upstream along both to the Adams County line, the potential is M/C. The potential diminishes farther from the source and also due to the gravels having been worked and reworked in urban areas.

4.1.4 Silver

Recovery of 2,332 ounces of placer silver is reported between 1922 and 1958, most likely from Clear Creek (Del Rio, 1960; Vanderwilt, 1947). Silver has been recovered as a byproduct of sand and gravel operations near the confluence of Clear Creek and the South Platte River (USGS MRDS, 2013). Clear Creek is designated L/C and the area surrounding the confluence of the creek with the South Platte River is assigned M/C for silver occurrence potential.

4.1.5 Iron

No iron production is reported in Adams County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Adams County.

4.1.6 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Adams County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.1.1 of this MPR) is designated L/B for germanium occurrence potential.

4.1.7 Titanium

No titanium production is reported for Adams County; however, economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone in Adams County is designated L/B for titanium occurrence potential.

4.1.8 Uranium

Although no uranium occurrences are known in Adams County, a large part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in Adams County are designated L/B for potential.

4.1.9 Vanadium

No vanadium production is reported in Adams County; however, three occurrences are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (USGS MRDS, 2013). Carnotite and tyuyamunite are reported at the Grover and Pawnee Buttes N.E. deposits (Nelson-Moore et al., 1978). Also, minor amounts of vanadium are reported from uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.1.10 Industrial Sand

Widespread Quaternary eolian sands in Adams County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in the RGFO region (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several industrial sand operations are noted in Adams County along the South Platte River, Box Elder Creek, and West Bijou Creek; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose in other counties (Arbogast et al., 2011). The Dawson Arkose is designated L/C for industrial sand potential.

4.1.11 Helium

Most of Adams County is designated L/C for helium occurrence potential due to its location in the Denver Basin.

4.1.12 Sand and Gravel

Del Rio (1960) reports production of over 9 million tons of sand and gravel, primarily from alluvium, in Adams County between 1953 and 1958. High-quality sand and gravel deposits within Adams County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Adams County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation, which host several sand and gravel operations in nearby Elbert County, as well as the Cretaceous Fox Hills Sandstone, which has been quarried on a small scale, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968).

4.1.13 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Adams County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone and Tertiary Dawson Arkose may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999). The Fox Hills Sandstone is designated L/C, and the Dawson Arkose is assigned L/B, for crushed stone aggregate occurrence potential.

4.1.14 Lightweight Aggregate

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, and the overlying Laramie Formation, composed of highly expansive claystones, also host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable source rocks for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Tertiary Arapahoe and Denver Formations and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay plus silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary regionally in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C, and the undivided Denver Formation and Dawson Arkose (mapped as TKdl) are designated M/B, for lightweight aggregate potential.

4.1.15 Clay

The Cretaceous Pierre Shale, which crops out in the eastern part of Adams County, hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Several small producing pits are developed in the Dawson Arkose in Adams County (USGS MRDS, 2013). The Pierre Shale and Laramie Formation are designated H/C, and the Dawson Arkose is designated M/C for clay occurrence potential. Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making; this unit is designated L/C for clay potential (Vanderwilt, 1947). A few sand and/or gravel pits also produce clay from the alluvium along the South Platte River in this and other counties; the alluvium mapped unit is designated L/C for clay potential.

4.1.16 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Adams County, the Cretaceous Fox Hills Sandstone and Tertiary Denver Formation and Dawson Arkose, although hosting sandstones in part, have no documented production of dimension stone. As sandstones, these units are designated M/B for dimension and building stone occurrence potential.

4.2 Arapahoe County

4.2.1 Coal

Arapahoe County, except the easternmost portion, lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). Brandt (2015) reports production of 36,259 tons of coal between 1864 and 2002, and Carroll and Bauer (2002) report production of 470 tons of lignite from the Paleocene Denver Formation between 1950 and 2001. Of an estimated 271 million tons of original coal resources under less than 3000 feet of overburden in the county, only 73 thousand tons are reportedly depleted, implying reserves of almost 271 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Arapahoe County is designated H/C for coal occurrence potential. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.2.2 Geothermal

Traditional / EGS Geothermal

The entirety of Arapahoe County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Arapahoe County contains no known hot springs or wells. Arapahoe County is designated as a mix of H/C and H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields are considered to have more certainty because of the general higher density of drilling and therefore higher level of confidence.

4.2.3 Gold

Small quantities of gold were first recovered in 1885 in Arapahoe County (Henderson, 1926). Placer gold has been mined from gravels and bars in Big Dry Creek, Little Dry Creek, and Cherry Creek. Vanderwilt (1947) attributes the gold as fine material reworked from the Tertiary Dawson Arkose and Castle Rock Conglomerate Formations (also see Desborough et. al., 1970). Production of 648 ounces of placer gold was reported between 1885 and 1941 (Vanderwilt, 1947). The Big Dry Creek, Little Dry Creek, and Cherry Creek are designated M/C for gold potential. The area displayed on the map is wider than the actual stream in order to make it visible at the scale shown.

4.2.4 Silver

About 108 fine ounces of placer silver were reportedly recovered in Arapahoe County between 1885 and 1941 (Henderson, 1926; Vanderwilt, 1947). These came mainly from Cherry Creek and Dry Creek placers. Cherry Creek is designated L/B from the southern county line to the Cherry Creek reservoir; Dry Creek is designated L/B from the southern county line to the South Platte River.

4.2.5 Iron

No iron production is reported in Arapahoe County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Arapahoe County.

4.2.6 Manganese

Wells et al. (1952) reported concentrations of 10.5 to 12.2 percent manganese oxide as interstitial fillings in sandstone at Buckley Field bombing range in Arapahoe County. Traver (1947) notes six deposits of nodular manganese in sandstone of the Denver Basin, east of the Rocky Mountain Front, from wartime studies of strategic minerals. Subsequent mapping has confirmed that manganese oxides, mainly psilomelane, occur as concretions, fracture fillings, and cement in the Tertiary upper Dawson Arkose. The upper Dawson Arkose along the western edge of the Denver Basin must be considered as a potential source for manganese.

Manganese has an occurrence potential of H/C in areas where mines have identified production of the commodity. Those mines include the Buckley Field Manganese Deposit sites and the Denver Basin Manganese Deposit site. The upper Dawson Arkose elsewhere in the county is assigned M/B for manganese occurrence potential. The White River Formation, which overlies the upper Dawson Arkose, is assigned L/B.

4.2.7 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Arapahoe County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.2.1 of this MPR) is designated L/B for germanium occurrence potential.

4.2.8 Titanium

Though no titanium production is reported for Arapahoe County, economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of neighboring Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone in Arapahoe County is designated M/B for titanium occurrence potential.

4.2.9 Uranium

Although no uranium occurrences are known in Arapahoe County, a large part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in Arapahoe County are designated L/B for potential.

4.2.10 Vanadium

No vanadium production is reported in Arapahoe County; however, three occurrences are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (USGS MRDS, 2013). Carnotite and tyuyamunite are reported at the Grover and Pawnee Buttes N.E. deposits (Nelson-Moore et al., 1978). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.2.11 Industrial Sand

Widespread Quaternary eolian sands in Arapahoe County are composed of well-sorted and well-rounded quartz grains. Significant production is reported from eolian sands in El Paso County, although only one occurrence is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001). Eolian sands are designated H/B for industrial sand occurrence potential in Arapahoe County. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in Arapahoe County along Cherry Creek, Box Elder Creek, Coal Creek, and West Bijou Creek (Schwochow, 1981). Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose throughout the RGFO region (Arbogast et al., 2011). The Dawson Arkose is designated L/C for industrial sand potential.

4.2.12 Helium

Parts of Arapahoe County are designated L/C for helium due to its location in the Denver Basin.

4.2.13 Sand and Gravel

Del Rio (1960) reports production of over 6 million tons of sand and gravel, primarily from alluvium, in Arapahoe County between 1954 and 1958. High-quality sand and gravel deposits within Arapahoe County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Cretaceous and Tertiary sedimentary rocks host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Arapahoe County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation, which host several sand and gravel operations in nearby Elbert County, as well as the Cretaceous Fox Hills Sandstone, which has been quarried on a small scale, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968). The Cretaceous Laramie Formation hosts several gravel operations in this and other counties (W. D. Carter, 1968). This unit is assigned M/C around the cluster of gravel pits.

4.2.14 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Arapahoe County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone, Tertiary Dawson Arkose, and overlying White River Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999). The Fox Hills Sandstone is designated L/C, and the Dawson Arkose and White River Formation are assigned L/B, for crushed stone aggregate occurrence potential.

4.2.15 Lightweight Aggregate

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the overlying Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Arapahoe and Denver Formations and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay plus silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C, and the undivided Denver Formation and Dawson Arkose (mapped as TKdl) are designated M/B, for lightweight aggregate potential.

Suitable expandable clays may be found in the Tertiary White River Formation, which is composed of ashy claystones and sandstones (Knepper et al., 1999). The White River Formation is assigned L/B for lightweight aggregate occurrence potential.

4.2.16 Clay

The Cretaceous Pierre Shale, which crops out in the eastern part of Arapahoe County, hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). The Laramie Formation and Pierre Shale are designated H/C, and the Dawson Arkose is designated M/C for clay potential. Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making; this unit is designated L/C for clay potential (Vanderwilt, 1947). The Tertiary White River Formation is known to host occasional claystones suitable for use in making bricks; this unit is assigned L/B for clay potential (Vanderwilt, 1947).

4.2.17 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Arapahoe County, the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation and Dawson Arkose, although partially hosting sandstones, have no documented production of dimension stone. As sandstones, these units are designated M/B for dimension and building stone occurrence potential.

4.3 Baca County

4.3.1 Geothermal

Traditional / EGS Geothermal

The entirety of Baca County is designated as L/A for high temperature/EGS geothermal resources due to the low EGS favorability (Augustine, 2011) and lack of analysis for traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Baca County contains no known hot springs or wells. Baca County is mostly designated as a mix of H/C and H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields and with a temperature >100°F in the central-eastern part of the county are considered H/C. Areas that do not meet the temperature requirement in the western and central-eastern portion of the county are designated as M/B. The rest of the county is considered H/B because it meets the temperature range for low temperature geothermal resources but is outside of named COGCC fields.

4.3.2 Gold

Gold production within Baca County totaled 14 ounces from 1885 to 1941 (Vanderwilt, 1947). Despite this earlier reported production, a Bureau of Mines investigation found no gold assays >0.005 oz/ton in 13 samples around the district (Soulé, 1956). Historic gold production in the Carrizo Creek district shows some potential, but subsequent testing indicates that gold mineralization may be rare and highly distributed. Therefore, the district is designated as L/B.

4.3.3 Silver

Production of 356 fine ounces of silver was reported from stratabound redbed copper deposits at the Independence mine in the Carrizo Creek district of Baca County between 1900 and 1917 (Fay, 1983; Soulé, 1956). Several other prospects report silver occurrences near the Independence mine (USGS MRDS, 2013). The Carrizo Creek district is designated M/C for silver occurrence potential. Silver occurs as a secondary commodity in pods and plugs in the Late Triassic Sheep Pen Sandstone of the Dockum Group at the Baca County No. 1 Prospect along North Carrizo Creek as noted in the USGS MRDS (2013); a small buffer around this occurrence is assigned M/C.

4.3.4 Copper-Lead-Zinc

Copper mineralization occurs primarily in the Carrizo Creek district of southwesternmost Baca County. Chalcocite, partly altered to malachite and occasional azurite, has reportedly been mined in canyons along Carrizo Creek within the upper Triassic Sheep Pen Sandstone of the

Dockum Group, in the overlying Jurassic Entrada (Exeter) Sandstone, and in the lower Cretaceous basal member of the Purgatoire Formation (alternatively reported as the Lytle or Cheyenne Sandstone) (Fay, 1983; Henderson, 1926; Kues and Lucas, 1987; McLaughlin, 1954). Mineralization occurs in veins and pods along bedding planes, joints, and fractures (Fay, 1983).

Copper production from 1900-1902 and 1915-1917 totaled 21,511 pounds, largely from the Independence mine on the southern side of Skull Canyon along East Carrizo Creek (Henderson, 1926). Soulé (1956) classifies the host rock, a porous, white, arkosic sandstone, as the basal member of the Purgatoire Formation, noting that the older Morrison Formation shales are exposed along the bottom near the end of the 524-foot-long adit. McLaughlin (1954) and Scott (1968) classify the Independence mine host rock as the Jurassic Entrada (Exeter) Sandstone whereas Fay (1983), in the frontispiece, claims it is the Sheep Pen Sandstone (Triassic), adding that “copper minerals have not been found above the Sheep Pen” (p.2-3). The USGS MRDS (2013) classifies it as Sheep Pen based on Fay (1983).

Due chiefly to the size and reported production of the Independence mine and the presence of a couple dozen smaller prospects nearby, the Carrizo Creek district is designated H/D. A buffer of the mapped Dakota Sandstone / Purgatoire Formation around the Carrizo Creek district is designated M/B. Four minor prospects (Baca County Nos. 1-4 as described by Fay (1983)) along Carrizo Creek near the Oklahoma border occur in the Dockum Group (Sheep Pen sandstone), and so the mapped Dockum Group in this area is designated M/C. The mapped Jurassic Morrison Formation / Entrada (Exeter) Sandstone surrounding this area is designated L/B due to the report by McLaughlin (1954) and geologic map by Scott (1968), as well as a copper mineralization in these units in bordering Bent County.

4.3.5 Iron

USGS MRDS (2013) reports the Baca County No. 1 Prospect included iron as a tertiary commodity in the Sheep Pen sandstone of the Dockum Group. Hematite is a common cementing agent of the sandstone, and analyses revealed upwards of 2,000 ppm iron (Fay, 1983). The Dockum group in this area is designated M/B for iron occurrence potential.

4.3.6 Manganese

Manganese has been identified as a tertiary commodity at the Baca County No. 1 Prospect in the Triassic Sheep Pen sandstone (Dockum Group) of southwestern Baca County (Fay, 1983). An area around this prospect is assigned M/C for manganese and the Dockum Group elsewhere is assigned L/B.

4.3.7 Titanium

USGS MRDS (2013) notes that copper ores found in the Sheep Pen Sandstone of the Dockum Group of the Carrizo Creek district host titanium. The Baca County No. 1 and No. 2 Prospects included titanium as a secondary commodity and analyses revealed upwards of 2,000 ppm titanium (Fay, 1983). The Dockum group in this county is designated M/B for titanium occurrence potential.

4.3.8 Uranium

There are no occurrences or reports of production of uranium in Baca County; however, several uranium prospects occur in Mesozoic sedimentary rocks in neighboring Bent and Las Animas Counties in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Moderate production of uranium is reported from these units in Pueblo County (Nelson-Moore et al., 1978). These units in Baca County are designated L/B for uranium occurrence potential.

4.3.9 Vanadium

Vanadium, less than 20 ppm, is associated with copper mineralization in the Triassic Sheep Pen Sandstone of the Dockum Group in southwestern Baca County (USGS MRDS, 2013). The Dockum Group is designated L/B for vanadium occurrence potential. Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

4.3.10 Limestone and Dolomite

There are no operating limestone mines within Baca County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State. The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale in the northwestern corner of Baca County is designated M/C for limestone and dolomite occurrence potential (Tweto, 1979a).

4.3.11 Industrial Sand

Quaternary eolian sands in Baca County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, and two DRMS-permitted occurrences are reported in southwestern Baca County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica (Vanderwilt, 1947). Industrial sand has also been reportedly recovered from the Lytle Sandstone Member of the Purgatoire Formation (Arbogast et al., 2011). The undifferentiated Dakota Sandstone and Purgatoire Formation are designated H/C for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no occurrences noted in Baca County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.3.12 Gypsum

There is no reported production of gypsum in Baca County; however, McLaughlin (1954) cites a 1931 log of a well drilled in the southwestern part of the county which records two 10-foot-thick beds of gypsum in the Triassic Dockum Group at depths of 250 and 705 feet. The Dockum Group directly overlies the gypsiferous beds of the Upper Permian Taloga Formation, Day Creek Dolomite (anhydrite), and Blaine Gypsum (descending order), all of which correlate with the Lykins Formation, known to host gypsum in other Colorado counties (Irwin, 1977; Maher, 1946; Maher and Collins, 1952; McLaughlin, 1954). The mapped Dockum Group and undivided Upper Permian units in Baca County are designated H/C for gypsum occurrence potential.

Three gypsum quarries are noted in nearby Las Animas County, all developed in the Ralston Creek Formation which also crops out in Baca County (Schwochow, 1981; USGS MRDS, 2013). Although no bedded gypsum is reported from within the Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). The Ralston Creek Formation in this region includes pink alabaster and white gypsum units (Scott, 1968a; Weist, 1965). The Jurassic undivided Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential.

Throughout the RGFO management area, the Cretaceous Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) contains no bedded gypsum, but abundant disseminated gypsum stringers and selenite crystals are reported in association with bentonite beds of the unit (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Colorado Group members are designated L/B for gypsum occurrence potential.

4.3.13 Helium

The Flank gas field is located on a nine mile long anticline on the edge of the Hugoton Embayment and was a gas storage field in the early 1990s (Bolyard, 1990). Test wells indicated the gas cap in the field was 0.82 percent helium (Sonnenberg and von Drehle, 1990). This field is stratigraphically and structurally controlled, occurring as a point bar in an ancient fluvial system (Bolyard, 1990). Other such point bar sands in the formation may also have helium potential but they are nearly randomly distributed. The area around the Flank field, the area along the anticline, and the area potentially contiguous with the Las Animas Arch farther north are designated M/C based on favorable geologic setting and positive helium gas analysis but lack of extensive drilling.

4.3.14 Sand and Gravel

Del Rio (1960) reports production of 110,000 tons of sand and gravel, primarily from alluvium, in Baca County between 1957 and 1958. High-quality sand and gravel deposits in Baca County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. There are a few DRMS-permitted sand and gravel quarries developed in Quaternary eolian deposits (Qe); eolian deposits are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in some areas; there are over a dozen DRMS permitted sand and gravel quarries, as well as USGS MRDS (2013) producers, reported in this unit across Baca County (W. D. Carter, 1968; Del Rio, 1960); this unit is considered M/D for sand and gravel potential. Sporadic sand and gravel operations are also developed in the Cretaceous Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation in this and other counties (W. D. Carter, 1968; USGS MRDS, 2013); these units are assigned L/C for sand and gravel potential.

4.3.15 Crushed Stone Aggregate

There is one past DRMS-permitted crushed stone aggregate operation in Baca County, likely developed in the Cretaceous Carlisle and Greenhorn Limestone Members of the Colorado Group, which host sporadic operations in other counties (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Colorado Group overall was only classified as a ‘fair’ source rock for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Colorado Group is designated M/B for crushed stone aggregate occurrence potential.

Small outcrops of Tertiary basalt occur in southwestern Baca County, one of which hosts a past DRMS-permitted crushed stone operation. Dark, dense, fine-grained extrusive rocks (traprock) like basalt satisfy the physical and chemical standards for high-quality crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Tertiary basalt is assigned H/C for crushed stone potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Triassic Dockum Group, Jurassic Morrison Formation, Cretaceous Dakota Sandstone, and Tertiary Ogallala Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There is one past DRMS-permitted crushed stone quarry developed in the Dakota Sandstone in Baca County. The Dakota Sandstone is designated L/C, and the Dockum Group, Morrison Formation, and Ogallala Formation are assigned L/B, for crushed stone potential.

4.3.16 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Although not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (slightly to highly expansive illite-montmorillonite) and may be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, and the Ogallala Formation is designated M/C, for lightweight aggregate occurrence potential.

A few outcrops of mostly mafic tuffs and breccias from Tertiary basaltic flows in southwestern Baca County may host perlite, scoria, or pumice (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/B for lightweight aggregate occurrence potential.

4.3.17 Clay

The clay-bearing Jurassic Morrison Formation and Cretaceous Purgatoire Formation, Dakota Sandstone, and Colorado Group (including the Graneros Shale) crop out in Baca County. The best quality refractory clays in the RGFO region are found in the Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; there is one DRMS (2018) permit to quarry clay in the undifferentiated Purgatoire Formation and Dakota Sandstone in Baca County, and numerous other prospects in these units occur throughout the region (Arbogast et al., 2011; Golson, 1980; Patterson, 1968; USGS MRDS, 2013; Waagé, 1953). The undifferentiated Purgatoire Formation and Dakota Sandstone are designated H/D for clay occurrence potential.

Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Morrison Formation, which hosts low-grade clay mines in other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). Several prospects developed in the Graneros Shale throughout the RGFO region have produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Morrison Formation and Colorado Group are assigned M/C for clay potential.

4.3.18 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Baca County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Ogallala Formation is designated L/B, and the Niobrara Formation is designated L/C, for dimension and building stone occurrence potential.

Significant production of high-quality dimension stone is reported from the Cretaceous Dakota Sandstone throughout the Front Range, although no production of dimension stone is noted from the plains region (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). The Dakota Sandstone is designated H/C, and the underlying, sandstone-bearing Jurassic Morrison Formation is assigned M/B, for dimension and building stone occurrence potential.

4.4 Bent County

4.4.1 Geothermal

Traditional / EGS Geothermal

The western part of Bent County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). The eastern portion also has moderate EGS favorability, but wasn't analyzed for traditional favorability and is therefore considered L/A.

Direct-Use / Low Temperature Geothermal

Bent County contains no known hot springs or wells. The majority of Bent County is designated as H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields are considered to be H/C. The extreme southwestern corner of the county doesn't meet the temperature requirements for low temperature geothermal resources and is therefore designated as M/B.

4.4.2 Copper-Lead-Zinc

In southwestern Bent County, Nelson-Moore et al. (1978) mention an old copper prospect called the Allen Jones property present in the Morrison Formation. There is also an outcrop of the Dockum Group nearby; both the outcrop of the Morrison and the Dockum Group are designated L/B in this area due to the documented occurrence and favorable rock type.

4.4.3 Uranium

A few uranium prospects and occurrences are found in Bent County, but none report production. The prospects and occurrences are in Mesozoic sedimentary rocks, either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Of note, sandstone samples at the Allen Jones copper pit assayed up to 1 percent U_3O_8 (USGS MRDS, 2013). Production from these units is reported in Pueblo County (Nelson-Moore et al., 1978). These units in Bent County are designated L/B for uranium occurrence potential.

4.4.4 Vanadium

There are no vanadium occurrences in Bent County; however, historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and

Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

4.4.5 Limestone and Dolomite

There are no operating limestone mines within Bent County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential. The Niobrara Formation is assigned M/D for potential.

4.4.6 Industrial Sand

Quaternary eolian sands in Bent County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, and one occurrence is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region. Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, although no production is reported for Bent County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries elsewhere assayed as high as 98.7 percent silica (Vanderwilt, 1947). Industrial sand has also been reportedly recovered from the Lytle Sandstone Member of the Purgatoire Formation (Arbogast et al., 2011). The undifferentiated Dakota Sandstone and Purgatoire Formation are designated H/C for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no occurrences noted in Bent County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.4.7 Gypsum

Three gypsum quarries are noted in nearby Las Animas County, all developed in the Ralston Creek Formation which extends into Bent County (McLaughlin, 1954; Schwochow, 1981; USGS MRDS, 2013). Although no bedded gypsum is reported from within the Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). Darton (1906) reports a 30-foot-thick bed of gypsum below the Morrison Formation at the Garden of the Gods (El Paso County). In Las Animas County, a massive gypsum bed, 5 feet thick, caps extensively exposed Triassic “redbeds” along Red Canyon near the Purgatoire River and likely corresponds to the Ralston Creek Formation (Darton, 1906). The Ralston Creek Formation in this region includes pink alabaster and white gypsum units (Scott, 1968a; Weist, 1965). The Jurassic undivided Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation or the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group members are designated L/B for gypsum occurrence potential throughout Bent County.

4.4.8 Helium

The southwest end of the Las Animas Arch begins in Bent County and contains the Wagon Trail gas field in the northeastern part of the county (Sonnenberg and von Drehle, 1990). Test wells indicated the gas contained 0.3 percent helium (Miesse, 1982). Most of Bent County lies in the core of the Las Animas Arch anticline, which is noted for lower helium values than the northern flanks (Sonnenberg and von Drehle, 1990) and is therefore designated M/D; however a portion of the northwest flank of the anticline in northwestern Bent County is designated H/D.

4.4.9 Sand and Gravel

Del Rio (1960) reports production of almost 300,000 tons of sand and gravel, primarily from alluvium, in Bent County between 1956 and 1958. High-quality sand and gravel deposits in Bent County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Bent County, the Cretaceous Colorado Group hosts numerous sand and gravel prospects and permitted quarries just north of the Arkansas River (USGS MRDS, 2013); this unit is designated M/D for sand and gravel potential. Sand and gravel operations are also developed in the Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation in this and other counties (W. D. Carter, 1968; USGS MRDS, 2013); these units are assigned L/C for sand and gravel potential.

4.4.10 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Bent County, likely developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Cretaceous Dakota Sandstone, Jurassic Morrison Formation, and Tertiary Ogallala Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There is one past DRMS-permitted crushed stone quarry developed in the Dakota Sandstone in Bent County. The Dakota Sandstone is designated L/C, and the Morrison and Ogallala Formations are assigned L/B, for crushed stone potential.

4.4.11 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and

Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (mixed layer illite-montmorillonite) and may be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, and the Ogallala Formation is designated M/C for lightweight aggregate occurrence potential.

4.4.12 Clay

The clay-bearing Jurassic Morrison Formation and Cretaceous Purgatoire Formation, Dakota Sandstone, Colorado Group (including the Graneros Shale), and Niobrara Formation (including the Smoky Hills Member) together cover most of Bent County. The best quality refractory clays in the RGFO region are found in the Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; there are several clay prospects in these units in southwestern Bent County and numerous others throughout the region (Arbogast et al., 2011; Patterson, 1968; USGS MRDS, 2013). The undifferentiated Purgatoire Formation and Dakota Sandstone are designated H/D for clay occurrence potential.

Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Morrison Formation; clay production is reported from one past DRMS-permitted mine and several USGS MRDS (2013) prospects in this unit in the southwest quadrant of this county (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). Several prospects developed in the Graneros Shale and Smoky Hills Member throughout the RGFO region have produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Morrison Formation, Colorado Group, and Niobrara Formation are assigned M/C for clay potential.

4.4.13 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Bent County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013).

The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Ogallala Formation is designated L/B, and the Niobrara Formation is designated L/C, for dimension and building stone occurrence potential.

Significant production of high-quality dimension stone is reported from the Cretaceous Dakota Sandstone throughout the Front Range, although no production of dimension stone is noted from the plains region (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). The Dakota Sandstone is designated H/C, and the underlying, sandstone-bearing Jurassic Morrison Formation is assigned M/B, for dimension and building stone occurrence potential.

4.5 Boulder County

4.5.1 Coal

The southeastern corner of Boulder County, which lies within the Boulder-Weld coal field and Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR), hosts numerous historic mines developed in the Upper Cretaceous Laramie Formation. Production of 43.3 million tons of coal between 1864 and 2002 from 103 past-producing (of 140 total) coal mines is reported in Boulder County (Brandt, 2015; Carroll and Bauer, 2002). Of an estimated 465.1 million tons of original coal resources under less than 3,000 feet of overburden in the county, roughly 92.5 million tons are depleted, implying reserves of 372.6 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Boulder County is designated H/D for coal occurrence potential around the area of producing mines in the Boulder/Weld coal field and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.5.2 Geothermal

Traditional / EGS Geothermal

The majority of Boulder County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the northeastern corner is considered M/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Boulder County contains two known wells at Eldorado Springs (75°F) and Haystack Butte (75°F), and one known spring at Eldorado Springs (77°F) (NREL, 2016). These locations are designated as H/D for direct use. Approximately the western ¾ of Boulder County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The rest of Boulder County is designated as a mix of H/C and H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields are considered to have a higher level of confidence.

4.5.3 Gold

The Deadwood diggings near the border of Boulder and Gilpin Counties was one of the earliest discoveries of placer gold in Colorado in 1859 (Parker, 1974). From there, exploration in the surrounding canyons revealed placer gravels along numerous creeks, including Gold Run, Fourmile, South Boulder, and North Beaver Creeks; placers were later worked in Central Gulch and James, upper Fourmile, Lefthand, Boulder, Coon Trail, and North St. Vrain Creeks (Parker, 1974). The sources of the placer gold, which is generally fine in Boulder County, are upstream lode deposits in the various mining districts (Parker, 1974). Placer deposits in Boulder County, outside mining districts, are considered L/C due to limited historic output (2,472 ounces from 1859 to 1957) and the fact that most are nearly exhausted by previous mining (Parker, 1974).

Lode gold discoveries soon followed the placers and gold tellurides were discovered in 1872 (Del Rio, 1960; Lovering and Goddard, 1950). Production of over 1 million ounces of lode gold is reported from 1859 to 1958 in Boulder County (Del Rio, 1960; Vanderwilt, 1947). In general, gold production dropped off considerably in the 20th century and has continued only sporadically ever since. Mineralization of gold-bearing veins of the CMB in Boulder County was localized by northwest-trending silicified fault zones of Laramide age known as “breccia reefs” (Del Rio, 1960; Lovering and Tweto, 1953).

Davis and Streufert (1990) estimated gold production at 450,000 troy ounces in the Gold Hill district between 1859 and 1990. Overlapping the Gold Hill district to the north and Magnolia district to the south, the Sugarloaf district is named for Sugarloaf Mountain, composed of a quartz monzonite stock. Estimated production of gold in the Sugarloaf district is 240,000 troy ounces from 1869 to 1990 (Davis and Streufert, 1990). The greater Gold Hill-Sugarloaf district was the chief gold producer in Boulder County (Koschmann and Bergendahl, 1968). The first, and most productive, lode discoveries in this region were in veins that fill fissures and faults in the Precambrian Boulder Creek granodiorite, which dominates the district (Davis and Streufert, 1990; Lovering and Goddard, 1950). The batholith interfingers with Precambrian biotite schists and gneisses of the Idaho Springs Formation, and mineralization is heavily localized by the northwest-trending breccia reefs (Goddard, 1947). Primarily telluride (petzite and sylvanite) ores, and secondarily pyritic ores, occur in mostly northeast-striking veins, and mineralization is concentrated where they intersect (Lovering and Goddard, 1950). The greater Gold Hill-Sugarloaf district area is designated H/D for gold occurrence potential.

The northern portion of the Magnolia district overlaps with the Sugarloaf and eastern Boulder Tungsten districts and produced some gold from 1875 to 1905 (Wilkerson, 1939). Davis and Streufert (1990) estimate production of 40,000 troy ounces of gold from 1875 to 1990. The area is underlain by Boulder Creek quartz monzonite and is cut by the northwest-striking Hoosier, Livingston, and Rogers breccia reefs and the Iron diabase dike (Lovering and Goddard, 1950). Northwest-striking fissure veins contain rich gold tellurides, especially in the Iron dike, and native gold is found in the oxidized zones of the veins (Lovering and Tweto, 1953). The Magnolia district is significant because of the richness of the ore, the variety of telluride minerals, and the association of the telluride ores with tungsten, vanadium, and molybdenum minerals (Lovering and Goddard, 1950). To the west, the rest of the Boulder Tungsten district hosts sporadic occurrences of gold in northwest-trending veins associated with the Rogers and Hurricane breccia reefs (Lovering and Tweto, 1953). The historic occurrence and production of gold in the greater Magnolia and Boulder Tungsten districts earn them a designation of H/D.

Gold was first reported in the Jamestown (Central) district, just north of the Gold Hill district, in 1865, and production of 210,000 troy ounces from then until 1990 is estimated by Davis and Streufert (1990); Lovering and Goddard (1950) and Vanderwilt (1947) report production of 57,641 ounces of mostly lode gold from 1901 to 1945. The southeastern portion of the greater Jamestown district area, including the Left Hand Creek district, is underlain by Idaho Springs Formation felsic schists and gneisses intruded on the south by Boulder Creek granodiorite and to the north by Silver Plume-aged granite (Longs Peak-St. Vrain batholith) (Boos and Boos, 1934; Goddard, 1947; Tweto, 1979a). The Precambrian rocks are cut by northwest-trending silicified breccia reefs, and intruded by Tertiary porphyry stocks and dikes (Goddard, 1947). The district center is dominated by a small sodic quartz monzonite porphyry stock to the north (Porphyry Mountain stock) adjacent to a larger granodiorite stock (Jamestown stock) to the south (Davis and Streufert, 1990; Goddard, 1947; Koschmann and Bergendahl, 1968). Northeasterly striking, gold-bearing telluride and pyritic quartz veins occur around the periphery of the stocks, mainly in the Longs Peak-St. Vrain Granite, and appear associated to them (Davis and Streufert, 1990; Goddard, 1947; Lovering and Goddard, 1950). The pyritic veins range in size from several inches to 3-feet wide, whereas the telluride veins are up to 10-feet thick; a few veins of both types range up to 30-feet thick (Koschmann and Bergendahl, 1968). Ore shipments averaged 0.06 to 1.29 ounces of gold per ton (Goddard, 1947). The greater Jamestown district area is designated H/D for gold occurrence potential.

At the headwaters of Left Hand and Fourmile Creeks, the Ward district in west-central Boulder County is attributed with an estimated production of 80,000 troy ounces of gold from 1861 to 1990 (Davis and Streufert, 1990). The district is underlain by biotite schists and gneisses of the Idaho Springs Formation and Longs Peak-St. Vrain Granite, both intruded by Laramide diorite and monzonite porphyry stocks (Boos and Boos, 1934; Del Rio, 1960; Lovering and Goddard, 1950). Ore occurs in veins or shoots and chimneys associated with felsic dikes in the granites and felsic gneisses (Koschmann and Bergendahl, 1968). The veins strike with the dikes, mostly in a west-northwest direction; the most productive veins are those associated with the breccia reef faults (Lovering and Goddard, 1950). Most of the gold came from quartz veins containing chalcopyrite; pyritic quartz veins also produced gold with minor molybdenite and wolframite

(Koschmann and Bergendahl, 1968). The gold occurrence potential for the Ward district is considered H/D based on its production history.

The Lake Albion district, 5 miles southwest of Ward, contains a single productive vein that strikes east through a hornblende monzonite porphyry. The vein ranges from a few inches to 10 feet, with a surrounding mineralized zone up to 30 feet wide (Lovering and Goddard, 1950). Production was limited due to asbestos in the gangue, but a “moderate quantity” of lead-gold ore was produced prior to 1910 (Lovering and Goddard, 1950). The area is designated H/D for gold occurrence potential.

The Caribou-Grand Island district was mainly a silver producer, but also hosts some lode and placer gold; Davis and Streufert (1990) estimated production of 42,000 troy ounces of gold from 1869-1990, although Vanderwilt (1947) reported just 8,617 ounces of gold between 1932 and 1945. The polymetallic No-Name vein is the most persistent and productive in the district, but gold averaged just 0.6 ounces per ton (Goddard, 1947; Lovering and Goddard, 1950). The Late Cretaceous to early Tertiary composite, primarily quartz monzonite, Caribou stock dominates the district and bounds the Boulder Creek quartz monzonite to the north and Precambrian felsic or biotite gneisses and schists to the southeast (Gable, 1984; Tweto, 1979a). The gold veins are confined mainly to the gneisses of the Idaho Springs Formation and are not present in the Caribou stock, suggesting they were emplaced earlier (Moore et al., 1957). The Caribou-Grand Island district has a designation of H/D.

The Eldora district lies just south of the Grand Island-Caribou district. The district is known for telluride-bearing veins that strike east to northeast through Precambrian biotite schist and felsic gneisses adjacent to the quartz monzonite porphyry of the Eldora (Bryan Mountain) stock (Gable, 1984; Goddard, 1947; Lovering and Goddard, 1950). No production amount is reported for this district, but an ore sample from the only productive mine of note (Enterprise) averaged 0.54 ounces of gold per ton (Davis and Streufert, 1990; Goddard, 1947). Minimal production but favorable geology and noted occurrences earn this district a designation of H/C for gold occurrence potential.

The areas surrounding these historic mining districts within the northern extent of the CMB in Boulder County, including rocks of the Idaho Springs Formation, the Boulder Creek Granite, the Longs Peak-St. Vrain Granite, and Tertiary intrusives, and creeks that drain these areas, are considered H/C where there are recorded gold occurrences in the USGS MRDS (2013) and H/B in an area devoid of occurrences. The northern border of the CMB is taken from Lovering and Goddard (1950). The same rocks outside the CMB are considered M/C, and then L/B, along a buffer north of the mining districts.

4.5.4 Platinum-Group Metals

In the Caribou-Grand Island district of Boulder County, platinum was reported by Eckel et al. (1997). This anecdotal report has never been substantiated, therefore the occurrence potential for PGM is assigned L/B for the Caribou-Grand Island district in Boulder County.

4.5.5 Silver

Boulder County produced over 9.4 million ounces of silver from 1859 to 1958 (Del Rio, 1960; Vanderwilt, 1947). Lode silver is found alongside most of the lode gold deposits, and there is also some production reported from silver placers (Vanderwilt, 1947). The general history and geology of the gold- and silver-bearing districts are discussed above in the gold section (4.5.3) of this county's MPR.

From 1932 through 1945, the Gold Hill district produced 215,289 fine ounces of silver and the neighboring Sugarloaf district to the south produced 48,751 ounces (Vanderwilt, 1947). Lovering and Goddard (1950) mapped 100 mines in the greater Gold Hill-Sugarloaf district area; most occur on northeast-trending fissure veins in close proximity to one of several northwest-trending breccia reefs mostly within Boulder Creek Granite and in a few cases near the contact with or in Precambrian biotite gneiss. Gold-telluride veins dominate, but pyritic quartz veins also yield silver (Lovering and Goddard, 1950). The Slide group of mines, along the Slide, Klondike, and Twin veins just south of Left Hand Creek and near the Hoosier Reef, accounted for production of 145,066 ounces of silver between 1934 and 1942 (Lovering and Goddard, 1950). Gray copper ore (silver-bearing tetrahedrite) hosting significant silver at the productive Yellow Pine and Logan mines occurs in veins near the juncture with the Hoosier breccia reef in the overlapping Gold Hill-Sugarloaf district area (Lovering and Goddard, 1950). Silver-lead ore at the Yellow Pine mine ranged from 33 to 1,440 ounces of silver per ton (Lovering and Goddard, 1950). Ore shipped from the Gold Hill district between 1878 and 1892 ranged from 2.5 to 1,056 ounces of silver per ton (Lovering and Goddard, 1953). The greater Gold Hill-Sugarloaf district area is designated H/D for silver occurrence potential.

The Jamestown district produced 208,900 ounces of silver from 1901 to1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). Lead-silver deposits occur chiefly as veins or irregular pipelike bodies inside or adjacent to breccia zones within the Precambrian Longs Peak-St. Vrain Granite and sometimes at the contact with or within a Laramide quartz monzonite porphyry stock; to a lesser extent, silver also occurs in the pyritic gold and telluride veins in Precambrian Boulder Creek Granite (Lovering and Goddard, 1950). Tenor of the lead-silver deposits in the district ranges from 2.8 to 155 ounces of silver per ton (Lovering and Goddard, 1950). The variety of silver deposits and historic production warrant a silver occurrence potential designation of H/D for the greater Jamestown district area.

The northern half of the Magnolia district overlaps the eastern portion of the Boulder Tungsten district and reportedly produced 1,946 fine ounces of silver from 1932-1945 (Vanderwilt, 1947). Silver-bearing gold-telluride and pyritic quartz veins occur in northwest-striking fissure fillings (Lovering and Goddard, 1950; Lovering and Tweto, 1953). In all significantly oxidized veins, silver is concentrated at depth in the zone of supergene enrichment below the water table (Lovering and Tweto, 1953). To the west, the rest of the Boulder Tungsten district hosts sporadic occurrences of silver-bearing tungsten veins associated with the Rogers and Hurricane breccia reefs (Lovering and Tweto, 1953). Despite limited reports of production, there are numerous silver-bearing mines and prospects in the northern Magnolia (eastern Boulder Tungsten) district area, and it is designated H/D for silver occurrence potential; the rest of the Boulder Tungsten district to the west is designated H/C.

The presence of silver was recognized in 1869 in the Caribou-Grand Island district (Henderson, 1926). This district contained rich silver ores and produced 91,853 fine ounces of silver from 1932-1945 (Vanderwilt, 1947). Ore minerals, including native silver, argentite, tetrahedrite, and cerargyrite, are concentrated in steeply dipping to vertical lead-silver veins that fill fissures in the Caribou monzonite porphyry stock (Lovering and Goddard, 1950; Moore et al., 1957). At the Caribou group of mines, tenor averaged 20 to 50 ounces of silver per ton, but oxidized zones ranged up to 300 ounces per ton (Lovering and Goddard, 1950; Moore et al., 1957). The Caribou-Grand Island district is designated as H/D for silver occurrence potential.

The Ward district produced 20,420 fine ounces of silver from 1932-1945 (Vanderwilt, 1947). Ore occurs in enlarged tabular bodies in veins of the Longs Peak-St. Vrain Granite or Idaho Springs Formation gneisses, both of which are intruded by Laramide diorite and monzonite porphyry stocks (Del Rio, 1960; Koschmann and Bergendahl, 1968; Lovering and Goddard, 1950). Silver comes mainly from pyritic gold-silver veins; the silver to gold ratio is 10:1, and the two metals are alloyed (Lovering and Goddard, 1950). The lead-silver veins of the White Raven mine are abundant in galena, lacking in gold, and may contain supergene wire (native) silver above the water table (Lovering and Goddard, 1950). Tenor of ore at the White Raven mine averaged 100 ounces of silver per ton (Lovering and Goddard, 1950). The district is designated as H/D for silver occurrence potential.

Elsewhere in the county, the area between the Ward and Boulder Tungsten districts hosts numerous mines and prospects reporting silver as a secondary or tertiary commodity, after gold; this widespread area is designated H/C for silver occurrence potential. The Eldora district has no recorded silver production, but is considered H/C for silver occurrence potential due to known silver mineralization in gold-telluride veins, as well as favorable geologic setting (Precambrian felsic gneiss and schist in contact with Tertiary intrusives). Buffers around the high potential areas hosting sporadic silver occurrences as noted by the USGS MRDS (2013) are assigned M/C for silver potential. Some silver is reported from alluviums of Boulder Creek, which drains highly mineralized districts; a buffer along Boulder Creek is designated L/B.

4.5.6 Copper-Lead-Zinc

The western half of Boulder County lies within the Precambrian core complex of the Front Range and the northeasternmost portion of the CMB. Boulder County has produced copper, lead, and zinc associated with the precious metal deposits of its historic mining districts within the CMB. Approximately 1.9 million pounds of copper, 11.2 million pounds of lead, and 88,700 pounds of zinc were produced from 1859 to 1958 (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). Base-metal mineralization primarily occurs in fissures and veins in association with Tertiary intrusives within Precambrian gneisses, granodiorite, and quartz monzonite (Cappa et al., 2000).

The Gold Hill district (including Rowena, Salina, and Sunshine districts) has produced base metals from silver-lead fissure veins that are commonly 5 feet (but up to 15 feet) wide (Lovering and Goddard, 1950). Ore minerals include argentiferous galena, gray copper, chalcopyrite, and sphalerite (Lovering and Goddard, 1950). The only massive sulfide deposit containing nickel, cobalt, and copper in Precambrian rock (Type 5) documented by Sheridan et al. (1990) is found at the Copper King mine, where calcic amphibolite is replaced by ore minerals, including chalcopyrite. Between 1935 and 1942, the Gold Hill district produced 501,130 pounds of copper, 890,900 pounds of lead, and 72,300 pounds of zinc, mostly from fissures and veins in the Boulder Creek Granite (Capp et al., 2000; Vanderwilt, 1947). The nearby Sugarloaf district produced 7,190 pounds of copper, 35,380 pounds of lead, and 5,400 pounds of zinc (Vanderwilt, 1947). Production, plus the distribution and variety of base-metal ores, earn the Gold Hill-Sugarloaf districts an occurrence potential of H/D.

The northeastern portion of the Boulder Tungsten district contains lead-silver ore near the Yellow Pine mine, and there are minor lead-silver-zinc deposits along the northern and southern borders (Lovering and Goddard, 1950). The northeastern portion is designated as H/D for copper-lead-zinc potential, whereas the southern border is designated H/C due to a number of lead-zinc mines noted in the MRDS (USGS MRDS, 2013).

The Caribou-Grand Island district produced minor amounts of base metals from silver-lead ore associated with the east-trending veins of the region (Lovering and Goddard, 1950). Between 1932 and 1945, the district produced 6,250 pounds of copper, 188,965 pounds of lead, and 4,000 pounds of zinc (Vanderwilt, 1947). Calais Resources, Inc. reports that underground operations prior to 1998 exposed significant mineralized material in its Cross Project claim within the Grand Island mining district (Business Wire, 2011). Additionally, a 2002 Calais report on the potential resources of its consolidated Caribou claims, which span the Caribou and Grand Island districts, indicate significant resources, primarily silver and gold, with lead, +/- copper, and +/- zinc (as galena, chalcopyrite, and sphalerite, respectively) as secondary commodities (Business Wire, 2011; USGS MRDS, 2013). Just north of the district, the Snowy Range mine produced some lead-gold ore prior to 1910 (USGS MRDS, 2013). The sulfide mineralization varies in an irregular pattern along and down the vein, but concentrated pods mined during the summer of

1909 averaged 41 percent lead with a small amount of zinc. The Caribou-Grand Island district region is designated as H/D for copper-lead-zinc potential.

The Jamestown (Central) district produced 156,811 pounds of copper, 1.2 million pounds of lead, and 7,000 pounds of zinc from 1901-1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). The base-metal mineralization is distributed around a small quartz monzonite porphyry stock of Porphyry Mountain in four types of deposits, including lead-silver veins and pipes, fluorspar pegmatites, and pyritic gold veins with chalcopyrite (Lovering and Goddard, 1950). Lead is produced from veins and irregular, pipe-like bodies within the Longs Peak-St. Vrain quartz monzonite, e.g., the Alice mine contains pipe-like structures that range from 3 to 8 feet wide and the Argo mine contains irregular bodies of lead-silver ore a few inches to several feet in diameter in a zone 8 to 10 feet wide (Lovering and Goddard, 1950). Ore minerals include argentiferous galena, gray copper, chalcopyrite, sphalerite, and pyrite (Lovering and Goddard, 1950). The lead-silver ore shipments reported by Lovering and Goddard (1950) ranged in grade from 1-40 percent lead and 0-5 percent copper. Most of the mines in the district are less than 600 feet deep, but there was no bottom to mineralized veins at that depth, leading Del Rio (1960) to conclude that there may be more ore bodies comparable in grade to be found at deeper areas in favorable structural settings. The Jamestown district is designated H/D for base-metal occurrence potential.

The Ward district accounted for notable base-metal production from veins similar to those in the Gold Hill and Jamestown districts, with 170,380 pounds of copper and 25,755 pounds of lead reported in the 1932-1945 time frame (Vanderwilt, 1947; Worcester, 1920). It should be noted that both Vanderwilt (1947) and Lovering and Goddard (1950) appear to place the deposits near Sunset and Copper Rock in this district, although they are located in the Sugarloaf district by other authors (e.g., Davis and Streufert, 1990). Lovering and Goddard (1950) document several ore types containing base metals in the district, including: gold-silver ores with chalcopyrite in pyritic quartz veins; lead-silver ore in the White Raven vein system (galena); copper ore (chalcopyrite and chalcocite); and tungsten ore associated with chalcopyrite scattered throughout the district. The Ward district region is designated as H/D for base-metal potential.

The Eldora and Magnolia districts are designated H/C and the Allens Park district is designated H/B for occurrence potential, as they have relatively minor reported production of copper, lead, or zinc, and their mineralization leans more towards tellurides (gold and silver) than base metals. The rocks of the Idaho Springs Formation, the Boulder Creek Granite, the Longs Peak-St. Vrain Granite-Quartz Monzonite, and Tertiary intrusives surrounding these historic mining districts in Boulder County are considered H/C. Further north they are H/B since they lie within the northern extent of the CMB and have some potential for copper-lead-zinc occurrence. North of the CMB (as defined by Lovering and Goddard (1950)), these rocks are designated M/B or L/B.

4.5.7 Iron

The Caribou Hill iron deposit in the Caribou-Grand Island district occurs in a mafic segregation, composed of magnetite-bearing pyroxenite and peridotite, of the Caribou Stock (Harrer and Tesch, 1959). The magnetite occurs in small mafic dikes and irregularly shaped intrusions within the larger monzonite; a body of magnetite pyroxenite west of Caribou is the largest occurrence and is composed of intergrown diopside, magnetite, and ilmenite locally cut by stringers of magnetite (Lovering and Goddard, 1950). The mafic portions of the Caribou stock are designated H/C. Nearby, Precambrian northwest-trending, iron-rich diabase dikes host titaniferous magnetite and limonite, and one occurrence is noted in neighboring Larimer County (Eggler, 1968; USGS MRDS, 2013). Mafic dikes are designated M/C for iron potential.

Iron has been recovered from scattered limonite, hematite, and siderite concretions in a thin bed above a coal seam in the Laramie Formation in southeastern Boulder County (Harrer and Tesch, 1959). The concretions contain up to 60 percent iron and weigh up to 1,000 pounds (Harrer and Tesch, 1959). An estimated 250 tons of iron ore were produced from the Marshal or Langford Surface Iron site (USGS MRDS, 2013). A buffer around this site is assigned H/D for iron occurrence potential; the Laramie Formation elsewhere is designated L/B. Limonite and siderite concretions are also reported in the Rusty Zone of the Cretaceous Pierre Shale in Pueblo County (Gilbert, 1897; Harrer and Tesch, 1959; Scott; 1969). The lower unit (Sharon Springs shale) of the Pierre Formation in Boulder County is designated L/B for iron occurrence potential.

Precambrian Silver Plume-aged granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-aged granite (Longs Peak-St. Vrain batholith) in Boulder County is assigned L/B. Iron-bearing minerals (especially pyrite) are reported in polymetallic veins, pegmatites, and stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential.

4.5.8 Manganese

Tungsten ore in the Boulder Tungsten district and northward in the Gordon Gulch area contains wolframite ($(FeMn)WO_4$) (Lovering and Goddard, 1950). Alabandite (MnS), as well as manganese oxides, coat ferberite crystals at the Forest Home mine in the Tungsten district, where hübnerite (MnWO4) is also found (Lovering and Tweto, 1953). Wolframite is also reported as dispersed in the Ward district (Lovering and Tweto, 1953). Manganese garnets are reported from the Left Hand Creek Pegmatite district at the Beryl Lode claim (Hanley et al., 1950). Anomalous concentrations of manganese are found in molybdenum-bearing pyritic quartz veins north of Rainbow Lakes near the Grand Island-Caribou district (Pearson and Johnson, 1980). An area encompassing the Ward, Grand Island-Caribou, and Boulder Tungsten districts, as well as the Left Hand Creek Pegmatite district, are designated M/C for manganese potential. Boulder Creek Granite and Idaho Springs Formation gneiss elsewhere in the county are L/B.

4.5.9 Molybdenum

There are some occurrences of molybdenum within the historic mining districts of Boulder County. In the Eldora district, molybdenite occurs as a fine-grained intergrowth with barite and is recognized in mine dumps by its deep-blue weathering (Lovering and Goddard, 1950). In 1918, 0.5 percent molybdenite ore was produced from pyritic quartz veins in Precambrian gneiss at the Big Horn Shaft, just northeast of the Grand Island-Caribou district (Eckel, 1961; King, 1964). West of the Grand Island-Caribou district, molybdenite was produced as a tertiary commodity (after uranium) at the Mountain Goat mine from veins in Precambrian gneiss and pegmatite (USGS MRDS, 2013). Though molybdenite commonly occurs in the pyritic gold veins in the Ward district, it has not been produced there (Lovering and Goddard, 1950). Molybdenite occurs in the Sunday mine and the Footwall vein of the Clyde mine in the Boulder Tungsten district (Lovering and Goddard, 1950). Some molybdenum was produced in conjunction with tungsten at the Cougar/Greyback mines of the Tungsten district (USGS MRDS, 2013). The Magnolia district is noted for an unusual association of molybdenite with gold telluride: the Mountain Lion mine in the district has pockets of massive molybdenite in porphyry dikes, and a few hundred pounds were produced (Eckel, 1961; Lovering and Goddard, 1950; USGS MRDS, 2013). King (1964) reports a low-grade molybdenum ore in a large vein in the Jamestown district; USGS MRDS (2013) lists one economic-grade occurrence, in the quartz-monzonite porphyry stock at the Porphyry Mountain prospect. Finally, one occurrence is reported in association with graphite and pitchblende at the Sisk property northwest of Lyons (USGS MRDS, 2013).

The Jamestown, Ward, Grand Island-Caribou, Eldora, Magnolia, and Boulder Tungsten districts, as well as the area between them where Precambrian igneous (Boulder Creek Granite) and Tertiary intrusives occur, are designated H/C due to scattered occurrences and minor production. Precambrian metamorphic and igneous rocks, outside of those areas mentioned above, are considered L/B due to favorable rock types.

4.5.10 Nickel

The Copper King mine in the Gold Hill district produced 3,000 tons of nickel ore in 1942 (Lovering and Goddard, 1950). A lenticular nickel-bearing amphibolite bed occurs in Precambrian Idaho Springs schist and is genetically related to a gabbro intrusion (dike) from the nearby Boulder Creek quartz monzonite (Lovering and Goddard, 1950). Sheridan et al., (1990) classify this ore as a Type 5 massive sulfide deposit containing nickel, copper, and cobalt. Nickel mineralization is varied but the chief ore is polydymite (Goddard and Lovering, 1942). Other minerals include niccolite and pentlandite (after pyrrhotite) with subsidiary nickel sulfides including bravoite, millerite, and violarite, as well as nickel oxide (Goddard and Lovering, 1942). Assays showed 0.48 to 6 percent nickel in the sulfide ore and 1.32 to 13 percent nickel in the oxidized ore (Goddard and Lovering, 1942). Goddard and Lovering (1942) estimated reserves at 44 million pounds of 0.5 to 3.0 percent nickel ore. The occurrence potential for nickel around the Copper King mine is assigned H/D. The Idaho Springs Formation in proximity to Boulder Creek quartz monzonite in the southwest quadrant of the county, where other gabbroic intrusions may occur, is designated H/B. Precambrian metamorphic (including Idaho Springs Formation) and igneous (including Boulder Creek quartz monzonite) rocks elsewhere are considered L/B.

4.5.11 Tungsten

Boulder County was the main tungsten producer in the RGFO region as well as in Colorado. Thirty of over 100 tungsten mines established in the Boulder Tungsten Belt since 1900 were considered significant producers (Voynick, 1994). The Tungsten, Marion, Good Friday, and Eureka mines remained active through the 1970s, but there are no currently active DRMS permits for tungsten mining in Boulder County.

The Boulder Tungsten district lies within the CMB and stretches from Boulder to Nederland (about 10 miles long and 1 to 3 miles wide), partly overlapping the Magnolia and Gold Hill districts. The belt is underlain almost entirely by the Precambrian Boulder Creek batholith with some Precambrian metamorphic rocks (Idaho Springs Formation) occurring in the west. The primary tungsten ore, ferberite ($FeWO_4$), fills steeply dipping fissures up to 3 feet wide and 700 feet deep with minimal replacement of the host rock, as well as occasional bodies 12 to 16 feet wide (Lovering and Goddard, 1950). Assays show ore grades range from 2 to 20 percent tungsten (Lovering and Goddard, 1950). Lovering and Goddard (1950) report an estimated 24,098 tons of 60 percent tungsten trioxide (WO_3; about 22.9 million pounds of tungsten) were produced in the district from 1900 to 1944. The most productive deposit, Conger mine, is composed of massive ferberite filling large lenticular bodies within a pegmatite and Boulder Creek Granite (Lovering and Goddard, 1950). The Conger mine produced an estimated 550,000 units of tungsten trioxide (WO_3; about 8.7 million pounds of tungsten) from 1900 to 1949 (Lovering and Goddard, 1950).

Primarily known for their gold production, the Magnolia and Gold Hill districts have also produced tungsten (ferberite) from veins in the Boulder Creek Granite. Notably, the Kekionga mine (Magnolia district) contains east-northeast trending ferberite-bearing veins in a shear zone that cut west-northwest-trending telluride veins (Lovering and Goddard, 1950). The Kekionga ferberite veins are smaller and ore grade is lower (just 2 percent WO_3) compared to the Boulder Tungsten district ores (Lovering and Goddard, 1950). The Logan mine (Gold Hill district) had moderate production of 5 to 10 percent WO_3 tungsten ore (Lovering and Goddard, 1950). The greater Boulder Tungsten district, including parts of Magnolia and Gold Hill districts, is H/D for occurrence potential. A buffer zone of the same rock types (Boulder Creek Granite and Idaho Springs Formation gneiss) immediately outside the district, including outlying areas of Magnolia and Gold Hill districts where MRDS (2013) occurrences are reported, are assigned a potential of M/C.

The Jamestown (Central), Ward, and Grand Island-Caribou districts have had several past producers of tungsten as a secondary or tertiary commodity after gold and silver. The tungsten-bearing veins are widely scattered in the districts and occur mostly in the Boulder Creek Granite and Idaho Springs Formation gneiss (Lovering and Goddard, 1950). The relatively minor production, although rock types are favorable, earn these districts an M/C rating for occurrence potential where past producers occur. Outside these areas, the same rock types with a lack of MRDS (2013) occurrences are designated L/B.

4.5.12 Beryllium

Through 1963, production of beryl from pegmatites in Boulder County amounted to 2,925 pounds (Meeves et al., 1966). The occurrence potential for beryllium is considered H/C in the pegmatites where Boulder Creek granodiorite contacts Precambrian metamorphic rocks in the Left Hand Creek and Gold Hill districts (Cappa, 1998; Del Rio, 1960; Hanley et al., 1950). No beryllium production is reported in the Boulder Tungsten district, but there are numerous pegmatite occurrences in the vicinity of the Boulder Creek granodiorite contact with metamorphic rocks (USGS MRDS, 2013). Beryllium potential is designated M/B in this district. Pegmatites also occur where Longs Peak-St. Vrain Granite contacts Precambrian metamorphic rocks in the Ward and Jamestown districts, but no beryllium production is reported and the appearance of beryl is low (Cappa, 1998; Del Rio, 1960; Hanley et al., 1950). These districts and the remainder of granitic rocks in the county are assigned an occurrence potential of L/B.

4.5.13 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Boulder County; however, the Denver Coal Region in the county (see section 3.1.1 and 4.5.1 of this MPR) is designated L/B for germanium occurrence potential.

The county produced 88,700 pounds of zinc, primarily from the greater Gold Hill-Sugarloaf districts, between 1859 and 1958; sphalerite is commonly reported (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.5.14 Rare Earth Elements

There is no REE production noted for Boulder County; however, several pegmatites developed in Precambrian and Tertiary igneous rocks host trace rare-earth minerals (Adams, 1968; Haynes, 1960; Olson and Adams, 1962). In the Jamestown district, cerite, allanite, monazite, and bastnaesite are hosted in aplite and pegmatite dikes in Precambrian Longs Peak-St. Vrain Granite and Laramide stocks (Adams, 1968; Haynes, 1960; Meeves et al., 1966; and Olson and Adams, 1962; USGS MRDS, 2013). Elsewhere in the county, the Sunset, Caribou, Bryan Mountain, and Apex Tertiary stocks host trace cerium, lanthanum, yttrium, neodymium, and ytterbium, although they are not economically concentrated (Gable, 1984). The Jamestown district area is designated L/C for REE occurrence potential; elsewhere in the county, Tertiary stocks are assigned L/B.

4.5.15 Niobium-Tantalum

Meeves et al. (1966) report "some" production of niobium-tantalum minerals in Boulder County. Anomalous niobium and tantalum occur in beryl- or potash feldspar-bearing pegmatites in biotite schist of the Precambrian Idaho Springs Formation in the Left Hand Creek pegmatite district, but no production is noted (Hanley et al., 1950; Martin, 1993). In the nearby Gold Hill district, beryl-bearing pegmatites host columbite and tantalite in Boulder Creek Granite (USGS MRDS, 2013). Buffers around these occurrences and also along dikes in the Boulder Tungsten district, which host a pegmatite swarm, are designated L/B for niobium-tantalum occurrence potential.

4.5.16 Tellurium

Boulder County has abundant occurrences of telluride minerals and even native tellurium. Recognition of telluride minerals as a compound of gold and silver came early in this area. The gold districts in the "Boulder Telluride Belt" contain arguably the greatest variety of telluride minerals in the country. How much tellurium may be available as a commodity by itself is unknown since only recently has there been an interest in elemental tellurium aside from additional minerals it forms with gold and silver.

The Gold Hill, Jamestown, Magnolia, Sunshine, Eldora and Caribou-Grand Island districts all contain one or more of the telluride minerals petzite, hessite, coloradoite, melonite, calaverite, sylvanite, altaite, krennerite (Geller, 1993). Native tellurium has been identified in many of the historic mines also. Occurrence potential for tellurium in the Gold Hill, Jamestown, Magnolia, Sunshine, Eldora, and Caribou-Grand Island historic mining districts is designated H/D due to identified mineralization. Precambrian gneiss with numerous gold and copper occurrences is assigned M/B for tellurium occurrence potential. The occurrence potential in the remainder of the county within Precambrian host rocks of gold and copper mineralization is L/B.

4.5.17 Titanium

In the Caribou district, the "Iron Dike" is composed of ultramafic and pyroxenite segregations that host ilmenite and titaniferous magnetite (Harrer and Tesch, 1959). These occur as veinlets and small lenses up to 8-inches thick, containing 2.5 to 36 percent TiO_2 (Harrer and Tesch, 1959). Henderson (1929) estimated a resource of 7,000 tons. The occurrence potential for titanium is considered H/C in the mafic portions of the Caribou stock.

Precambrian northwest-trending, mafic dikes from the Larimer-Boulder county line to the Magnolia district in southeastern Boulder County host titaniferous magnetite, and one titanium occurrence is noted in Larimer County (Eggler, 1968; USGS MRDS, 2013). Eckel (1961) reports that coarse nodules of picrotitanite (magnesian ilmenite) occur in a 6-to 8-mile-long extension of this dike in the Magnolia district. Buffers along Precambrian mafic dikes are designated M/C for titanium potential.

Potential economic concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). This unit in Boulder County is designated L/B for titanium potential.

Economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone in Boulder County is designated L/B for titanium occurrence potential.

4.5.18 Uranium

Boulder County is one of the more important uranium producing areas in the RGFO management area. About 189,000 pounds of U_3O_8 have been mined in the county, all from veins or Tertiary intrusives in the Precambrian crystalline rocks (Nelson-Moore et al., 1978). Sims and Sheridan (1964) described 42 uranium veins in the county, along with one uranium occurrence in the Dakota Sandstone in the foothills of the Front Range. Although uranium-bearing veins are widespread across the county, uranium concentrations are mainly found in the Jamestown district, with some also in the Gold Hill and greater Caribou, Grand Island, and Eldora district areas (Sims and Sheridan, 1964). Nearly all of the uranium produced in Boulder County is from the Fair Day mine (~183,000 pounds of U_3O_8 from 0.44 percent ore), with much of the remainder from the Victory mine (1,900 pounds), both in the Jamestown district (Nelson-Moore et al., 1978). At the Fair Day mine, mineralization is concentrated in northeastward-trending veins near their termini with northwest-trending faults in Precambrian Silver Plume-aged granite and Idaho Springs Formation biotite gneiss; uranium minerals include uraninite, coffinite, autunite, and torbernite ($Cu(UO_2)_2(PO_4)_2$) (Nelson-Moore et al., 1978; Sims and Sheridan, 1964). The greater Jamestown district area is designated H/D for uranium occurrence potential.

Numerous uranium occurrences, including the highly productive Schwartzwalder mine, are found along northwest-trending Tertiary fault systems or breccia reefs in this and Jefferson Counties (Nelson-Moore et al., 1978; USGS MRDS, 2013). The Gold Hill district area is cut by 6 breccia reefs, including the Hoosier and Maxwell reefs, and is host to over a hundred base- and precious-metal mines (Lovering and Goddard, 1950). Several uranium occurrences and anomalous radioactivity, but no production, are reported in this district (Nelson-Moore et al., 1978). The greater Gold Hill district area is assigned M/C for uranium potential. Elsewhere in the county, buffers along northwest-trending breccia reefs and one notable mafic dike are designated M/C for uranium occurrence potential in Boulder County.

The greater Caribou, Grand Island, and Eldora districts area is host to numerous base- and precious-metal mines, some of which record anomalous uranium occurrences or radioactivity (Nelson-Moore et al., 1978). The Mountain Goat claims produced 8 pounds of U_3O_8 from 0.11 percent ore from a pegmatite in the Precambrian Boulder Creek Granite and Idaho Springs Formation (Nelson-Moore et al., 1978). Samples at the Caribou mine assayed 1.45 percent U_3O_8 (uraninite), but no production is reported (Nelson-Moore et al., 1978). The greater Caribou, Grand Island, and Eldora districts area is designated M/C for uranium occurrence potential. Tertiary intrusive stocks throughout the county are also designated M/C for uranium potential.

Several uranium prospects occur in Mesozoic sedimentary rocks of other counties in the Jurassic undivided Morrison, Entrada, and Ralston Creek group and the Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from these units is also reported in Larimer, Pueblo, and Park Counties (Nelson-Moore et al., 1978). All these units in Boulder County are designated L/B for uranium potential.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

Part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. Two non-producing uranium occurrences in the undifferentiated Laramie Formation and Fox Hills Sandstone unit are noted in Nelson-Moore et al. (1978) and the USGS MRDS (2013); these geologic units in Boulder County are designated L/B for potential.

4.5.19 Thorium

Uranothorite ($(Th,U)SiO_4$) is reported from fluorite-bearing veins in Tertiary diorite at the Blue Jay mine in the Jamestown district of Boulder County (Schwochow and Hornbaker, 1985; Sims and Sheridan, 1964). In the Gold Hill district, thorium is reported from veins in Precambrian Boulder Creek Granite at the underground More mine (USGS MRDS, 2013). Buffers along major faults in Precambrian rocks within the region of the heavily mineralized breccia reefs are designated L/B for thorium occurrence potential; the Tertiary intrusive fluorite-bearing stocks of the Jamestown district are also assigned L/B for thorium potential.

4.5.20 Vanadium

Several vanadium occurrences are reported in Boulder County, and production is reported from claims developed in the Kekionga-Magnolia gold telluride vein in the Precambrian Idaho Springs Formation (Fischer, 1962; Lovering and Goddard, 1950). Samples containing roscoelite assayed up to 6.28 percent V_2O_5 and averaged 4.3 percent (Fischer, 1962; Lovering and Goddard, 1950). Production of 12 pounds of vanadium from 30 tons of 0.02 percent V_2O_5 ore from a faulted contact between Precambrian granite and gneiss is reported at the Kipp (Miller) Lease (Nelson-Moore et al., 1978). Vanadium is reported from several other uranium prospects developed in northwest-trending brecciated fault zones in the Precambrian Idaho Springs Formation of Boulder County, although no production is noted (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, vanadium is reported from the titaniferous magnetite deposit in a pyroxenite dike at the Caribou mine (USGS MRDS, 2013). Buffers along breccia reef faults and dikes in Precambrian crystalline rocks are designated L/C for vanadium occurrence potential.

A Jefferson County mine yielded 256 pounds of vanadium from 678 tons of 0.02 percent V_2O_5 ore in the Cretaceous Dakota Sandstone (Nelson-Moore et al., 1978). Also, carnotite occurs in several other Dakota Sandstone prospects in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). The undifferentiated Morrison Formation, Entrada Sandstone, and Dakota Sandstone mapped unit is designated H/C for vanadium occurrence potential in Boulder County.

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.5.21 Fluorspar

In 1873, fluorspar was first produced in the Jamestown district (Aurand, 1920; Van Alstine, 1968). Deep violet, purple, wine-colored, and rare colorless fluorite crystals of the Jamestown district are commonly reported from veins and breccia zones related to a Tertiary sodic quartz monzonite porphyry stock (Aurand, 1920; Eckel, 1961; Goddard, 1946; Scott, 1968b). The breccia zones range up to 70-feet wide and over 400 feet in length, whereas veins are up to 20 feet wide and 1,000 feet long (Aurand, 1920; Goddard, 1946; Van Alstine, 1947). A large deposit of metalliferous fluorite ore at the Alice mine assayed up to 71.2 percent CaF_2 with a high silica content, earning it a class 3 (metallurgical grade); most veins host between 60 and 85 percent CaF_2 (Aurand, 1920; Van Alstine, 1947). Production of 33,826 tons of acid-grade (class

1) fluorspar and 65,838 tons of metallurgical-grade (class 3) fluorspar was reported between 1903 and 1944 in the Jamestown district (Van Alstine, 1947). From 1944 to 1973, production of 700,000 tons of acid-grade fluorspar is reported from the Burlington mine; the Jamestown district accounted for about 60 percent of total State production through 1973 (Brady, 1975). The Tertiary stocks, and a surrounding buffer, are designated H/D for fluorspar occurrence potential.

The CMB in Boulder County hosts numerous northeast-trending porphyry dikes and northwest-trending faults and pegmatites are abundant (Goddard, 1947). Average content of fluorine (ppm) in Central Colorado measured highest in Precambrian igneous rocks and alkalic diatremes, followed by Precambrian metamorphic and Tertiary intrusive rocks (Wallace, 2010). In Boulder County, concentrations of fluorite are associated with the many fissure veins and bostonite dikes hosted primarily by the Precambrian Boulder Creek granodiorite and—to a lesser extent—the Longs Peak-St. Vrain granite and Idaho Springs biotite gneiss (Brady, 1975; Tweto, 1987). Also, a kimberlite diatreme, 128 feet in diameter, occurs in Boulder Creek Granodiorite near Green Mountain southwest of Boulder; diatremes in nearby Larimer County assayed up to 8,600 ppm fluorine (Hausel, 1998; Wallace, 2010). Precambrian igneous rocks, as well as the area around the Green Mountain diatreme, are designated H/C, biotite gneiss is assigned M/C, and hornblende gneiss is assigned M/B for fluorspar potential throughout the county.

4.5.22 Diamond and Gemstones

Deep violet, purple, and wine-colored fluorite crystals of the Jamestown district are commonly reported from veins and breccia zones related to a Tertiary sodic quartz monzonite porphyry stock, and some are of gem-quality (Eckel, 1961; Goddard, 1946; Scott, 1968b). The Tertiary stocks hosting these crystals are designated H/D for gemstone occurrence potential. The greater Jamestown district region is cut by numerous northeast-trending porphyry dikes and northwest-trending faults and hosts numerous pegmatites (Goddard, 1947). Precambrian rocks surrounding the Jamestown district are designated H/C for gemstone potential.

A kimberlite diatreme, 128 feet in diameter, occurs in Boulder Creek granodiorite near Green Mountain southwest of Boulder, but no diamonds are yet reported (Hausel, 1998). A buffer around the area is designated M/B for diamond occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks are designated M/C, and biotite gneisses and schists are assigned M/B, for gemstone occurrence potential elsewhere in the county (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954). Pegmatites are known to occur in the Longs Peak-St. Vrain batholith, and this unit is designated L/B for gemstone occurrence potential (Boos, 1954).

4.5.23 Pegmatite Minerals

The Left Hand Creek Pegmatite district in central Boulder County hosts pegmatites in Precambrian schist marginal to Boulder Creek granodiorite and the Longs Peak-St. Vrain batholith (Boos and Boos, 1934; Galbraith, 1960). Zoning is not common, nor well developed, although some of the weak zoning reveals beryl in the pegmatite cores. The dominant mineralogy consists of quartz, potassium feldspar, and plagioclase; major accessories are beryl and muscovite; minor accessories include garnet, columbite, and tourmaline (Galbraith, 1960). Minerals of economic interest are beryl, feldspar and scrap mica, and Martin (1993) reports anomalous niobium and tantalum in the district’s pegmatites.

Meeves et al. (1966) report production of 195 tons of scrap mica from pegmatites in Boulder County through 1963. In the Left Hand Creek district, the New Girl mine produced 240 tons of potassium feldspar through 1942 (Baillie, 1962). The Beryl Lode mine was the most extensively worked, producing small amounts of beryl and mica during the WWI period (Martin, 1993). Other named mines and prospects in the area include the Elkhorn, the Cal-Wood Mica, and the Highline. Reserves of feldspar and mica in this district are thought to be small (Baillie, 1962; Hanley et al., 1950). The greater Left Hand Creek district, including the Jamestown, Central, and Gold Hill districts, is considered H/D for pegmatite mineral occurrence.

Numerous pegmatites in the Boulder Tungsten district are known to host metallic minerals (e.g., tungsten) but none have reported production of feldspar or mica (Lovering and Tweto, 1953). The pegmatites occur along contacts of the Boulder Creek- or Silver Plume-aged batholiths and Precambrian gneiss and schist and are composed primarily of feldspar (approximately 60 to 85 percent), quartz, and biotite (Lovering and Tweto, 1953). The zone around the Boulder Tungsten district pegmatite swarm is designated M/B for occurrence potential. In the rest of the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B.

4.5.24 Industrial Abrasives

A kimberlite diatreme, 128 feet in diameter, was identified in Boulder Creek granodiorite near Green Mountain southwest of Boulder, but no diamonds are reported yet (Hausel, 1998). A buffer around the area is designated M/C for industrial abrasive (diamond and garnet) occurrence potential. The greater Jamestown district is host to numerous pegmatites and hosts abundant garnet in calc-silicate rocks near contacts of Precambrian metamorphic and igneous rocks (Eckel, 1961; Lovering and Goddard, 1950). The western Boulder Tungsten mining district also hosts numerous pegmatites, and both district areas are assigned H/C for industrial abrasive potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks are designated M/C for industrial abrasive occurrence potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive potential (Boos, 1954).

4.5.25 Limestone and Dolomite

There are no limestone occurrences in Boulder County; however, the Pennsylvanian-Permian Ingleside and Fountain Formations, correlative with the Maroon and Minturn Formations which host limestone occurrences in several counties, hosts prospects in neighboring Larimer County. This unit is designated M/C for limestone and dolomite potential. There are 2 limestone quarries developed in the Permian Minnekahta and Forelle Limestones of the Lykins Formation in neighboring Jefferson County; the Lykins Formation is designated L/C for limestone potential. The Cretaceous Greenhorn Limestone hosts prospects elsewhere in the State; the undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale (Colorado Group) is designated M/C for limestone and dolomite occurrence potential.

4.5.26 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Numerous DRMS-permitted industrial sand operations and past production is reported from these units in Boulder County (Schwochow, 1981). The Lykins Formation and Dakota Sandstone are designated H/D for industrial sand occurrence potential.

Quaternary eolian sands in eastern Boulder County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in this and nearby counties (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential.

4.5.27 Gypsum

There are no reported gypsum occurrences in Boulder County; however, there are many reports of massive white and gray gypsum at the base of the Jurassic Morrison Formation in a unit almost always correlated with the Ralston Creek Formation throughout the RGFO region (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). George (1920) reports gypsum beds up to 60 feet thick below the Morrison Formation at the Garden of the Gods and Glen Eyrie in El Paso County. A massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8-mile section above the Permian-Triassic Lykins Formation and just below the Morrison Formation is reported at Perry Park in neighboring Douglas County (George, 1920). In Jefferson County, some production was reported from a massive gypsum bed up to 20 feet thick along Bear and Deer creeks in the Lykins Formation (George, 1920; Scott, 1963; Withington, 1968). The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/C for gypsum occurrence potential in Boulder County.

Throughout the RGFO management area, the Cretaceous Niobrara Formation and Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Also, granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Niobrara Formation and the underlying Colorado Group (George, 1920). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in Boulder County.

4.5.28 Helium

The eastern part of Boulder County is designated L/C for helium due to its location near the Denver Basin.

4.5.29 Sand and Gravel

Del Rio (1960) reports production of over 1.5 million tons of sand and gravel, primarily from alluvium, in Boulder County between 1956 and 1958. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, as well as glacial drift (Qd) and Tertiary gravels (Tgv), are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary units of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Boulder and other counties, the Paleozoic Fountain and Lykins Formations and Cretaceous Dakota and Fox Hills Sandstones host sporadic sand and gravel operations, and they are more known for their industrial sand production (W. D. Carter, 1968; Schwochow, 1981); these units are assigned L/C for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grü) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.5.30 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Boulder County, developed in limestone members of the Colorado Group, although limestone in the overlying Fort Hays Member of the Cretaceous Niobrara Formation may crop out in the area as well (Tweto, 1979a). The Niobrara Formation and Colorado Group may host suitable source rocks where the limestone is dense, well-consolidated, and free from abundant joints and fractures (Knepper et al., 1999; Langer and Knepper, 1995). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Colorado Group is designated H/D for crushed stone aggregate occurrence potential.

Tertiary intrusive rocks occur sporadically throughout the county; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz, which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Laramide intrusive rocks meet the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999) and are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Longs Peak-St. Vrain pluton and satellites in Boulder and Larimer Counties, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed Precambrian Boulder Creek pluton and satellites were classified as only ‘fair’ source rocks by Knepper et al. (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Longs Peak-St. Vrain batholith is designated H/C, and the Boulder Creek Granite is assigned M/C, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-

Permian Fountain Formation, the Permian-Triassic Lyons Sandstone and Lykins Formation, the Jurassic Morrison Formation, and the Cretaceous Dakota and Fox Hills Sandstones (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone at its contact with the Colorado Group, as well as in the undivided Lykins Formation and Lyons Sandstone, in this and nearby counties. The Dakota Sandstone is designated H/D, the undivided Lykins Formation and Lyons Sandstone are assigned M/C, the Fox Hills Sandstone is designated L/C, and remaining sedimentary rocks are assigned L/B, for crushed stone potential.

4.5.31 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the overlying Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the mountains of Colorado, including in Precambrian igneous and metamorphic rocks of Boulder County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The relatively unweathered Longs Peak-St.

Vrain granitic pluton is designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

4.5.32 Clay

Several DRMS-permitted quarries and over a dozen USGS MRDS (2013) clay occurrences are noted in Boulder County. The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone); many prospects occur in this unit in this and other counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation and Dakota Sandstone are designated H/D for clay occurrence potential.

Most prospects developed in the Cretaceous Graneros Shale (Colorado Group) throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). Several Boulder County clay quarries produce from the Colorado Group; this unit is assigned M/D in areas of reported mines and M/C elsewhere for clay potential. There are several clay prospects developed in the Permian-Triassic Lykins Formation along the Front Range; this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated M/C for clay occurrence potential.

The Cretaceous Pierre Shale, which crops out in the eastern part of Boulder County, hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making; there is one clay prospect developed in this unit (Vanderwilt, 1947). The Pierre Shale and Laramie Formation are designated H/C for clay potential; the Fox Hills Sandstone is assigned L/C for clay potential.

Two clay mines are developed in altered Tertiary igneous rocks: weathered felsite, a fine-grained volcanic rock, yields clay at one location, and the other occurs in weathered Laramide intrusives (USGS MRDS, 2013). Buffers around these occurrences are designated M/C for clay potential.

4.5.33 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Boulder County hosts granites, sandstones, and conglomerates that have been quarried for dimension stone, including Precambrian Silver Plume-aged granite, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian Lyons Sandstone, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

Silver Plume-aged granite to granodiorite has been quarried for dimension stone in the RGFO region, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). Silver Plume-aged granite is designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. Limited outcrops of Tertiary intrusives throughout Boulder County are assigned L/B for dimension stone potential.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Sharps (1963) described over 30 sandstone quarries, primarily in the Lyons Sandstone, in Larimer and Boulder Counties; many buildings on the University of Colorado-Boulder campus used this material. These units are designated H/D for dimension and building stone occurrence potential; the Fountain Formation and Codell Sandstone capping the Colorado Group are assigned M/C for dimension stone potential. The Cretaceous Fox Hills Sandstone has no documented production of dimension stone and is designated M/B for dimension and building stone occurrence potential.

4.6 Broomfield County

4.6.1 Coal

The entirety of Broomfield County lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). There no past-producing coal mines noted within county boundaries. The Denver Coal Region in Broomfield County is designated H/C for coal occurrence potential. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.6.2 Geothermal

Traditional / EGS Geothermal

The majority of Broomfield County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the southwest is considered M/C because of moderate EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Broomfield County contains no known springs or wells. The majority of Broomfield County, which lies within named COGCC fields, is considered H/C for low temperature and/or co-produced geothermal resources. The southern part of Broomfield County is designated as H/B. The entirety of the county is above the 100°F temperature threshold for low temperature and co-produced resources.

4.6.3 Iron

No iron production is reported in Broomfield County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Broomfield County.

4.6.4 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Broomfield County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.6.1 of this MPR) is designated L/B for germanium occurrence potential.

4.6.5 Uranium

Although no uranium occurrences are known in Broomfield County, part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in Broomfield County are designated L/B for potential.

4.6.6 Vanadium

No vanadium production is reported in Broomfield County; however, carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.6.7 Helium

Most of Broomfield County is designated L/D for helium due to its location near the Denver Basin.

4.6.8 Sand and Gravel

High-quality sand and gravel deposits in southwestern Broomfield County are found in youngest floodplain and low-elevation terraces mapped Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Broomfield County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation, as well as the Cretaceous Fox Hills Sandstone and overlying Laramie Formation, all of which host sporadic sand and gravel operations in this or other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968; Schwochow, 1981).

4.6.9 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Broomfield County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone and Tertiary Dawson Arkose may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999). The Fox Hills Sandstone is designated L/C, and the Dawson Arkose is assigned L/B, for crushed stone aggregate occurrence potential.

4.6.10 Lightweight Aggregate

Often mapped together, the Arapahoe and Denver Formations contain claystone beds bearing up to 95 percent moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C for lightweight aggregate potential. The underlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The undivided Fox Hills Sandstone and Laramie Formation are designated M/B for lightweight aggregate occurrence potential.

4.6.11 Clay

There are no reported clay producers in Broomfield County; however, abundant kaolinite with significant montmorillonite occur in shale of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making as well (Vanderwilt, 1947). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). The undifferentiated Laramie Formation and Fox Hills Sandstone, as well as the Dawson Arkose are designated M/C for clay potential.

4.6.12 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Broomfield County, the Cretaceous Fox Hills Sandstone and Tertiary Denver Formation and Dawson Arkose, although hosting sandstones in part, have no documented production of dimension stone. As sandstones, these units are designated M/B for dimension and building stone occurrence potential.

4.7 Chaffee County

4.7.1 Geothermal

Traditional / EGS Geothermal

The entirety of Chaffee County has high to moderate EGS favorability (Augustine, 2011); traditional geothermal favorability is high in the north-central area, moderate along a north-south band through the center of the county, and low on the eastern and western sides (Williams et al., 2008). These combinations lead to the northern area being designated H/B, the central area M/C, and the east and west sides of the county M/B. An area in the extreme south-central of the county is considered H/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Three significant geothermal areas are identified in Chaffee County: the Mount Princeton-Chalk Cliffs area, the Poncha Springs area, and the Cottonwood Springs area (located roughly 6 miles southwest of the Town of Buena Vista). The hottest spring in Colorado (Hortense Hot Spring) and several of the hottest thermal features in the State are all found in the Mount Princeton-Chalk

Cliffs area. The temperature of Hortense is 181°F, whereas the temperatures of the Mount Princeton Hot Springs are 111 to 153°F, and nearby wells in the area produce water at 102 to 180°F (NREL, 2016; Barrett and Pearl, 1978; Cappa and Hemborg, 1995). Temperatures at Poncha Hot Springs range from 133°F to 158°F, and at Cottonwood Springs are ~129°F (NREL, 2016; Barrett and Pearl, 1978; Cappa and Hemborg, 1995).

The Mount Princeton-Chalk Cliffs and Cottonwood Springs areas lie along the Sawatch Fault, a major, north-northwest-trending, rift-related fault at the eastern base of the Sawatch Range. The fault is down to the east, and has ruptured as recently as the late Quaternary. Both geothermal areas occur in places where there are steps or *en echelon* strands of the fault (Morgan and Witcher, 2011), a geologic setting similar to many known geothermal areas in the Basin and Range Province in Nevada.

Held and Henderson (2012) briefly summarized geothermal exploration activities in the Mount Princeton-Chalk Cliffs area, probably the most extensively explored geothermal area in Colorado. Amax Exploration Company drilled about 40 geothermal gradient holes there from 1973 to 1975. Mount Princeton Geothermal LLC, in partnership with the Colorado School of Mines, CGS, and Colorado Governor's Energy Office, conducted geologic, geochemical, and geophysical studies and drilled some geothermal gradient holes in the Mount Princeton-Chalk Cliffs area between 2006 and 2010. Magnetotelluric geophysical investigations were conducted for Mount Princeton Geothermal LLC in 2011 and 2012. These studies suggest there is a shallow lower temperature geothermal reservoir in the vicinity of the hot springs and possibly a deeper higher temperature target with 300°F temperatures at depths of 2,500 to 3,500 feet further east beneath the valley floor (Held and Henderson, 2012).

Initial geological and geophysical studies were also conducted between 2009 and 2011 at Poncha Hot Springs by the City of Salida, Hendco Services, CGS, Colorado School of Mines, and Colorado Governor's Energy Office (Held and Henderson, 2012). A magnetotelluric geophysical study was performed there in 2011 and 2012, which resulted in discovery of a low resistivity geothermal target about 1,600 feet deep. Easley et al. (2011) also describe some of the exploration work at Poncha Hot Springs and point out the presence of helium isotopes in the water, suggestive of a mantle-source gas signature.

All of the known springs and wells, as well as currently operating direct use sites (NREL, 2016) in Chaffee County are designated as H/D potential for direct use. Wells or springs with a temperature of >122°F have a 5 mile buffer zone that is H/D potential, as the U.S. EERE (2004) and NREL (2016) deem this the distance sufficiently hot waters can be transported for direct use. There is a small area west of Poncha Springs designated H/B due to the fact that the estimated temperature is above the 100°F threshold for low temperature and/or co-produced resources. The rest of Chaffee County outside the above-mentioned geothermal areas is considered M/B.

4.7.2 Gold

The first gold discoveries in Chaffee County were placers. The Cache Creek Park and Clear Creek Placers, as well as placers along the Arkansas River—notably Georgia Bar near the northern border with Lake County—were discovered in 1859 (Henderson, 1926). Placering in other creeks and gulches followed soon after, and the discovery of lode gold occurred around 1867 to 1868 (Koschmann and Bergendahl, 1968). Many districts are known to have produced gold in Chaffee County, but production was relatively small except for the Monarch-Garfield and Chalk Creek districts (Koschmann and Bergendahl, 1968). From 1859 to 1945, the county produced 290,749 ounces of lode gold and 77,976 ounces of placer gold (Vanderwilt, 1947). An additional 1,710 ounces were reported from 1946-1958 (Del Rio, 1960).

The Chalk Creek district lies along the upper reach of Chalk Creek near the Continental Divide on the east boundary of the county and the RGFO region. Dings and Robinson (1957) report production of 111,003 ounces of gold from 1901 to 1949, almost entirely from the Mary Murphy mine. Bedrock in the district is largely Tertiary quartz monzonite of the Mount Princeton batholith (Tweto, 1979a; Vanderwilt, 1947). Free gold was mined from primary and oxidized ore in polymetallic quartz veins in ore shoots up to 50 feet thick and 1 mile long (Dings and Robinson, 1957). The Chalk Creek district is designated H/D for gold occurrence potential.

The Monarch-Garfield district lies south of the Chalk Creek district near Monarch Pass. Though primarily a silver-lead-zinc district, 11,589 ounces of gold were produced from 1901 to 1949 (Dings and Robinson, 1957). The building of a railroad to the district in 1883 was a major factor in the growth of the mines; ten years later, the silver crash depleted the district but demand for zinc revived it once again around 1913 (Crawford, 1913). Over the life of the district the Madonna mine was the major producer, accounting for 50 percent of the district's production (Koschmann and Bergendahl, 1968). Bedrock geology of the district consists of Precambrian granites overlain by Paleozoic sedimentary rocks (Dings and Robinson, 1957; Vanderwilt, 1947). The sedimentary units are highly folded and faulted, with three significant northwest-trending faults, the Madonna, Lake and Mayflower faults, and numerous local faults (Crawford, 1913). Several Tertiary intrusives are found within and near the district, including the Mount Pomeroy and Mount Princeton quartz monzonite stocks as well as dikes (Dings and Robinson, 1957). Gold occurs in both bedded replacement deposits in limestone and veins in Precambrian gneiss, Paleozoic sedimentary rocks, and Tertiary intrusives (Davis and Streufert, 1990). The replacement deposits are the more productive of the two, and occur as mantos in limy beds, particularly the Manitou Dolomite (Dings and Robinson, 1957). The vein deposits occur mainly in the Mount Princeton quartz monzonite and occasionally in the adjacent Belden and Minturn Formations or Precambrian gneiss, with thicknesses from 1 to 4 feet and lengths up to 4,000 feet (Dings and Robinson, 1957). Both types of deposit are polymetallic with native gold occurring in the veins (Davis and Streufert, 1990). The Monarch-Garfield district is designated H/D for gold occurrence potential.

The Granite district extends into Lake County, and hosts two large mines: the Yankee Blade and Belle of Granite (Cappa and Bartos, 2007). Hedlund et al. (1983) estimate about 65,000 ounces of gold were produced from the Granite district, mostly in the 1800s from the Yankee Blade and Belle of Granite mines; Vanderwilt (1947) reports production of 788 ounces of lode gold in the Granite district between 1932 and 1945. Granite district geology is complex, with heavily faulted Boulder Creek- and Silver Plume-aged granites, as well as migmatites, amphibolites, and Tertiary rhyolite dikes associated with mineralization (Hedlund et al., 1983; Tweto, 1979a). The vein swarm on Yankee Blade Hill contains 19 veins in a 2,054-foot interval, with veins up to 3,000 feet long and 1-3 feet wide (Hedlund et al., 1983). The Granite district area is designated H/D.

The greater Turret district region contains gold in metamorphosed Precambrian sulfide deposits (Davis and Streufert, 1990; Sheridan et al., 1990). Several mines (e.g., Gold Bug, Golden Wonder, and Vivandiere) along Cat Gulch produced gold (up to 2 ounces per ton) from quartz veins related to a diorite porphyry dike (USGS MRDS, 2013). Southwest of Cat Gulch, several other mines produced mainly copper and zinc with a small amount (e.g., 0.02 ounce per ton at Sedalia mine) of gold (USGS MRDS, 2013; Vanderwilt, 1947). Turret district area geology is highly variable and includes the southern extreme of a quartz monzonite pluton and a metamorphosed and faulted sequence of Precambrian sedimentary and volcanic rocks that host stratabound exhalative sulfides (Sheridan and Raymond, 1978, 1984b; Heyl, 1964; Boardman, 1971). The greater Turret district area is designated M/D for gold occurrence potential. The area around the Sedalia mine is assigned L/C.

Four districts in central Chaffee County have produced minor gold from polymetallic veins in Precambrian granite: Free Gold and Four Mile districts lie east of the Arkansas River, and Cottonwood and Riverside districts lie west of the river (Davis and Streufert, 1990). The Winfield-La Plata district of northwestern Chaffee County produced gold from polymetallic veins in Laramide intrusives (Davis and Streufert, 1990). These districts were small producers of gold, with no more than a few hundred ounces reported (Vanderwilt, 1947). In the Riverside district, the Lienhart mine was the main producer from polymetallic veins in Tertiary granodiorite (Brock and Barker, 1972). The Trout Creek district, mainly known for its pegmatites, did produce a small amount of gold from 1932-1939 (Vanderwilt, 1947). All of these districts are designated as M/C.

The placers of Chaffee County include the Arkansas River, Brown's Canyon, Cache Creek, Clear Creek, Cottonwood, Free Gold, Lost Canyon, and Mt. Shavano placers (Davis and Streufert, 1990). Placer gold is sourced from various lode deposits, as well as glacial moraines in the upper creek valley (Parker, 1974). The traverse of the Arkansas River through the Granite district is designated H/D. Cache Creek is designated H/D in its lower reach near the Arkansas River within the Granite district and H/C in its upper reach due to past production. Cottonwood and Clear Creeks are designated M/C. Chalk Creek drains the productive Chalk Creek district and is designated M/B for gold potential. Brown’s Creek is assigned H/C in its lower reach near the Arkansas River. Historically and/or currently producing placers areas are considered H/C, due to documented occurrence and geologic setting. Areas with similar alluviums and glacial drift near to producing areas are designated as M/C. The Arkansas River outside these already designated areas is assigned M/B for potential. Alluviums outside these areas are designated L/B.

In the remainder of Chaffee County, the areas surrounding historic mining districts and including rocks of Precambrian metamorphic basement and Tertiary intrusives are considered M/C where there are recorded gold occurrences in the USGS MRDS (2013). The same rocks outside documented gold occurrences are considered M/B or L/B.

4.7.3 Platinum-Group Metals

In Chaffee County, Eckel (1961) reports PGMs in placer deposits along the Arkansas River near Buena Vista. Peridotite dikes are reported by Hedlund et al. (1983) upstream near the Otero pump station and were noted to be extensively prospected, perhaps for PGM minerals. The occurrence potential for PGMs in the Arkansas River from the Otero Pump station to south of Buena Vista is L/B.

4.7.4 Silver

Production of 5.4 million ounces of silver was reported from Chaffee County between 1859 and 1958 (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). Dings and Robinson (1957) report production of 971,118 ounces of silver from 1901 to 1949 from the Mary Murphy group of mines in the Chalk Creek district. The Chalk Creek mineralization is found in pyritic quartz veins that fill faults and fissures in the Mount Princeton quartz monzonite (Dings and Robinson, 1957). The Chalk Creek district is designated H/D for silver occurrence potential. Tertiary intrusives peripheral to the district with past producers are designated H/C and those with minor occurrences are assigned M/C.

Dings and Robinson (1957) report production of almost 1.1 million ounces of silver between 1901 and 1949 in the Monarch-Garfield district, chiefly from the Madonna group of mines. Silver occurs primarily in bedded replacement deposits in Paleozoic dolomitic limestone of the Manitou and Fremont Formations and secondarily in veins in Precambrian felsic gneiss, Paleozoic sedimentary rocks, and Tertiary intrusives (Davis and Streufert, 1990; Dings and Robinson, 1957). In this district, the tenor of the ore from samples varied widely, ranging from 5 to over 5,000 ounces of silver per ton (Dings and Robinson, 1957). The Monarch-Garfield district area is designated H/D for silver occurrence potential. Precambrian metamorphic rocks surrounding the district are assigned M/C for silver potential.

To the northwest, the La Plata/Winfield district had minor production of silver from veins in the Tertiary Twin Lakes porphyry (Vanderwilt, 1947). The Twin Lakes porphyry is designated H/C for silver potential. Mineralized veins of the Laramide Whitehorn quartz monzonite porphyry stock host assorted precious and base metals, including silver (Vanderbilt, 1947). The Whitehorn stock is assigned an occurrence potential of M/C.

There are numerous silver occurrences and minor past producers found in Precambrian felsic metamorphic rocks in proximity to faults, some of which occur in association with stratabound exhalative sulfides (Sheridan et al., 1990). Smaller silver production is reported from the Granite (439 ounces), Riverside (4,196 ounces), and Turret (100 ounces) districts (Vanderwilt, 1947). Buffers around these occurrences are designated M/C for silver occurrence potential. Precambrian felsic metamorphic rocks elsewhere in the county are assigned M/B. Anomalous "redbed-type" concentrations of silver are noted from the Pennsylvanian Minturn Formation, and this unit is designated L/B for silver occurrence potential. About 914 ounces of placer silver was recovered in Chaffee County from 1909 to 1945 (Vanderwilt, 1947); like in Lake County, from which it flows, the Arkansas River is assigned L/C for silver potential.

4.7.5 Copper-Lead-Zinc

Chaffee County has been a significant source of base metals, producing 10.1 million pounds of copper, 133.7 million pounds of lead, and 30.9 million pounds of zinc during the years 1859 to 1958 (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). Most of the historic districts have been small producers, but along the southwestern border of the county the Chalk Creek and Garfield-Monarch districts dominated production.

From 1901 to 1949, the Chalk Creek district (chiefly the Mary Murphy mine) was attributed with 1.4 million pounds of copper, 18.7 million pounds of lead, and 14.5 million pounds of zinc (reported as gross metal content by Dings and Robinson, 1957). The Chalk Creek mineralization is found in pyritic quartz veins (up to a mile long and 10 feet thick) that primarily fill faults and fissures in the Mount Princeton quartz monzonite (Dings and Robinson, 1957). Principal ore minerals include galena, sphalerite, and some chalcopyrite; oxidized ore minerals include cerussite and smithsonite (Dings and Robinson, 1957). Though the Chalk Creek district is classified H/D for base-metal occurrence, the Mary Murphy mine dominated production, and potential in the rest of the district may be unequally distributed.

The Garfield-Monarch district **(**primarily the Garfield and Madonna mines) produced 372,220 pounds of copper, 1.1 million pounds of lead, and 694,500 pounds of zinc (Vanderwilt, 1947). The Garfield-Monarch mineralization was accomplished by replacement of Paleozoic carbonates (especially the Manitou Formation dolomite); lenses and pods occur along bedding faults, or grains are disseminated (Dings and Robinson, 1957). Productive ores from the Madonna mine are mostly oxidized and include cerussite, galena, smithsonite, and some malachite (USGS MRDS, 2013). Garfield mine ores occur mostly in marbleized Manitou Dolomite at or near the contact with the Silver Plume Quartz Monzonite and include sphalerite, galena, and chalcopyrite as well as copper, lead, and zinc oxides (Dings and Robinson, 1957). The Garfield mines produced 372,220 pounds of copper, 579,624 pounds of lead, and 1.7 million pounds of zinc between 1901 and 1949 (Dings and Robinson, 1957). The Cinderella and nearby mines, just to the southeast of the Garfield-Monarch district, are classified by Sheridan et al. (1990) as Type 1 Precambrian exhalative sulfide deposits and are past producers. The Garfield-Monarch district, as well as the area around the Cinderella mine, is designated H/D due to favorable geologic environment (polymetallic replacements and veins) as well as past production.

In the southeastern portion of the county, the Turret district has limited potential production, although the nearby Sedalia mine was once the largest copper mines in Colorado. The Turret district produced 5,700 pounds of copper but no lead or zinc (Vanderwilt, 1947). Operations at the Sedalia mine occurred between 1881 and 1923 (Heinrich, 1981). Lindgren (1908) reports production of 60,000 to 75,000 tons of 5 percent copper ore, averaging 400 tons per month at the time of publication. The Turret district (e.g., the Copper King and Independence mines) and Sedalia mine are categorized as copper-zinc skarns developed mainly in amphibolites and secondarily in gneisses and schists, by Heinrich (1981). Sheridan et al. (1990) classify it as a Type 1 (upper-amphibolite facies) Precambrian exhalative sulfide deposit. A distinguishing characteristic of Precambrian sulfide ores in this area is the considerable manifestation of the zinc spinel, gahnite (Heinrich, 1981; Sheridan and Raymond, 1984b). The Sedalia deposit displays massive replacement of the amphibolite host and contains an extraordinary variety of base-metal ore minerals, including the chief producers, chalcopyrite and sphalerite, as well as gahnite, galena, covellite, chalcocite, cerussite, smithsonite, chrysocolla, cuprite, azurite, and malachite (Heinrich, 1981). Production potential at the Sedalia mine was estimated by Sheridan and Raymond (1984b) at a million tons of 4 percent copper and 6 percent zinc ore plus some lead. The Turret district and Sedalia mine are H/D due to recorded historic production as well as favorable geologic environment.

To the south of the Turret / Sedalia area lies the Cleora district which hosts a distinct type of skarn containing both copper and tungsten. In Colorado, copper, copper-zinc, and tungsten skarns are typical; a tungsten-copper skarn is unusual (Heinrich, 1981). The copper-tungsten mineralization occurs in quartzose veins as large as 3 feet wide by 200 feet long and in metasomatized amphibolite within a gneissic host (Heinrich, 1981). In the district, the Stockton mine (Gertrude vein) was the largest producer, and ore minerals include chalcopyrite, chrysocolla, cuprite, and scheelite (USGS MRDS, 2013). Sheridan et al. (1990) classify the Stockton mine tungsten-copper deposits as Type 4: pre-metamorphic veins containing tungsten +/- copper. Cleora is designated H/C for occurrence potential.

The overlapping Granite, Hope, and Lost Canyon districts in northern Chaffee County (shared with Lake County) produced 11,150 pounds of lead and 865 pounds of copper, according to Vanderwilt (1947), during the years 1932 to 1945. Past production of secondary ores of copper, lead, and zinc are reported at the Washington, Majenta, and New Year mines. Pyritic quartz veins in Precambrian gneiss contain gold, galena, chalcopyrite, and sphalerite. The Granite-Hope district is considered M/C for base-metal occurrence potential.

The Riverside (Mount Harvard) district was attributed with 9,220 pounds of copper and 48,750 pounds of lead (Vanderwilt, 1947). The Wapaca, Mt. Harvard, and Tamarack mines were past producers of copper and lead sulfides (some copper oxides) associated with quartz veins in Precambrian gneiss or granite (USGS MRDS, 2013). To the northwest, the La Plata / Winfield district had past production of silver with minor production of base-metal sulfides (mostly galena) associated with Tertiary intrusives (Vanderwilt, 1947). Due to production, the La Plata / Winfield and Riverside districts are designated H/D.

The Gladstone mine in the Cottonwood district of western Chaffee County had minor past production (4,810 tons of 1-2 percent lead ore) in quartz-sulfide veins and that area is designated H/C (U.S. Bureau of Mines, 1989). The redbeds of the Minturn and other Paleozoic rocks are noted for anomalous copper concentrations (e.g., Wallace et al., 1997; Wallace and Keller, 2003) and are designated H/B. The Calumet mine lies on the border region of the Tertiary Whitehorn Granodiorite and the Minturn/Belden Formations, and is a primary producer of iron with some copper (chalcopyrite). The area around the Calumet mine is H/C. Vanderwilt (1947) notes there are small veins that carry base metals in the Whitehorn stock in nearby northwesternmost Fremont County, so the Calumet district (continuous with the Whitehorn district in Fremont) is designated M/C; the Whitehorn Granodiorite elsewhere is M/B. In the remainder of Chaffee County, the areas surrounding historic mining districts and including rocks of Precambrian basement and Tertiary intrusives are considered M/C where there are recorded copper-lead-zinc occurrences in the USGS MRDS (2013). The same rock types outside the documented copper-lead-zinc occurrences are M/B.

4.7.6 Iron

Iron was mined in the Turret district of Chaffee County at the Calumet-Hecla-Smithville group of magnetite mines beginning in 1882 (Harrer and Tesch, 1959). The mine produced an estimated $11 million worth of iron ore by 1900 (Osborn and Rainwater, 1934). Magnetite and hematite, as masses, and pyrite as veins, occur as replacements of mostly carbonates in a contact metamorphic zone where the Upper Cretaceous-Tertiary Whitehorn stock (Calumet granodiorite) intruded the Mississippian Leadville Dolostone (Behre et al., 1936; Wrucke, 1974). The magnetite ore body is about 50 feet thick, 500 feet wide, and at least 1,800 feet long; early ores assayed up to 60.9 percent iron (Harrer and Tesch, 1959). With depth, ore increased in pyrite (sulfur) and decreased in percentage iron (43 percent), and future mining would likely require extensive beneficiation (Harrer and Tesch, 1959). The Turret district area is designated H/D for iron occurrence potential. The contact region between the Whitehorn stock and Leadville Dolostone where no mines occur is assigned H/B; the Whitehorn stock and Leadville Dolostone elsewhere are assigned L/B for iron potential.

The Boss Lake group of iron mines host magnetite as replacement deposits where Tertiary intrusives contact the Leadville Dolostone and Belden Shale in the Garfield-Monarch district (Harrer and Tesch, 1959). Samples assayed 64.2 percent iron, and although no production is reported, some magnetite is stockpiled on the property (Harrer and Tesch, 1959; USGS MRDS, 2013). A buffer around this occurrence is designated M/C.

Iron-bearing minerals (especially magnetite and pyrite) are reported in polymetallic veins, pegmatites, and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks in the county are designated L/B for iron occurrence potential.

4.7.7 Manganese

Manganese oxides, including psilomelane and pyrolusite, fill fractures in Paleozoic sedimentary rocks and aplites from the Cleora to Turret districts (Taylor et al., 1984). Limited production was reported from manganese deposits, estimated at a few tons to a few thousand tons of ore, in limestone at the Liberty Hill claims north of Salida (Jones, 1920). At the Black Beauty Deposit, Black Jack Group, and Venture Lode mine, pyrolusite and rhodonite occurs with iron in a breccia zone between Tertiary igneous and Paleozoic sedimentary rocks (USGS MRDS, 2013). Manganese oxide ore replaces limestone at the Victory mine about 10 miles northwest of Salida (Wells et al., 1952). Psilomelane occurs with tungsten at the Sage claim, northeast of Salida, in fractures of a breccia zone associated with the Oligocene Antero Formation (USGS MRDS, 2013). Black manganese oxides are associated with numerous fluorspar deposits of the nearby Browns Canyon district (Van Alstine and Cox, 1969; Wallace 2010). Also, Jones (1920) reports some production in nearby Wellsville (Fremont County). The area around the Browns Canyon, Turret, and Cleora districts, including Salida, are designated H/C for manganese potential.

Elsewhere, manganese occurs in gangue from metallic ores of the Grizzly Peak Caldera Complex in northwestern Chaffee County, including the Red Mountain and La Plata-Winfield districts. Rhodochrosite is widespread in Laramide intrusive rocks at the Banker mine in the La Plata-Winfield district (Eckel, 1961; USGS MRDS, 2013). Rhodonite and rhodochrosite occur as intergrowths with quartz in Tertiary intrusive rocks at the Mary Murphy and nearby mines of the Chalk Creek district (Eckel, 1961). Massive manganese oxides, in association with Tertiary intrusives in Paleozoic sedimentary rocks, are reported from the Delaware and Rainbow-Eagle mines of the Monarch district (Crawford, 1913; Dings and Robinson, 1957). Hübnerite ($MnWO_4$) in quartz veins occur in a Tertiary quartz-monzonite porphyry in the Mount Aetna pegmatite mining district (Dings and Robinson, 1957). Tertiary igneous rocks throughout Chaffee County, including the Red Mountain, La Plata-Winfield, Cottonwood, Mineral Basin, Chalk Creek, Mount Antero, and Garfield-Monarch districts are designated M/C for manganese potential.

4.7.8 Molybdenum

Numerous claims and prospects of molybdenum are found within and adjacent to the plutons associated with the Grizzly Peak Caldera Complex, which spans southwestern Lake and northwestern Chaffee Counties in the RGFO region, as well as southeastern Pitkin and northeastern Gunnison Counties (Fridrich et al., 1998; USGS MRDS, 2013). Several mining companies drilled potential targets in the Red Mountain and La Plata-Winfield district areas (Gese and Scott, 1993; Ranta, 1974; U.S. Bureau of Mines). Anomalous molybdenite mineralization was realized around the East (Chaffee County) and West (Gunnison County) Red Mountain area, especially near quartz-latite and rhyolite dikes (Gese and Scott, 1993). Results suggest that both the Winfield Peak and Middle Mountain areas host a buried Climax-type molybdenum deposit (U.S. Bureau of Mines, 1989). The Tertiary intrusions of northwestern Chaffee County are designated H/C for molybdenum occurrence potential.

West-central Chaffee County, including the Cottonwood, Mineral Basin, Chalk Creek, Mount Antero, and Garfield-Monarch districts, is underlain by Tertiary intrusives as well, and is host to another dozen molybdenum occurrences (USGS MRDS, 2013). The California claims along Browns Creek valley produced some low-grade molybdenum ore during WW I (Dings and Robinson, 1957). Streaks of molybdenite up to 2 inches thick and 2 feet long and occasional pods weighing up to 30 pounds occur in and alongside veins in the Mount Pomeroy quartz monzonite (Dings and Robinson, 1957; Eckel, 1961). Taylor et al. (1984) postulate molybdenum porphyry deposits at depth in and adjacent to the Tertiary Mount Antero granite pluton and the Mount Princeton batholith (especially in proximity to the Mount Aetna quartz monzonite porphyry dike) due to the presence of anomalous molybdenum and beryl in veins and dikes (e.g., California mine). The Tertiary intrusions of west-central Chaffee County are designated H/C for accumulation of molybdenum.

Molybdenite is reported from a copper-zinc skarn (Independence mine) in a shear zone in Precambrian gneiss adjacent to the Boulder Creek quartz monzonite. (Heinrich, 1981). The boundary along the Boulder Creek and metamorphic unit, including the Independence mine area, is assigned M/C for molybdenum potential. Tertiary intrusive rocks elsewhere in the county are M/B. Precambrian igneous and metamorphic rocks in the rest of the county are assigned L/B.

4.7.9 Nickel

The Copper King mine in the Jones Mountain district, south of the Mineral Basin district, is situated in Precambrian granite (Boulder Creek) and is listed as a past producer of nickel (Dunn, 2003; USGS MRDS, 2013). Nickel is reported as a tertiary commodity at the Little Guy molybdenum mine located near the boundary of Boulder Creek Granite and Tertiary intrusives east of the La Plata-Winfield district (USGS MRDS, 2013). Anomalous concentrations of nickel were reported from assays of the Bonus Group pegmatites in Boulder Creek Granite along Longs Gulch northwest of Salida (Wallace et al., 1997). Small buffers around these occurrences are

M/C for nickel potential. Precambrian metamorphic and igneous rocks elsewhere are designated L/B.

4.7.10 Tungsten

There are a couple dozen mines or occurrences of tungsten in Chaffee County, primarily in the Cleora district, although production was minor. Heinrich (1981) reports eight tungsten-copper skarn deposits in the Cleora district, but only one reported production (Stockton mine). The skarns occur as tabular, east-northeast trending veins in amphibolite, and one deposit, 3 feet wide by 200 feet long, fills a shear zone in gneiss (Heinrich, 1981). Other deposits are lensoid, often concentrated near pegmatites, and, per Heinrich (1981), are “genetically linked to the Boulder Creek Granite.” Sheridan et al. (1990) classify the Stockton mine deposit as Type 4, pre-metamorphic veins containing tungsten and/or copper in association with stratabound exhalative deposits. This type of tungsten vein system may indicate the presence of a larger, concealed stratabound deposit (Sheridan, et al., 1990).

Southwest of the Cleora district, the Poncha Pass district has several occurrences of tungsten as scheelite including the Poncha Pass and Lucky claims. Sheridan et al. (1990) classify the Poncha Pass claim as a Type 3, stratabound exhalative deposit bearing tungsten +/- copper; Heinrich (1981) classifies both deposits as tungsten skarns and notes the Poncha Pass claim occurs as a 2-foot-wide zone in amphibolite. Both occur in areas of Boulder Creek Granite but neither claim has reported economical production.

Minor tungsten occurrences are noted in early Precambrian gneiss in proximity to Tertiary intrusives (Belser, 1956). Hübnerite-bearing quartz veins occur in a Tertiary quartz-monzonite porphyry in the Mount Aetna pegmatite mining district (Dings and Robinson, 1957). A few prospects occur in veins of sedimentary units near the Turret district. The tungsten occurrence potential around the Cleora district is considered H/D. Areas of Precambrian metamorphic and igneous rocks with MRDS (2013) tungsten occurrences (e.g., Poncha Pass district) are considered M/C. Areas with the same rocks without occurrences are designated L/B.

4.7.11 Beryllium

Through 1963, production of beryl from pegmatites in Chaffee County amounted to 49,805 pounds (Meeves et al., 1966). Crystals of the beryllium silicates, beryl, phenakite (Be_2SiO), aquamarine ($Be_3Al_2(SiO_3)_6$), and bertrandite, are found in abundance near the peaks of Mount Antero and White Mountain (Adams, 1953; Eckel, 1961). At the Atlas Group mines (White Mountain) and the Mount Antero claims, the crystals occur in cavities and veins of granite and quartz monzonite related to the Tertiary Princeton batholith intrusive complex (Adams, 1953). Several elliptical bodies 10 feet wide by 50 feet long, composed locally of 90 percent beryl by volume, are found on the southwest slopes of Mount Antero (Dings and Robinson, 1957). Beryllium-bearing quartz veins of the nearby California mines occur in Tertiary Mount Pomeroy quartz monzonite, also related to the Princeton batholith (Adams, 1953). The Mount Antero district area is assigned H/D for beryllium potential, with a buffer zone of H/C around it. Rocks related to the Princeton intrusive complex surrounding this area are M/B.

Beryllium production through 1963 amounted to 25,489 pounds from pegmatites of the greater Turret district (Hanley et al., 1950; Meeves et al., 1966). Numerous beryllium-bearing pegmatite prospects occur near the contact of Boulder Creek batholith facies granite and Precambrian gneiss (Tweto, 1979a; USGS MRDS, 2013). The greater Turret district is designated H/C for beryllium potential. North of the Turret district, beryllium potential is considered M/C for the Trout Creek Pegmatites district, where beryl and gadolinite have been reported in Boulder Creek batholith facies granite. Precambrian granitic rocks in the rest of the county are considered L/B for beryllium potential.

4.7.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Chaffee County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Production of 30.9 million pounds of zinc between 1859 and 1958 is reported in Chaffee County; sphalerite ore is commonly found at the many zinc mines (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.7.13 Rare Earth Elements

In Chaffee County, rare-earth minerals were reportedly mined from beryl-bearing pegmatites along faults in Precambrian Boulder Creek Granite or Idaho Springs Formation gneiss in the Turret district area, but no production statistics are available (Leibold et al., 1986). One or more rare-earth minerals, including allanite, euxenite, gadolinite, monazite, and xenotime are reported from a half dozen pegmatite mines in the greater Trout Creek Pegmatite district (Adams, 1968; Hanley et al., 1950; Haynes, 1960; Olson and Adam, 1962; USGS MRDS, 2013). Euxenite masses up to 8 inches in diameter are reported from pegmatites in Boulder Creek Granite at the Yard and Clara May mines in this area (Eckel, 1961; Hanley et al., 1950; Heinrich, 1957). Buffers around these areas are designated M/C for REE occurrence potential.

4.7.14 Niobium-Tantalum

Precambrian crystalline rocks in the Turret and Trout Creek districts of Chaffee County host beryl-bearing pegmatite deposits, some of which host columbite and tantalite as accessory or trace elements (Heinrich, 1957; Meeves et al., 1966). About 1,100 pounds of niobium and tantalum were produced as byproducts in Chaffee County, chiefly from diorite pegmatite dikes in Boulder Creek Granite and Idaho Springs Formation banded gneiss in the Turret district, through 1963 (Meeves et al., 1966; Van Alstine and Cox, 1969). Based on specific gravity measurements, beryl samples from the northeast-trending Bonus Extension pegmatite zone contains up to 35 percent Ta_2O_5 (Van Alstine, 1974). Euxenite masses up to 8 inches in diameter are reported from pegmatites in Boulder Creek Granite at the Yard and Clara May mines in the Trout Creek Pass area (Eckel, 1961; Hanley et al., 1950; Heinrich, 1957). Beryl-bearing pegmatites in Mount Antero Granite (e.g., California vein) host minor microlite and columbite (Dings and Robinson, 1957; Sharp, 1976; USGS MRDS, 2013). The block of Precambrian rocks that host the Turret district pegmatites is designated M/C for niobium-tantalum occurrence potential. A buffer around the Trout Creek pegmatite district is designated L/C, and another around the Mt. Antero pegmatite zone is assigned L/B.

4.7.15 Tellurium

There is no reported production of tellurium in Chaffee County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.7.16 Titanium

Precambrian northwest-trending, mafic dikes in Larimer and Boulder Counties host titaniferous magnetite, and one titanium occurrence is noted in Larimer County (Eggler, 1968; USGS MRDS, 2013). Buffers along two Precambrian mafic dikes in eastern Chaffee County are designated L/B for titanium potential.

4.7.17 Uranium

No uranium production is reported for Chaffee County; however, over a dozen uranium occurrences are described in the literature (Nelson-Moore et al., 1978; USGS MRDS, 2013). Most of these occurrences are associated with prospects or mines that produced base and/or precious metals in the Mosquito Range on the east side of the Arkansas River (Nelson-Moore et al., 1978). Several mines and prospects are in veins or pegmatites in Precambrian rocks, and some are near contacts between Precambrian or Tertiary rocks and Paleozoic sedimentary rocks, including Ordovician-Mississippian carbonate units (Nelson-Moore et al., 1978). Grab samples from these occurrences assayed up to 2.99 percent U_3O_8 (at the Swiss Boy and Silver Crop mines in Tertiary monzonite stock of the Twin Lakes pluton in the Grizzly Peak Caldera Complex) although averages were much lower (Nelson-Moore et al., 1978). Buffers around all occurrences are designated L/C for uranium occurrence potential.

Tertiary siliceous tuffs are source rocks for uranium leached and reprecipitated in nearby fractures and faults (Olson, 1988). Production of nearly 500 pounds of uranium is reported from seams associated with the Chester group of faults underlying Tertiary tuffs in Saguache County; these faults extend into Chaffee County (Nelson-Moore et al., 1978). The D and J ore body hosts uranium in this unit in the Marshall Pass area, although production quantities were not made public. Mineralized veins of the Laramide Whitehorn quartz monzonite porphyry stock host assorted precious and base metals, with reports of uranium (Nelson-Moore et al., 1978; Vanderbilt, 1947). Tertiary intrusives in Chaffee County are designated L/B for uranium occurrence potential.

4.7.18 Thorium

Feldspar pegmatites in Precambrian Boulder Creek Granite host thorium in the Trout Creek Pegmatite and Turret districts of Chaffee County (Hanley et al., 1950; Nelson-Moore et al., 1978). Monazite and masses of euxenite up to ten inches thick are sporadically distributed throughout the pegmatites and likely can only be economically recovered as secondary commodities to feldspar (Hanley et al., 1950). Thorium occurs with REEs and uranium at the Lucky John 2 mine which is developed in a northeast-trending mafic dike that intruded Precambrian granite; samples assayed 0.54 to 0.74 percent ThO_2; no production is noted (Nelson-Moore et al., 1978). Buffers along faults in these areas are designated L/C for thorium occurrence potential.

4.7.19 Vanadium

There is no vanadium production reported for Chaffee County, but Nelson-Moore et al. (1978) report that samples collected from a dump at the Gold Bug claim, which is developed in a northwest-trending mafic porphyry dike in Precambrian Boulder Creek Granite, contained 0.05 percent V_2O_5. Buffers along several Tertiary dikes in the Boulder Creek Granite in this area are designated L/B for vanadium occurrence potential.

Vanadium is reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in Park, Fremont, and Custer Counties; samples assayed up to 0.59 percent V_2O_5 (Nelson-Moore et al., 1978; Schwochow and Hornbaker, 1985; USGS MRDS, 2013). The Minturn Formation is assigned L/C for vanadium occurrence potential.

Significant uranium and vanadium production is reported from the Eocene Echo Park Formation and overlying Oligocene Tallahassee Creek Conglomerate in Fremont County (Nelson-Moore et al., 1978). The few small remnants of Echo Park Formation and Tallahassee Creek Conglomerate in Chaffee County are designated H/C for vanadium potential.

4.7.20 Fluorspar

Average abundance of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, as well as in some Tertiary intrusives, all of which are found in Chaffee County (Wallace, 2010). The Browns Canyon district was one of the nation's largest producers of fluorspar from 1927 until 1949. Massive, white, fine-grained, or botryoidal fluorite occurs in fissure veins up to 40 feet wide and traceable for 400 feet that fill faults between the Precambrian Boulder Creek Granite, Precambrian hornblende gneiss, and

Tertiary rhyolite porphyry (Brady, 1975; Del Rio, 1960; Vanderwilt, 1947; Wallace, 2010). About 130,000 tons of metallurgical-grade (about 85 percent CaF_2) fluorspar was produced (Brady, 1975). The area around the Browns Canyon district is designated H/D for fluorspar occurrence potential.

Countless miarolitic cavities in pegmatites host gem-quality minerals including fluorite and fluorite-bearing topaz in the upper 500 feet of the Tertiary Princeton granitic batholith at the peaks of Mount Antero, Mount White, and Baldwin (Carbonate) Mountain in Chaffee County (Adams, 1953; Eckel, 1961; Heinrich, 1957; Pearl, 1972; Wallace, 2010). Well-formed, octahedral, dodecahedral, or twinned, pale green to purple fluorite crystals up to 6 inches in diameter have been found (Pearl, 1972). Non-gem-quality fluorite is also found for about 2,500 feet below this zone in pegmatitic schlieren (Eckel, 1961). Buffers around these peaks are designated H/C for fluorspar occurrence potential; a band of Tertiary rocks around this area is assigned H/B for fluorspar potential.

Fluorite occurs in the lithophysae of Tertiary rhyolite on Ruby, Bald, and Sugarloaf Mountains, as well as Dorothy Hill, all near Nathrop (Eckel, 1961; Pearl, 1972; Wallace, 2010). These four Nathrop Domes are composed of peraluminous to metaluminous flow-banded, fluorine-enriched topaz rhyolite intruded into Precambrian Boulder Creek Granite; fluorine abundance averaged 1,080 ppm, and related volcanic rocks (obsidian, perlite, and vitrophyre) measured up to 5,500 ppm (Wallace, 2010; Wegert et al., 2013). Buffers around these four rhyolite domes are designated H/C for gemstone occurrence potential.

Fluorspar has been mined (especially in the 1940s) about 1 mile southeast of the community of Poncha Springs and in the vicinity of Poncha Pass (east of U.S. Highway 285). White and light purple fluorite occurs in veins up to a few feet thick and coats breccia in faults between Precambrian hornblende gneiss and Tertiary intrusives (Brady, 1975; Wallace, 2010). A few other prospects are developed in Precambrian Boulder Creek Granite, biotite gneiss, and Tertiary intrusives (USGS MRDS, 2013). Outside of the Browns Canyon area, Precambrian igneous rocks are designated H/C and Precambrian biotite gneiss is assigned M/C for fluorspar occurrence potential. Precambrian hornblende gneiss is assigned M/C in the area of fluorine prospects and M/B elsewhere for fluorspar potential. Tertiary intrusives hosting fluorine prospects in northwestern Chaffee County are designated M/C for fluorine potential.

4.7.21 Diamond and Gemstones

Countless small pegmatites bearing miarolitic cavities hosting gem-quality beryl (especially aquamarine, as well as phenakite and bertrandite), smoky quartz, clear quartz, fluorite, garnet (spessartite), and topaz occur in the upper 500 feet of the Tertiary Princeton granite batholith at the peaks of Mount Antero, Mount White, and Baldwin (Carbonate) Mountain in Chaffee County (Adams, 1953; Eckel, 1961; Heinrich, 1957; Pearl, 1972). Aquamarine crystals, some a deep-blue color weighing up to 12 carats, and yellow twinned phenakite crystals up to 2 inches thick have been recovered (Pearl, 1972). Single, clear, prismatic quartz crystals up to 5.5 inches in diameter, smoky quartz crystals weighing up to 50 pounds, and beryl crystals up to 7 inches long are also reported (Eckel, 1961). Well-formed, octahedral, dodecahedral, or twinned, pale green to purple fluorite crystals up to 6 inches in diameter have been found (Pearl, 1972). Gemstones of lesser quality are also found for about 2,500 feet below this zone in pegmatitic schlieren (Eckel, 1961). Aquamarine and beryl are reported from veins and dumps of the California molybdenum workings near the head of Browns Creek in the same area (Pearl, 1972). This region is designated H/D for gemstone occurrence potential. West of Mount Antero, pink rhodochrosite crystals have been recovered from the Mary Murphy group of mines developed in the Princeton batholith (Eckel, 1961). The Princeton batholith in the area surrounding the Mount Antero region is assigned M/C for gemstone potential. In the nearby Monarch district north of Garfield, massive to crystalline almandine commonly occurs in a contact-metamorphic zone in the vicinity of Taylor Mountain and near the head of Taylor Gulch (Eckel, 1961); this area is assigned M/C for gemstone potential.

Deep-red to cinnamon-brown gem-quality dodecahedral or trapezohedral spessartite crystals occur in the lithophysae of Tertiary rhyolite on Ruby, Bald, and Sugarloaf Mountains, as well as Dorothy Hill, all near Nathrop (Eckel, 1961; Pearl, 1972). These four Nathrop Domes are composed of peraluminous to metaluminous flow-banded “topaz rhyolite” characterized by fluorine enrichment (Wegert et al., 2013). Apache tears (gem-quality black obsidian) and prismatic wine-yellow topaz with common double terminations are also found (Eckel, 1961; Pearl, 1972). Buffers around these four rhyolite domes are designated H/D for gemstone occurrence potential.

Many beryl-bearing pegmatites, some also hosting garnet, quartz, and tourmaline, occur near the contact of Precambrian Boulder Creek granite and Idaho Springs felsic gneiss in the Turret district north of Salida (USGS MRDS, 2013). Beryl crystals 1 foot thick and 8 feet long have been recovered from the Rock King prospect developed at the contact of Boulder Creek Granite and Leadville Limestone; 3,287 pounds of beryl were produced (Hanley et al., 1950; Pearl, 1972). Deep-blue gem sapphire (corundum), epidote crystals up to 2 inches long, and grossular (garnet) are reported from a contact metamorphic zone in Paleozoic sedimentary rocks (Leadville Limestone?) and Whitehorn Granodiorite at the Calumet iron mine (Pearl, 1972; USGS MRDS, 2013). Bright-blue, foot-long beryl crystals have been recovered from the Combination pegmatite (Hanley et al., 1950; Pearl, 1972). Greenish-blue, euhedral beryl crystals up to a foot long were reported from the Mica-Beryl mine; 500 pounds of beryl were produced (Hanley et al., 1950). Beryl crystals up to a foot in diameter and 3 feet long were reported from the Bonus Extension group of mines (Meeves et al., 1966). Well-formed dodecahedral almandine crystals weighing 15 pounds, as well as apple-green chrysoprase, are known from the Sedalia mine, developed in Precambrian felsic schist about 3.5 miles southwest of the Turret district cluster of mines (Eckel, 1961; Pearl, 1972). The greater Turret district area is designated H/D for gemstone occurrence potential.

Abundant rose quartz, chalcedony, green, and purple fluorite, tourmaline, and red and yellow jasper are reported from pegmatites in Boulder Creek granodiorite in the Trout Creek Pass region, notably at the Clora May, Luella, and Yard group of mines (Eckel, 1961 Pearl, 1972). This region is designated H/C for gemstone occurrence potential.

Abundant rhodochrosite crystals occur in veins of Laramide intrusive rocks at the Banker molybdenum and bismuth mine in the Winfield district (Eckel, 1961); a buffer around this mine is designated M/C for gemstone occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks are designated L/C, and biotite gneisses and schists are assigned L/B, for gemstone occurrence potential (Lovering and Goddard, 1950). The lower occurrence potential of gemstones in Precambrian metamorphic rocks of Chaffee County compared to other counties (e.g., Boulder or Clear Creek) is due to the relative lack of known gemstone, beryl, and fluorite prospects and commercially developed pegmatites in these rocks outside the greater Turret district area. The Precambrian Boulder Creek Granite and Cretaceous Whitehorn stock, which are relatively devoid of pegmatites, are designated L/A for gemstone occurrence potential (Boos, 1954).

4.7.22 Pegmatite Minerals

Meeves et al. (1966) reports production of 787 tons of scrap mica and 7,970 pounds of sheet mica from pegmatites in Chaffee County through 1963. The Turret Mining district hosts the largest concentration of pegmatites in the county, which were primarily mined in the 1940s for feldspar and mica (Martin, 1993). The Homestake mine pegmatite was once the largest source of feldspar (albite) in Colorado (Pearl, 1972). Production at the Homestake mine amounted to 95,588 tons of feldspar from zoned pegmatites near the contact of Boulder Creek batholith-aged granite and Precambrian felsic gneiss (Baillie, 1962; Tweto, 1979a). The nearby Last Chance Spar-Mica Dyke prospect had a few hundred tons of reported production of feldspar (microcline) through 1962 (Baillie, 1962).

The Trout Creek Pass district hosts a cluster of feldspar- and mica-bearing pegmatites in Precambrian Boulder Creek batholith-aged granite. Feldspar crystals up to 14 feet long and biotite books 2 feet thick are reported at the Clora May mine (Hanley et al., 1950). Hanley et al. (1950) estimated reserves of feldspar at 1,000 tons apiece at the Crystal #8 and Clora May mines.

Clusters of feldspar- and mica-bearing pegmatites in the greater Turret and Trout Creek districts are designated H/D for pegmatite mineral occurrence potential. Elsewhere in the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are assigned L/B for pegmatite mineral potential. Switzer (1939), Adams (1953), Dings and Robinson (1957), Del Rio (1960) and Sharp (1976) have described the geology and mineralogy of the pegmatite deposits within the Tertiary Princeton batholith intrusive complex in the Mount Antero and Chalk Creek districts region. Though no production of feldspar or mica is reported, the Tertiary rocks of this region are designated M/B for pegmatite mineral occurrence potential.

4.7.23 Industrial Abrasives

Countless small pegmatites bearing miarolitic cavities hosting gem-quality minerals including garnet (spessartite) occur in the upper 500 feet of the Tertiary Princeton batholith granite at the peaks of Mount Antero, Mount White, and Baldwin (Carbonate) Mountain (Adams, 1953; Eckel, 1961; Heinrich, 1957; Pearl, 1972). The region around these peaks is designated H/C for industrial abrasive occurrence potential. In the nearby Monarch district just north of Garfield, massive to crystalline almandine and andradite commonly occurs in a contact-metamorphic zone (Paleozoic limestone and Precambrian granite) in the vicinity of Taylor Mountain and near the head of Taylor Gulch (Eckel, 1961). A buffer along this contact is assigned M/C for industrial abrasive potential.

Many garnet-bearing pegmatites, some also hosting gemstones, occur near the contact of Precambrian Boulder Creek granite and Idaho Springs felsic gneiss in the greater Turret district area north of Salida (USGS MRDS, 2013). Masses of grossular are found in a contact metamorphic zone in Paleozoic limestone and Whitehorn granodiorite at the Calumet iron mine (Eckel, 1961; Pearl, 1972; USGS MRDS, 2013). Blue rhombohedral plates of corundum occur in schist in this area, and some production was reported for its use as an abrasive (Eckel, 1961). Well-formed dodecahedral almandine crystals weighing up to 15 pounds, as well as some corundum, are reported from the Sedalia mine, developed in Precambrian felsic schist about 3.5 miles southwest of the Turret district cluster of pegmatites (Eckel, 1961; Pearl, 1972). Masses of garnet are sporadically distributed at the Combination, Last Chance, and Rock King prospects (Hanley et al., 1950). The greater Turret district region is designated H/D for industrial abrasive occurrence potential.

Abundant spessartite crystals, many gem-quality, occur in the lithophysae of Tertiary rhyolite on Ruby, Bald, and Sugarloaf Mountains, as well as Dorothy Hill, all near Nathrop (Eckel, 1961; Pearl, 1972). These four Nathrop Domes are composed of peraluminous to metaluminous flow-banded “topaz rhyolite”, characterized by fluorine enrichment (Wegert et al., 2013). Buffers around these units are designated H/C for industrial abrasive occurrence potential.

Pegmatites hosting garnet and gemstones occur in Boulder Creek granodiorite in the Trout Creek Pass region, notably at the Crystal No. 8, Clora May, Luella, and Yard group of mines (Eckel, 1961 Pearl, 1972). This region is designated H/C for industrial abrasive occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks and the Cretaceous Whitehorn stock, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.7.24 Limestone and Dolomite

In Chaffee County, there are two limestone quarries developed in Paleozoic limestone units, including the undifferentiated Leadville, Williams Canyon, and Manitou Limestones and the Minturn and Belden Formations (USGS MRDS, 2013). The Leadville group of limestones has historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). The Leadville limestone group is designated H/D for limestone and dolomite occurrence potential in the area of known occurrences and H/C elsewhere. The Pennsylvanian Minturn and Belden Formations hosts one limestone prospect and is designated L/C for limestone potential throughout the county.

4.7.25 Industrial Sand

Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in the RGFO region, including one at the confluence of Trout Creek and the Arkansas River in Chaffee County; a buffer along this portion of the river is assigned M/C for industrial sand potential.

4.7.26 Gypsum

Productive gypsum quarries in nearby western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation, equivalent to the Chubb evaporite member in South Park (Brill, 1952). Minturn gypsum is known from the Swissvale, Badger Creek, Howard, and Coaldale areas of the Arkansas River corridor in Fremont County, and this unit extends into Chaffee County (Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). Vanderwilt (1947) mentioned reports of gypsum of unknown quality and quantity in Chaffee County; however, there are no USGS MRDS (2013) prospects noted. In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential; the evaporite facies of the Minturn Formation is designated M/C.

4.7.27 Sand and Gravel

There are several USGS MRDS (2013) sand and gravel occurrences and DRMS-permitted quarries developed in Quaternary deposits, principally along the Arkansas River corridor, in Chaffee County. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which is more deeply weathered and friable, as well as glacial drift (Qd), are assigned H/C for potential (Arbogast et al., 2011). A few sand and gravel prospects occur along Trout Creek (USGS MRDS, 2013); a buffer around these prospects is assigned L/C for sand and gravel potential.

4.7.28 Crushed Stone Aggregate

Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures, with no deleterious chemical constituents (Knepper et al., 1999). Dense limestones and dolomites comprise about 70 percent of production nationwide (Langer and Knepper, 1995; Knepper et al., 1999). Cambrian to Mississippian limestones and quartzites, mapped as MC or MDO in Chaffee County, are assigned H/D in areas with developed operations and H/C elsewhere, for crushed stone potential.

Tertiary intrusive rocks occur throughout the county; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz, which is detrimental to cement-making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Tertiary intrusive rocks are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The typically weathered, foliated, and jointed Precambrian Boulder Creek Granite is classified as a 'fair' source rock by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Boulder Creek Granite is assigned M/C for crushed stone aggregate potential. Precambrian biotite schist (Idaho Springs Formation) is assigned L/B, felsic and hornblendic gneisses are assigned H/B, and undivided metamorphic rocks are assigned M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian Minturn and Tertiary Dry Union Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). These sedimentary rocks are assigned L/B for crushed stone aggregate occurrence potential.

4.7.29 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the mountains of Colorado, including in Precambrian igneous and metamorphic rocks of Chaffee County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). There are several past DRMS-permitted vermiculite operations developed in these rocks (Del Rio, 1960). The relatively unweathered Cretaceous Whitehorn Granodiorite is designated L/B, and the more weathered Precambrian Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Significant outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite; pumice occurs at Ruby Mountain near Nathrop (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

The Pennsylvanian Minturn and Tertiary Dry Union Formations bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

4.7.30 Clay

There is no reported clay production in Chaffee County; however, poor quality alluvial clay is reported from a gravel pit along a tributary to Cottonwood Creek (Patterson, 1968; USGS MRDS, 2013). Abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). The undifferentiated Minturn and Belden Formations and mapped Quaternary unit around the gravel pit are designated L/B for clay occurrence potential.

4.7.31 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Chaffee County hosts granites, sandstones, and limestones that have potential to be quarried for dimension stone, including the Precambrian Silver Plume Granite, Cambrian to Mississippian sedimentary rocks, and Tertiary intrusives (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

Production of dimension stone is reported from the Cretaceous Whitehorn Granodiorite, chiefly for monuments and memorial stones (Schwochow, 1981; Sharps, 1963). Rose pink granite, which was carved to create the Mormon Battalion Monument in Salt Lake City, was produced from the Whitehorn Granodiorite near Cameron Mountain (Keller and Widmann, 2002). The Silver Plume Granite has been quarried for dimension stone in other counties, although where weathered, fractured, or highly jointed, granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Silver Plume Granite is designated H/C, and the Whitehorn Granodiorite is designated H/D, for dimension stone potential. The older and more weathered Boulder Creek Granite is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Production is reported from the Sawatch Quartzite, Manitou Formation, and Leadville Limestone in several counties from undifferentiated Cambrian through Mississippian limestones, dolomites, and sandstones that are mapped as MDO or MC (Del Rio, 1960; Schwochow, 1981; Tweto, 1979a). Crawford (1913) describes a gray to dark-blue, fine- to coarse-grained quartzite, likely to take a polish and suitable for monumental dimension stone, in the Garfield district along Taylor Gulch; marble is also reported. Partially metamorphosed and marbleized Leadville Limestone is quarried in Pueblo, Fremont, and Chaffee Counties; stone from the ‘Beulah marble’ in Pueblo County adorns the Colorado State Capital building (Arbogast et al., 2011; Schwochow, 1981). The Cambrian to Mississippian mapped units (MDO or MC) in Chaffee County are designated H/D for dimension stone potential. The Pennsylvanian Minturn Formation hosts numerous sandstone and limestone beds throughout its extent, but there are no reports of dimension stone production from this unit (Arbogast et al., 2011; Cappa and Bartos, 2007); this unit is assigned M/B for dimension stone potential.

The Tertiary Princeton batholith intrusive complex, composed of quartz monzonite and granite, underlie Mounts Princeton and Antero, White Mountain, and Baldwin (Carbonate) Mountain (Adams, 1953; Crawford, 1913; Dings and Robinson, 1957). Crawford (1913) reports the quartz monzonite is suitable for dimension and building stone due to a favorable texture, composition, color, and likely the ability to take a polish, with the added benefit of only moderate jointing and faulting, allowing for larger blocks to be quarried. At least one past DRMS permit to quarry granitic dimension stone in the Mount Antero region was issued. Granitic rocks related to the Princeton batholith intrusive complex are assigned H/B for dimension and building stone occurrence potential.

The Tertiary Wall Mountain Tuff is a welded rhyolitic ash-flow tuff that occurs as isolated remnants in Chaffee County (Arbogast et al., 2011; Del Rio, 1960; Scarbrough, 2001; Tweto, 1979a). The deposits have been quarried in Douglas County for high-quality dimension and building stone (Del Rio, 1960). The Wall Mountain Tuff is designated H/D for dimension stone potential; other Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.8 Cheyenne County

4.8.1 Geothermal

Traditional / EGS Geothermal

The majority of Cheyenne County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The whole county does have moderate favorability for EGS (Augustine, 2011), so the western portion that was analyzed by the USGS (2008) is considered M/B.

Direct-Use / Low Temperature Geothermal

Cheyenne County contains no known springs or wells. The majority of Cheyenne County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas of Cheyenne County are designated as H/C. The entirety of the county is above the 100°F temperature threshold for low temperature and co-produced resources.

4.8.2 Uranium

There is no recorded production of uranium in Cheyenne County; however, several occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.8.3 Limestone and Dolomite

There are no limestone prospects in Cheyenne County, but the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). Limited outcrops of the Niobrara Formation occur in the southernmost part of the county; the Niobrara Formation is assigned M/D for limestone and dolomite occurrence potential.

4.8.4 Industrial Sand

Widespread Quaternary eolian sands in Cheyenne County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County; however, no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications;

however, several past and current DRMS-permitted industrial sand operations are noted in this and other counties; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no occurrences noted in Cheyenne County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.8.5 Helium

As of December of 2016, there was one helium refining plant, operated by DCP Midstream, in Cheyenne County (USGS MYB, 2014). This plant likely was producing from the Las Animas Arch gas field given its location, although it is on the Wattenberg pipeline, meaning it may be refining helium out of gas from the Mid-Continent. The Bledsoe Ranch oil and gas field on the northwest flank of the Las Animas Arch in northwestern Cheyenne County tested positive for 1.9 percent helium (Sonnenberg and von Drehle, 1990). Lower BTU values (possibly indicating higher helium concentrations) occur along the northern “nose” of the Las Animas Arch anticline, and particularly along the Brandon sub-axis (Sonnenberg and von Drehle, 1990). As most of the county is part of the northern anticline, it is all designated H/D for helium potential, except for the extreme northeastern corner.

4.8.6 Sand and Gravel

High-quality sand and gravel deposits in Cheyenne County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). This unit is designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in this and other counties (W. D. Carter, 1968); this unit is considered M/D for sand and gravel potential in Cheyenne County.

4.8.7 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Cheyenne County; however, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Ogallala Formation is assigned L/B for crushed stone aggregate occurrence potential.

4.8.8 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in the RGFO region from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Ogallala Formation is designated M/C, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.8.9 Clay

There are no USGS MRDS (2013) or DRMS clay occurrences in Cheyenne County; however, the Cretaceous Pierre Shale and Niobrara Formation crop out in parts of the county. The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it elsewhere (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Smoky Hill Member of the Niobrara Formation has produced some low-grade clay in other counties (Arbogast, 2011; Patterson, 1968). The Pierre Shale is designated H/C, and the Niobrara Formation is designated M/C, for clay occurrence potential.

4.8.10 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Cheyenne County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). Small outcrops of the Cretaceous Niobrara Formation occur on the county's southern border; the Fort Hays Member has been sporadically quarried for limestone dimension stone in other counties (USGS MRDS, 2013). The Ogallala Formation is designated L/B, and the Niobrara Formation is designated L/C, for dimension and building stone occurrence potential.

4.9 Clear Creek County

4.9.1 Geothermal

Traditional / EGS Geothermal

The majority of Clear Creek County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the southwest is considered M/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Three springs and one well exist in the Idaho Springs area with temperatures ranging from 68 to 115^{o}F (NREL, 2016). All are associated with the Indian Springs resort. The source of the geothermal waters is thought to be faults in Precambrian crystalline rocks (Repplier et al., 1982). The Precambrian rocks are locally are intruded by Tertiary granitic dikes typical of the CMB, which are several times more radioactive than other typical granites (Wells, 1960), suggesting radioactive decay potentially may be the source of the heat. The most thorough investigation of the Indian Springs area by Repplier et al. (1982) was unable to confidently determine the source of the geothermal waters or the total size of the resource area; in general they concluded that the waters were likely of meteoric origin, controlled by faults, and that the thermal system was probably localized.

Electrical resistivity and soil mercury studies were conducted by Repplier et al. (1982). Due to anthropogenic and topographic complications, the resistivity study was of limited use. A significant mercury anomaly was detected, although it was uncertain whether it was related to the geothermal system or to mineralization in the bedrock. Geothermometry estimates of the subsurface reservoir temperatures by Barrett and Pearl (1978) ranged from 138 to 448^{o}F, but they questioned the validity of the results because some of the assumptions in the model were apparently violated.

All of the wells and the direct use site of the Indian Hot Springs are designated as H/D potential for direct use. About ¾ of Clear Creek County is considered M/B for low temperature and/or co-produced geothermal resources. The southern, western, and eastern margins of Clear Creek County are designated as M/C, as those areas are above the 100°F temperature threshold for low temperature and co-produced resources.

4.9.2 Gold

One of the first major gold finds in Colorado occurred in Clear Creek County on April Fools' Day in 1859, when placer gold was found at Idaho Bar where Chicago Creek flows into Clear Creek at the present site of Idaho Springs (Henderson, 1926). Not long after, lode gold was discovered nearby (Voynick, 2002). Over 17 million ounces of gold were produced from 1859 through 1958 in Clear Creek County (Del Rio, 1960; Lovering and Goddard, 1950; Vanderwilt, 1947). Placer gold production in the county amounted to about 140,000 ounces between 1859 and 1945 (Vanderwilt, 1947).

The greater Idaho Springs district, comprising several smaller subdistricts, including Virginia, Jackson Bar, and Ohio, is located in northeastern Clear Creek County and is host to a series of ore bodies that extend into the Central City district of Gilpin County. Early on, the lode mines were largely deserted after the oxidized ore was depleted, but mining was rejuvenated with the opening of a mill in Blackhawk in 1868 capable of economically processing the more complex ores. Gold production generally declined after 1942. The geology of the greater Idaho Springs district consists of interlayered Precambrian gneisses and migmatitic gneisses intruded by Boulder Creek Granodiorite and Silver Plume Granite (Moench et al., 1962). Mineralization in the district consists of polymetallic veins, some rich in gold (Wells, 1960). The greater Idaho Springs district is credited with production of over 5.2 million ounces of lode gold and 111,000 ounces of placer gold between 1932 and 1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). The gold occurrence potential of this region is considered H/D due to historic gold production. An area bordering the district to the east is assigned H/C due to limited gold occurrences; further east to the county border is assigned M/B where the area is devoid of occurrences.

In the greater Lawson-Dumont district area, including the Montana, Downieville, and Coral (Cascade) subdistricts, placer deposits at the junction of Fall River and Clear Creek initiated activity in 1859, followed shortly by the discovery of gold-bearing oxidized veins near Dumont. Boulder Creek Granite and Silver Plume Granite intrude Precambrian biotite or felsic gneisses and schists, and Tertiary polymetallic and pyritic quartz veins host gold and occupy fissures and fractures in the Precambrian rocks (Hawley and Moore, 1967). Base-metal mineralization is spatially related to Tertiary porphyries (Hawley and Moore, 1967). Native gold occurs in minimal amounts and in places is coarse-grained due to supergene enrichment where veins are oxidized (Hawley and Moore, 1967). Production of 3,248 ounces of lode gold is reported from this area between 1932 and 1945 by Vanderwilt (1947); Hawley and Moore (1967) report production of 10,009 ounces of gold between 1901 and 1952 from a couple dozen mines from this district. The greater Lawson-Dumont-Fall River district is designated H/D for silver potential.

Harrison and Wells (1956) credit the Freeland-Lamartine district area of central Clear Creek County with production of about 100,000 ounces of gold between 1905 and 1953. The geology is composed of Precambrian biotite schists and gneisses to the northwest and Boulder Creek Granite to the southwest, both intruded by Precambrian quartz diorite, pegmatites and Silver Plume Granite. Tertiary dikes and plugs of quartz monzonite, alaskite, and bostonite characterize the district and are associated with the gold and sulfide deposits. Mineralization is concentrated in pods or lenses at the intersections of pyritic quartz veins near porphyritic intrusives (Harrison and Wells, 1956). The most extensively worked mine is the Lamartine group, located in1867, which is credited with production of over 78,000 ounces of gold through 1952 (Harrison and Wells, 1956). The Freeland-Lamartine district is designated H/D.

Lode gold was discovered in the greater Georgetown-Silver Plume (Griffith) district in 1859. Like elsewhere in the county, the geology consists of Precambrian biotite gneisses and granite of the Silver Plume batholith (Tweto, 1979a). Tertiary stocks and dikes of various compositions are abundant. Gold mineralization occurs primarily in pyritic quartz veins along a northeast-trending gold belt a mile wide, bounded by similarly trending silver belts to the northwest and southeast (Spurr et al., 1908). Production of 27,807 ounces of lode gold is credited to the district from 1907 to 1945 (Lovering and Goddard, 1950; Vanderbilt, 1947). The potential for gold occurrence in this area is assigned H/D due to historic mine production and favorable geology.

The Empire district, north of the Georgetown district, is credited with production of over 90,000 ounces of gold between 1932 and 1945 (Vanderwilt, 1947). Davis and Streufert (1990) estimate production at over 500,000 ounces of gold in the greater Empire district from 1862 to 1990. Numerous mines and prospects were worked within and adjacent to Precambrian quartz monzonite porphyritic intrusions associated with Boulder Creek-aged granite (Spurr et al., 1908; Tweto, 1979a; USGS MRDS, 2013). The region around the Empire district is designated H/D for gold occurrence potential.

The greater Alice-Yankee Hill-Lincoln district area, shared with Gilpin County, has several lode and placer gold occurrences noted for past production (USGS MRDS, 2013). Production of 702,214 ounces of gold is reported between 1932 and 1945 from this district, primarily from the Alice mine, which first opened in 1883 (Lovering and Goddard, 1950; Vanderwilt, 1947). Precambrian biotite schists and gneisses are intruded by Boulder Creek Granodiorite and a Tertiary stock of quartz monzonite. Gold-bearing stockworks in the quartz monzonite were the most productive, along with pyritic quartz veins in the Precambrian rocks (Lovering and Goddard, 1950). Lovering and Goddard (1950) also point out that significant promise remains for a large volume of sulfide ore south of the Alice mine beneath glacial debris. The greater Alice-Yankee Hill-Lincoln district area is designated H/D for gold occurrence potential.

Southwest of Georgetown, the Peru-Argentine district crosses the Continental Divide in southwestern Clear Creek County into adjacent Summit County, mostly on Kelso and McClellan Mountains (Lovering and Goddard, 1950). The geology is characterized by Silver Plume Granite, Tertiary Montezuma quartz monzonite stock and dikes, and rhyolite and dacite intrusions in Precambrian schists and gneisses. Production of about 17,514 ounces of gold is reported from polymetallic veins of sphalerite-galena-pyrite-chalcopyrite plus silver minerals (Lovering and Goddard, 1950; Vanderwilt, 1947). The Peru-Argentine district is designated H/D for gold occurrence potential.

A few minor past producers and occurrences of gold are noted around the Dailey (Atlantic) and Geneva Creek districts. These districts are designated H/C for gold occurrence potential. A belt in the western county from the border with Summit County to the border with Gilpin County devoid of gold occurrences is designated H/B due to proximity to the CMB and producing gold mines, as well as favorable geology. An east-trending portion of the county adjacent to the CMB and producing districts with several minor gold occurrences is designated M/C for gold potential due to favorable geology but limited production. A small portion of the Pikes Peak batholith, assigned M/B in multiple counties for sporadic gold occurrence, is found in the southeastern corner of the county.

4.9.3 Platinum-Group Metals

Platinum was reported by Eckel et al. (1997) in the Centennial mine of the Georgetown district and as a placer of native platinum in black sands in Clear Creek. Both of these occurrences were reported before 1920, and there were no reports of PGMs from Clear Creek County in Peterson (1994). Therefore, the occurrence potential for PGM is assigned L/C for the Georgetown district in Clear Creek County.

4.9.4 Silver

Clear Creek County has been the largest producer of silver in Colorado, with more than 61 million ounces produced between 1866 and 1958 (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). The general history and geology of the gold- and silver-bearing districts are discussed above in the gold section (4.9.2) of this county's MPR.

The greater Idaho Springs district area is credited with production of over 4.3 million ounces of silver between 1904 and 1959 (Moench, 1966). Polymetallic, lead-silver, and gold-silver telluride veins associated with Tertiary porphyries and plutons fill faults and fissures in interlayered Precambrian felsic and biotite gneisses and pegmatites of the Idaho Springs Formation (Lovering and Goddard, 1950; Moench et al., 1962). As is true in the rest of the county, most veins trend northeast along with the porphyry dikes and intersect Precambrian northwest-trending faults (Moench, 1966). The greater Idaho Springs district area is designated H/D for silver occurrence potential.

Harrison and Wells (1959) report production of 1.1 million ounces of silver from the Chicago Creek mining district. This district is underlain by Precambrian biotite gneiss, Boulder Creek Granite/Granodiorite, and Silver Plume Quartz Monzonite (Harrison and Wells, 1959; Tweto, 1979a). Ore-bearing pyritic quartz or lead-silver veins strike northeast, most in association with numerous Laramide porphyry dikes, within all foundation rocks throughout the district (Harrison and Wells, 1959). The Chicago Creek district is designated H/D for silver occurrence potential.

Bordering the Chicago Creek district, the greater Freeland-Lamartine district area is credited with production of 3.28 million ounces of silver the between 1868 and 1953 (Harrison and Wells, 1956). The chief producer was the Lamartine mine, where an estimated 2.68 million ounces of silver were produced from 12 miles of workings along the Lamartine vein (Harrison and Wells, 1956). Silver was mined primarily from lead-silver veins, and to a much lesser extent from pyritic quartz veins, as well as oxidized zones (Harrison and Wells, 1956). The host rocks are Precambrian biotite gneiss and schist, as well as Silver Plume and Boulder Creek Granites, and the most productive ore bodies occur as pods or lenses where veins intersect (Harrison and Wells, 1956). The greater Freeland-Lamartine district area is designated H/D for silver occurrence potential.

Hawley and Moore (1967) report production of 973,993 ounces of silver from over a dozen of the largest mines in the greater Lawson-Dumont district area, including the Montana, Downieville, Morris, Mill Creek, Fall River, and York Gulch districts, from 1904 to 1952. Pyritic quartz, polymetallic, and lead-silver veins fill northeast- or northwest-striking faults and fissures formed in Precambrian biotite or felsic gneisses (Idaho Springs Formation) and Tertiary stocks during the Laramide orogeny; ore is concentrated at intersections (Hawley and Moore, 1967). Argentite, cerargyrite, polybasite, proustite, tennantite, and native silver have all been reported from this district (Hawley and Moore, 1967). The greater Lawson-Dumont district area is designated H/D for silver occurrence potential.

Production of 1.3 million ounces of silver is credited to the Argentine-Peru district from 1869 to 1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). Polymetallic and lead-silver veins strike northeast in association with quartz monzonite porphyry dikes related to the Montezuma quartz monzonite stock in Precambrian biotite or felsic gneisses and schists (Lovering and Goddard, 1950; Tweto, 1979a). The greater Argentine-Peru district area is designated H/D for silver occurrence potential.

To the north of the Argentine-Peru district, the greater Georgetown-Silver Plume-Griffith district area is credited with production of 3.4 million ounces of silver between 1907 and 1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). The Silver Plume Granite forms stocks and dikes in the Precambrian felsic and biotite gneisses and schists of the Idaho Springs Formation, and both are intruded by Laramide quartz monzonite porphyry stocks and dikes (Lovering and Goddard, 1950). Silver ore is most heavily concentrated along two flanking belts of a northeast-trending, mile-wide gold belt, which also hosts minor silver (Lovering and Goddard, 1950). Silver-bearing pyritic quartz and lead-silver veins follow the trend of northeasterly to northwesterly trending porphyries and average 20 to 30 ounces of silver per ton, whereas oxidized zones host ores ranging up to 300 ounces of silver per ton (Lovering and Goddard, 1950). The greater Argentine-Peru district area is designated H/D for silver occurrence potential.

Elsewhere in the county, the Empire-Union district area is credited with extraction of 20,000 ounces of silver between 1932 and 1945 (Vanderwilt, 1947). Polymetallic veins host silver in

Precambrian Idaho Springs Formation, Boulder Creek Granite, and Silver Plume Granite in association with Laramide quartz monzonite stocks and dikes (Lovering and Goddard, 1950; Tweto, 1979a; USGS MRDS, 2013). Further north, the Alice-Yankee Hill-Lincoln district area produced 77,584 ounces of silver between 1933 and 1945 mostly from lead-silver veins in Precambrian felsic gneiss and schist (Lovering and Goddard, 1950). Vanderwilt (1947) reports production of 5,073 ounces of silver from the Geneva Creek district in the southwestern portion of the county. There are a few past producers noted on the USGS MRDS, 2013, all located in Precambrian biotite gneiss in proximity to a Tertiary pluton. The Empire and Alice district areas are designated H/D for silver occurrence potential, and the Geneva Creek district is assigned H/C. Favorable geologic units bordering the high potential areas in the county that have a few occurrences are assigned M/C; those units devoid of occurrences are M/B.

4.9.5 Copper-Lead-Zinc

Although better known for its gold and silver, Clear Creek County produced a considerable amount of base metals during the years 1859-1958, with about 15 million pounds of copper, 203 million pounds of lead, and 40 million pounds of zinc being reported between 1859 and 1958 (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). Clear Creek County lies mostly within the CMB and entirely within the Front Range Precambrian core complex. Precambrian gneisses, schist, granodiorite, quartz monzonite, and amphibolite predominate, although they are in places intruded by Tertiary bodies. Mineralization is restricted primarily to veins related to Laramide intrusions (Cappa et al., 2000).

The greater Idaho Springs district was the most productive region in the county. Vanderwilt (1947) reports production of 1.1 million pounds of copper, 7.3 million pounds of lead, and 706,955 pounds of zinc between 1932 and 1945. Chalcopyrite, galena, and sphalerite ores occur primarily in veins associated with granitic gneiss, pegmatites, and porphyry dikes, but a few productive bodies occur in breccia that have been cemented by ore minerals (Lovering and Goddard, 1950). Ore grades average 17 percent copper, 54 percent lead, and 32 percent zinc but vary considerably (Lovering and Goddard, 1950).

Hawley and Moore (1967) report production of 438,961 pounds of copper, 4.1 million pounds of lead, and 1.6 million pounds of zinc in the greater Lawson-Dumont district area, including the Montana, Downieville, Morris, Mill Creek, Fall River, and York Gulch districts, from 1901 to 1952. Three assays of massive galena from the Lawson-Dumont district showed 10.2 to 76.5 percent lead (Lovering and Goddard, 1950).

Production of about 500,000 pounds of copper, 12 million pounds of lead, and 1.6 million pounds of zinc is reported in the Freeland-Lamartine district by Harrison and Wells (1956). Precambrian biotite gneiss and schist, as well as Silver Plume and Boulder Creek Granites, host pyritic quartz, polymetallic, and lead-silver veins (Harrison and Wells, 1956). Bordering the Freeland-Lamartine district to the southeast, the Chicago Creek district area is credited with

46,000 pounds of copper, 1.3 million pounds of lead, and 500,000 pounds of zinc in a similar geologic setting from about 1885 through 1955 (Harrison and Wells, 1959).

The Griffith district, including Georgetown, Silver Plume, and Queens districts, produced 349,792 pounds of copper, 24.6 million pounds of lead, and 23.9 million pounds of zinc from 1932 to 1945 (Vanderwilt, 1947). Two base-metal ore types dominate this region: galena-sphalerite ore with subordinate chalcopyrite and gray copper, and pyritic ore with chalcopyrite and secondary galena and sphalerite (Lovering and Goddard, 1950). Ores occur in fissure vein complexes and porphyry dikes found in Precambrian gneiss (Idaho Springs Formation) that have been cut by Silver Plume Granite and Tertiary intrusives. Base-metal grades range widely from 2 to 50 percent lead and 4 to 40 percent zinc (Vanderwilt, 1947).

Other base-metal producing districts include the Peru-Argentine, which produced about 1.2 million pounds of copper, 15 million pounds of lead, and 135,453 pounds of zinc between 1869 and 1945 (Lovering and Goddard, 1950; Vanderwilt, 1947). The Alice-Yankee Hill district is credited with over 720,000 pounds of copper and 46,000 pounds of lead (Vanderwilt, 1947).

Precambrian rocks around the historic districts and within the CMB are designated H/D for base-metal occurrence potential. Rocks to the east with fewer MRDS (2013) reported occurrences are designated H/C. Southeast of the CMB, Precambrian rocks are assigned M/B, then L/B further southeast where there are no USGS MRDS (2013) occurrences; gneisses rank higher than granites for potential of sulfide deposits.

4.9.6 Iron

Bog-type iron deposits occur along the Geneva Creek valley where hydrous iron-oxides, chiefly limonite, have been (and continue to be) deposited in layers up to 15 feet thick from springs (Harrer and Tesch, 1959). An approximately 1.5-mile-stretch up to 500 feet wide was worked at the Iron Clad Placer (West Geneva Iron) deposit, and samples assayed 51 to 55 percent iron (Harrer and Tesch, 1959; USGS MRDS, 2013). The area along Geneva Creek is designated H/C for iron occurrence potential.

The Henderson porphyry molybdenum deposit, the product of at least 10 Oligocene rhyolitic intrusions into the Precambrian Silver Plume quartz monzonite, hosts magnetite as a primary accessory (Carten et al., 1988). The Henderson mine lists iron as a tertiary commodity, although no production statistics are provided (USGS MRDS, 2013). The greater Henderson mine group area is designated M/C for iron occurrence potential. The Silver Plume Granite elsewhere in the county is assigned L/B.

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). A buffer around two minor USGS MRDS (2013) iron past producers is assigned L/C, and Precambrian metamorphic rocks elsewhere are designated L/B for iron occurrence potential. The Pikes Peak batholith is designated L/B for iron potential due to sporadic occurrences in related rocks in other counties.

4.9.7 Manganese

Manganiferous ankerite is found in association with silver ore in a wide seam and other fissures of Silver Plume granodiorite at the Stevens (Banker) mine southeast of Georgetown (Lovering, 1935; USGS MRDS, 2013). Manganese carbonate ores are found in veins in numerous silver and gold mines (e.g., Griffith Lode and Cliff mine) around the Silver Plume-Georgetown district (Lovering and Goddard, 1950). Hübnerite ($MnWO_4$) in quartz veins occurs in Precambrian granite at the Henderson and Urad molybdenum mines of northwestern Clear Creek County and in Precambrian gneiss at the Puzzler mine (Lawson-Dumont district) (Theobald et al., 1983; USGS MRDS, 2013). The Silver Plume batholith, including the area around these mines, is considered M/C for manganese potential.

4.9.8 Molybdenum

Clear Creek County is the home of the world's largest primary molybdenum producer, the Henderson mine, operated by Climax Molybdenum Company in the Dailey (Atlantic or Jones Pass) district just west of Empire. The Henderson porphyry molybdenum deposit is the product of at least 11 Oligocene rhyolitic intrusions into the Precambrian Silver Plume quartz monzonite that make up the Red Mountain intrusive complex (Carten et al., 1988; Wallace et al., 1978). First discovered was the smaller and shallower Urad deposit, which yielded 14 million tons of 0.35 percent molybdenite (MoS_2) before being exhausted in 1974 (Carten et al., 1988). Production in the larger, deeper Henderson mine began in 1976 and yielded over 770 million pounds of 0.44 percent molybdenite from 1976 to 2003 (Climax Molybdenum, 2016). The nearby Puzzler vein assayed about 2 percent MoS_2 (Lovering and Goddard, 1950). The greater Red Mountain area is H/D for molybdenum potential; a buffer around this area where Silver Plume quartz monzonite could host related dikes and veins of the Red Mountain intrusive complex is H/C.

The Clifford mine (Eureka district) and Resolute Lode (Chicago Creek district) are listed as past producers of molybdenum, although no data are available (USGS MRDS, 2013). These sites occur in Tertiary polymetallic veins in Precambrian metamorphic rocks. Molybdenite is reported in six mines of the Lawson-Dumont district, occurring in Tertiary porphyry at the Mary mine and in pyritic quartz veins in Precambrian gneiss at the Dubuque mine (Hawley and Moore, 1967). Wulfenite crystals are reported in veins of the Silver Plume Granite at the Diamond mine in the overlapping Freeland-Lamartine district (Eckel, 1961; USGS MRDS, 2013). The Lawson-Dumont and Freeland-Lamartine districts area and a buffer around the Clifford mine and Resolute Lode are assigned M/C. In the remainder of the county, Tertiary intrusive units are M/B; Precambrian metamorphic and igneous rocks outside these areas are L/B.

4.9.9 Nickel

Anomalous concentrations of nickel are reported from assays of pitchblende in the Fall River and Lawson-Dumont districts (Hawley and Moore, 1967). Niccolite (NiAs) is found in pitchblende-bearing polymetallic veins in Precambrian biotite gneiss in the Almaden and Golconda mines of the Fall River district (Hawley and Moore, 1967). Precambrian metamorphic and igneous rocks throughout the county are designated L/B for nickel potential.

4.9.10 Tungsten

Tungsten was produced as a secondary or tertiary commodity at three molybdenum mines (Henderson, Urad, and Puzzler) in Clear Creek County (USGS MRDS, 2013). The Henderson and Urad mines, as well as another occurrence, are found in the Red Mountain area in the northwestern part of the county. The hübnerite-bearing quartz veins occur in Precambrian granite (Boulder Creek or Silver Plume Granite) and are associated with Tertiary intrusives, especially porphyries (USGS MRDS, 2013). The Puzzler mine, located in the Lawson-Dumont district, is developed in Precambrian gneiss. The Silver Plume batholith, including the area around these mines, is considered H/C for tungsten potential. The remainder of the county is assigned L/B.

4.9.11 Beryllium

Numerous Precambrian pegmatites hosting beryl, chrysoberyl, and bertrandite crystals, some as much as 1000 pounds, occur within the Clear Creek Pegmatite Province of northeastern Clear Creek County and neighboring southeastern Gilpin and western Jefferson Counties (Del Rio, 1960; USGS MRDS, 2013). Meeves (1966) reports 8,796 lbs. of beryl production through 1963 from mines in this district. This area is designated H/C for beryllium occurrence potential. Numerous pegmatites are recorded in the historic districts of Georgetown-Silver Plume, Freeland-Lamartine, and Chicago Creek with minor beryl and rare bertrandite, but no beryllium production is recorded. Granitic rocks throughout the county are assigned L/B for beryllium occurrence.

4.9.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Clear Creek County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Production of 40 million pounds of zinc was recorded between 1859 and 1958 in Clear Creek County; sphalerite ores from mineralized veins in Precambrian granitic rocks are commonly reported from the many zinc mines (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around clusters of known zinc mines or individual mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.9.13 Rare Earth Elements

Within the Clear Creek Pegmatite Province, spanning northeastern Clear Creek County into western Jefferson County, REE mineralization is present within beryl-bearing pegmatites in Precambrian Idaho Springs Formation gneiss, and some production is reported (Haynes, 1960; Meeves et al., 1966; USGS MRDS, 2013). Monazite occurs in zoned pegmatites at the Grover group of mines, and xenotime occurs in dikes at the Saddleback Mountain (Snyder) claims (Adams, 1968; Meeves et al., 1966; USGS MRDS, 2013). Allanite, gadolinite, and xenotime are reported from the Floyd Hill pegmatite claims (Haynes, 1960). A buffer around the Clear Creek Pegmatite Province area is designated M/C for REE occurrence potential.

Tertiary alkalic porphyries at the Henderson and Urad molybdenum mine complex are host to ubiquitous trace REEs (especially LREEs) in monazite, xenotime, aeschynite $(Y,Ce)(Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$, and fluocerite (Desborough and Mihalik, 1980). A buffer around the Henderson-Urad complex is designated L/C for REE potential. Trace REEs are found in Tertiary intrusive stocks of nearby Boulder and Gilpin Counties (Gable, 1984). Tertiary stocks are assigned L/B for REE potential.

4.9.14 Niobium-Tantalum

Meeves et al. (1966) report production of 188 pounds of niobium-tantalum minerals from pegmatites in Clear Creek County through 1963. The Clear Creek Pegmatite Province is home to thousands of pegmatites hosted by Precambrian Idaho Springs Formation gneiss and Boulder Creek Granite (Boos, 1954). Columbite, tantalite, microlite, samarskite, and euxenite are reported from several zoned beryl-bearing pegmatites in Idaho Springs gneiss of the Clear Creek Pegmatite Province (Hanley et al., 1950; Heinrich, 1957; Nelson-Moore et al., 1978). Buffers along pegmatite zones of the Clear Creek Pegmatite Province are designated M/C for niobium-tantalum occurrence. Geochemical analyses reveal that the Oligocene Henderson porphyry molybdenum intrusion into Precambrian Silver Plume quartz monzonite hosts ilmenorutile and aeschynite that are enriched in niobium and tantalum, although no production is reported (Carten et al., 1988; Desborough and Mihalik, 1980). The area around the Henderson complex is assigned L/C for niobium-tantalum potential.

4.9.15 Tellurium

Telluride minerals, including petzite, hessite, and sylvanite, have been identified in the Georgetown-Silver Plume, Argentine-Peru, and Idaho Springs-Central City districts (Eckel, 1961). Gold-telluride ore is reported from several mines in the Idaho Springs-Central City district (shared with Gilpin County). Due to these reports and significant gold and copper production, these districts, as well as a few others, are designated H/C for tellurium occurrence potential. Precambrian metamorphic rocks hosting numerous past producers of gold or copper are designated M/B. Precambrian rocks elsewhere in the county are assigned L/B for tellurium potential.

4.9.16 Titanium

Concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). Force (1976b) notes rutile routinely occurs in sillimanite zones of higher-grade metamorphic rocks. Samples up to 4.2 percent rutile are reported from a unit which is 11 to 100 feet thick, and sphene and ilmenite occur in the surrounding units (Sheridan et al, 1968.) Sheridan et al. (1968) determined that the concentration and purity of the rutile deems this occurrence worthy of further investigation as an ore of titanium. This unit, in the Clear Creek-Jefferson County border area, is designated H/C for titanium occurrence potential; elsewhere this unit is assigned L/B.

Ilmenorutile-rutile and titaniferous magnetite are all reported from the Henderson group of molybdenum mines in the Oligocene Henderson rhyolitic stockwork, which intruded the Precambrian Silver Plume Granite (Carten et al., 1988; USGS MRDS, 2013). The area around these mines is designated H/C for titanium occurrence potential.

4.9.17 Uranium

Numerous uranium occurrences and radioactive anomalies exist in Clear Creek County, but only 541 pounds of U_3O_8 production is reported (Nelson-Moore et al., 1978). Uranium is reported at 66 base- or precious-metal mines where mineralization occurs primarily in Tertiary veins in Precambrian crystalline rock (Nelson-Moore et al., 1978). Most of the produced uranium came from the Highlander (245 pounds) and Spanish Bar (196 pounds) mines, both in the greater Idaho Springs district area (Nelson-Moore et al., 1978). The Idaho Springs district area is designated H/C for uranium occurrence potential.

Numerous uranium occurrences, including the highly productive Schwartzwalder mine, are found along northwesterly trending Tertiary fault systems or breccia reefs in Boulder and Jefferson Counties, some of which extend into Clear Creek County (Nelson-Moore et al., 1978). A couple of uranium occurrences and radioactive anomalies (e.g., Beaver Brook), but no production, are reported along these breccia reefs in this county (Nelson-Moore et al., 1978; Sims and Sheridan, 1964). Buffers along these major faults are designated M/B for uranium occurrence potential in Clear Creek County. Elsewhere in the county, numerous base- or precious-metal mines report uranium occurrences or radioactive anomalies; buffers around these occurrences are assigned L/C for uranium potential.

4.9.18 Thorium

Although the USGS MRDS (2013) does not indicate any thorium occurrences in Clear Creek County, Nelson-Moore et al. (1978) report that the Grover pegmatite deposits in Precambrian metamorphic rocks contain monazite and samarskite. Buffers around faults in Precambrian metamorphic rocks, as well as around the Grover pegmatite deposits, are assigned L/B for occurrence potential.

4.9.19 Vanadium

In Clear Creek County, minor sporadic vanadium occurs in Tertiary polymetallic veins, pegmatites, and bostonite porphyry dikes intruded in Precambrian Idaho Springs Formation gneiss (Nelson-Moore et al., 1978). The only reported production is 4 pounds of vanadium recovered from 7 tons of 0.03 percent V_2O_5 ore at the Bonanza mine (Nelson-Moore et al., 1978). Buffers along mapped Tertiary dikes throughout the county are designated L/C for vanadium occurrence potential.

4.9.20 Fluorspar

In Clear Creek County, three prospects host green- to purple-colored fluorite in fissure veins and bostonite dikes that cut the Precambrian Silver Plume Granite; another fluorite prospect occurs in biotite gneiss (Aurand, 1920; Brady, 1975). The CMB in Clear Creek County is locally cut by northeast-trending porphyry dikes and northwest-trending faults and hosts numerous pegmatites, all in rocks known to host fluorite elsewhere (Goddard,1947). Also, fluorite mineralization in Tertiary alkalic porphyries associated with hydrothermal activity at the Henderson and Urad molybdenum mines is reported; two samples contained 44,000 and 75,000 ppm fluorine (Aurand, 1920; Cappa, 2007; Carten et al., 1988; Lüders et al., 2009; Theobald et al., 1983; Wallace, 2010). Average content of fluorine (ppm) in Central Colorado measured highest in Precambrian igneous rocks, followed by Precambrian metamorphic and Tertiary intrusive rocks (Wallace, 2010). Precambrian igneous rocks are designated H/C, Precambrian biotite gneiss and Tertiary intrusives are assigned M/C, hornblende gneiss is assigned M/B, and the Tertiary alkalic rocks near the Henderson mine are designated H/C for fluorspar occurrence potential.

4.9.21 Diamond and Gemstones

Countless pegmatites are known from the Clear Creek Pegmatite Province in northeastern Clear Creek County, some of which host gemstones. Beryl, aquamarine, amethyst, amazonite, garnet, and rose quartz have been recovered from numerous named pegmatites (Boos, 1954; Eckel, 1961). Beryl, garnet, topaz, and tourmaline are reported from the Jacobsen group of mines (USGS MRDS, 2013). The Santa Fe Mountain, Snyder, and Floyd Hill (Ajax) pegmatites are noted for aquamarine and massive rose quartz occurrences (Eckel, 1961; Scott, 1968a). Crossing the Jefferson-Clear Creek county line is a unique west-trending gneissic mineral belt about 7,000 feet long and up to 100 feet thick; significant amounts of rutile and topaz are found (Sheridan et al, 1968). The Clear Creek Pegmatite Province is designated H/D for gemstone occurrence potential.

Rhodochrosite and fluorite mineralization in veins and dikes associated with hydrothermal activity at the Henderson and Urad molybdenum mines is reported (Cappa, 2007; Carten et al., 1988; Lüders et al., 2009; Theobald et al., 1983). A buffer around this area is designated M/C for gemstone occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks outside of the Clear Creek Pegmatite Province are designated M/C for gemstone occurrence potential; biotite gneisses and schists are assigned M/B for gemstone potential in Clear Creek County (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954). Pegmatites are known to occur in the Silver Plume batholith; this unit and the correlative Indian Creek plutons in southeastern Clear Creek County are assigned L/B for gemstone potential (Boos, 1954; Boos and Aberdeen, 1940).

4.9.22 Pegmatite Minerals

The Clear Creek Pegmatite Province covers northeastern Clear Creek and west-central Jefferson Counties (Heinrich, 1957). These pegmatites produced commercial feldspar and scrap mica beginning in the 1890s (Hanley et al., 1950). Meeves et al. (1966) report historical production through 1963 for Clear Creek County of 5,208 pounds of sheet mica and 210 tons of scrap mica. Almost 51,000 pounds of scrap mica and 23,000 pounds of mine-run (book) mica were produced at the Ajax mica mine in the 1940s (Hanley et al., 1950). The Clear Creek Pegmatite Province is designated H/D for potential. Elsewhere in the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B.

4.9.23 Industrial Abrasives

Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Countless pegmatites are known from the Clear Creek Pegmatite Province in northeastern Clear Creek County, many of which host garnet (Boos, 1954; Eckel, 1961). Several past producers or prospects developed in tabular zoned pegmatites concordant with Precambrian gneissic layers note garnet as a primary or tertiary commodity (USGS MRDS, 2013). The Clear Creek Pegmatite Province is designated H/D for industrial abrasive occurrence potential. Clusters of garnet-bearing pegmatites occur near contacts of Precambrian igneous and metamorphic rocks in the combined Freeland-Lamartine-Chicago Creek and Georgetown-Silver

Plume districts (USGS MRDS, 2013). Precambrian schist hosting up to 50 percent industrial grade corundum is reported several miles east of Georgetown (Vanderwilt, 1947). Buffers around these pegmatite clusters and occurrences are designated H/C for industrial abrasive potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.9.24 Sand and Gravel

There are a few sand and gravel pits developed in Quaternary glacial drift (Qd) in Clear Creek County; this unit and Tertiary gravels (Tgv), are assigned H/C for potential (USGS MRDS, 2013). Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.9.25 Crushed Stone Aggregate

Tertiary intrusive rocks occur sporadically throughout Clear Creek County; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Laramide intrusive rocks meet the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999) and are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Silver Plume Granite is deemed an excellent source rock for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, weathered, foliated, and jointed Precambrian Boulder Creek-aged granites, like the Mount Evans batholith in Clear Creek County, are classified as only 'fair' source rocks by Knepper et al. (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Silver Plume Granite is designated H/C, and the Mount Evans batholith is assigned M/C, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

4.9.26 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the mountains of Colorado, including in Precambrian igneous and metamorphic rocks of Clear Creek County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The relatively unweathered Silver Plume, Indian Creek, and Pikes Peak granitic plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

4.9.27 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Clear Creek County hosts Precambrian igneous rocks that have been quarried for dimension stone, including the Pikes Peak, Silver Plume, and Indian Creek Granites (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Precambrian Pikes Peak and Silver Plume-aged granites have been quarried for good-quality dimension stone, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak, Indian Creek, and Silver Plume Granites are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. Scattered outcrops of Tertiary intrusives are assigned L/B for dimension stone potential.

4.10 Crowley County

4.10.1 Geothermal

Traditional / EGS Geothermal

The entirety of Crowley County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Crowley County contains one known well at Maurer Ranch with a reported temperature of 73°F (NREL, 2016). This well is designated as H/D for direct use. The rest of Crowley County is designated H/B for low temperature and/or co-produced geothermal resources.

4.10.2 Uranium

There is no recorded production of uranium in Crowley County; however, several occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.10.3 Limestone and Dolomite

There are no limestone prospects in Crowley County, but the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). The Niobrara Formation, found in the southeastern quarter of the county, is assigned M/D for limestone and dolomite occurrence potential.

4.10.4 Industrial Sand

Widespread Quaternary eolian sands in Crowley County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

4.10.5 Gypsum

No gypsum production is reported in Crowley County; however, very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation is barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-formation limestone beds of the Niobrara (Scott, 1969). The Niobrara Formation is designated L/B for gypsum occurrence potential in southeastern Crowley County.

4.10.6 Helium

The eastern part of Crowley County covers the western flank of the Las Animas Arch anticline. East Crowley County has an H/D designation for helium potential due to favorable geologic setting.

4.10.7 Sand and Gravel

High-quality sand and gravel deposits in Crowley County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

4.10.8 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Crowley County; however, the Fort Hays Member of the Cretaceous Niobrara Formation has been quarried for crushed limestone in other counties (Schwochow, 1981). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide (Langer and Knepper, 1995). The Niobrara Formation is designated M/C for crushed stone aggregate occurrence potential.

4.10.9 Lightweight Aggregate

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (mixed layer illite-montmorillonite) and may be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.10.10 Clay

There are no USGS MRDS (2013) or DRMS clay occurrences in Crowley County; however, the Cretaceous Pierre Shale and Niobrara Formation together cover about a third of the land surface. The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it elsewhere (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Smoky Hill Member of the Niobrara Formation has produced some low-grade clay in other counties (Arbogast, 2011; Patterson, 1968). The Pierre Shale is designated H/C, and the Niobrara Formation is designated M/C, for clay occurrence potential.

4.10.11 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Crowley County, the Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential.

4.11 Custer County

4.11.1 Geothermal

Traditional / EGS Geothermal

The entirety of Custer County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Custer County contains no known wells or springs. Custer County is designated as a mix of H/C and M/B for low temperature and/or co-produced geothermal resources, depending on if the predicted temperature for wells is above the 100°F threshold for low temperature and co-produced resources.

4.11.2 Gold

Custer County gold production, primarily from silver-gold lodes or lead-silver veins, amounted to 107,252 ounces between 1872 and 1958 (Del Rio, 1960; Vanderwilt, 1947). Davis and Streufert (1990) estimate production of 125,000 ounces of gold from the combined Rosita and

Silver Cliff districts between 1872 and 1990. The discovery of lode material in the Rosita Hills district in 1872 initiated activity in the area, followed by the 1874 Humboldt-Pocahontas vein discovery and the 1877 opening of the Bassick mine (Cross, 1896). Mineralization in the greater Rosita Hills district area, including Silver Cliff, Querida, and Hardscrabble districts, is controlled by faults and joints resulting from subsidence of the Tertiary caldera (Cappa, 1998). The Bassick mine was the largest producer in the district, occurring in a volcanic breccia pipe in the Rosita Andesite (Cappa, 1998). The Tertiary volcanics in this area are designated H/D for gold occurrence potential where the USGS MRDS (2013) reports mines and H/C in areas devoid of known gold occurrences.

To the northeast of the greater Rosita Hills district, a cluster of mines producing gold as a secondary or tertiary commodity from fractures and faults in Precambrian felsic and hornblendic gneiss is found (USGS MRDS, 2013). A buffer around this cluster is designated H/C. Precambrian felsic metamorphic rocks elsewhere contain some gold in thorium veins and exhalative sulfide deposits, and these rocks are assigned M/B (Christman et. al., 1953; Sheridan et. al., 1990).

In northwesternmost Custer County, the Big Horn and Cloverdale mines produced gold from fractures, likely related to the nearby Tertiary Rito Alto stock, in the Sangre De Cristo Formation (Tweto, 1979a; USGS MRDS, 2013). A buffer around the stock is designated H/C.

In southeastern Custer County, gold occurs in a breccia pipe associated with the Tertiary Deer Peak volcanics at the Ophir Creek claims (USGS MRDS, 2013). A buffer of the Tertiary intrusives around this mine is designated M/C.

4.11.3 Silver

Custer County is credited with production of 4.7 million ounces of silver between 1872 and 1958 (Del Rio, 1960; Vanderwilt, 1947). Dual Tertiary alkalic caldera complexes intruded into Precambrian felsic metamorphic foundation rocks of the Silver Cliff and Rosita Hills mining districts are host to precious- and base-metal ores (Cappa, 1998). The Bassick mine, occurring in a volcanic breccia pipe in the Rosita Andesite, produced the most silver in the Rosita Hills district and in the county, with grades ranging from 60 to 200 ounces of silver per ton (Cappa, 1998). The Bull Domingo deposit in the Silver Cliff district occurs in a breccia pipe, and grades range from 10 to 12 ounces of silver per ton (Cappa, 1998). Mineralized fracture fillings, especially the Humboldt-Pocahontas vein, also yielded economical concentrations of silver (Cappa, 1998). The Tertiary intrusives and bordering Precambrian metamorphic rocks in the greater Rosita Hills, Querida, Silver Cliff, and Hardscrabble district area are designated H/D for silver occurrence potential.

There are numerous silver occurrences and minor past producers found in Precambrian felsic gneiss along faults east of the greater Rosita Hills district; a buffer around these occurrences is designated H/C for silver occurrence potential. Precambrian felsic metamorphic rocks elsewhere in the county are assigned M/B.

Mineralized fractures in the Deer Park volcanics in southeastern Custer County host silver at half a dozen minor past producers (USGS MRDS, 2013). A buffer around this area is assigned H/C for silver occurrence potential.

In northwestern Custer County, anomalous silver is reported from contacts of the Tertiary Rito Alto stock with the surrounding Minturn Formation, and silver was produced from related veins along bedding planes in the Sangre de Cristo Formation at the Rito Alto mine (Johnson et al., 1984). Epithermal veins filling fractures at the contact of Precambrian felsic gneiss and Paleozoic Sangre de Cristo sedimentary rocks host silver at the Verde Creek deposit in the Verde district (USGS MRDS, 2013). Mineralized fractures in Precambrian felsic gneiss just south of the Rosita Hills caldera complex host silver at the Skek City mine (USGS MRDS, 2013). Silver occurs in a Precambrian exhalative sulfide xenolith located within the San Isabel granodiorite along the Amethyst Creek at the Marion mine in southeasternmost Custer County. Buffers around these occurrences are considered M/C for silver occurrence potential. Anomalous "redbed-type" concentrations of silver are noted from the Pennsylvanian Minturn Formation, and this unit is designated L/B for silver occurrence potential.

4.11.4 Copper-Lead-Zinc

Custer County mines have produced a significant quantity of base metals, primarily in the Silver Cliff volcanic complex, from 1872 through 1958, including 626,825 pounds of copper, 42 million pounds of lead, and 1.9 million pounds of zinc (Del Rio, 1960; Vanderwilt, 1947). The Silver Cliff volcanic complex spans the Central district, which includes the Silver Cliff, Hardscrabble, Rosita Hills, and Querida districts (CGS, 2015c). Vanderwilt (1947) reports copper, zinc, and lead are found primarily in veins and breccia pipes. Eckel (1961) adds that the breccia fragments within the ancient volcanic necks are encased in concentric sheaths of ore minerals. Mineralization within these veins and breccia pipes is most prolific at the Bassick and Bull Domingo mines (Eckel, 1961). During the 1932-1945 time frame, production at the Silver Cliff / Hardscrabble district amounted to 16,800 pounds of copper, 1.0 million pounds of lead, and 875,000 pounds of zinc; the Rosita Hills / Querida district accounted for 430 pounds of copper and 37,900 pounds of lead. Based on past production, the greater Central district is assigned H/D for occurrence potential of copper-lead-zinc. Tertiary volcanics south of Rosita Hills are L/B as only one MRDS (2013) prospect (lead) occurs, and then only with vein potential, not massive sulfide deposit.

The Oak Creek district (also known as the Ilse or Spaulding district) in the Wet Mountains of northeastern Custer County is a belt along a large fault where cerussite is the dominant ore mineral (Eckel, 1961; CGS, 2015a). Vanderwilt (1947) reports production of 300,000 tons of 5 percent to 8 percent ore prior to 1895 at the Terrible mine; he reports production of an additional

24,200 pounds of lead from 1940 to 1943. Mineralization was isolated to a broad fault zone in the area, so the district is considered H/C. The surrounding Precambrian igneous and metamorphic rocks along shear zones of the Wet Mountains contain base metals in Tertiary thorium veins (Nelson-Moore et al., 1978) and as metal sulfides (Type 1; Sheridan et al., 1990). The Precambrian units of the Wet Mountains, northwest of line from about McKenzie Junction to Querida, are designated H/C; southeast of that the designation is M/B, as there are far fewer MRDS (2013) occurrences, but the geologic setting is still favorable.

In the southeastern portion of the county and the Wet Mountains, south of St. Charles Peak and a few miles west of San Isabel, the Marion mine is classified as a productive Type 1 Precambrian exhalative sulfide deposit (Sheridan et al., 1990). Calc-silicate gneiss hosts sulfide lenses, and the primary ores are sphalerite, chalcopyrite, and galena (Heinrich, 1981). The USGS MRDS (2013) reports an estimate of resources (made in 1956) of 609,000 tonnes of 9.1 weight-percent zinc and 1.4 weight-percent copper ores. The Marion mine area is designated H/D.

Along the western portion of the county, the lower Sangre de Cristo Formation hosts lead (e.g., Cloverdale mine) and copper (e.g., Rita Alta mine) mineralization in fractures. The lower Sangre de Cristo Formation and other Paleozoic redbeds are noted for anomalous copper concentrations (e.g., Lindsey and Clark, 1995) and are designated H/B. Due to minor mineralization in quartz veins, the Rito Alto stock region in the northwest of the county is designated L/B. The Precambrian gneiss adjacent to the Gem Park alkali complex (shared with Fremont County) is assigned M/C for occurrence potential.

4.11.5 Iron

Iron has been reported in the volcanic eruptive centers of the Rosita Hills and Silver Cliff complexes as magnetite in banded rhyolite (Emmons, 1896). Mineralized fissures at the contacts of the Tertiary volcanics and Precambrian gneiss contain pyrite, limonite, and hematite ores at the Wahl mine (USGS MRDS, 2013). Harrer and Tesch (1959) report manganiferous limonite at the Wahl group of mines containing upwards of 43.4 percent iron. About 3,900 tons of iron ore were produced from ore ranging from 34 to 47 percent iron (Harrer and Tesch, 1959). Iron oxides replace mafic minerals throughout the Tertiary volcanic units and numerous past producers are noted on the USGS MRDS (2013) (Cappa, 1998). The volcanic rocks of the Rosita Hills and Silver Cliff districts are assigned an iron occurrence potential of H/D.

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential. Precambrian Silver Plume-related granites (e.g., the San Isabel pluton in Custer County) are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Pegmatites intruded in the San Isabel batholith host abundant magnetite and hematite intergrowths (Boyer, 1962). Silver Plume-related granite in the county is assigned L/B.

4.11.6 Manganese

Production of manganese oxides from veins and mineralized fractures in rhyolite of the Silver Cliff (Rosita) volcanic center was reported at the Nutter prospect (Cappa, 1998; USGS MRDS, 2013). About 10 other mines or prospects are located in the Silver Cliff volcanic center. The volcanic rocks around these occurrences are designated H/C for manganese potential. Other Tertiary igneous rocks in the county are L/B for potential.

Psilomelane, manganite, and pyrolusite production is reported from rhyolitic breccia of the alkalic San Isabel pluton at the Victory claims located in eastern Custer County (USGS MRDS, 2013; Wells et al., 1952). The low-grade ore was easily concentrated to 31.3 percent manganese by simple washing and sizing (Wells et al., 1952). Rhodochrosite is found in mineralized veins of Precambrian gneiss at the Mystery Lode northeast of the Querida district (USGS MRDS, 2013). The San Isabel pluton is M/C for manganese potential. Other Precambrian rocks are L/B throughout the county.

4.11.7 Molybdenum

Though the Silver Cliff and Rosita Hills districts are dominated by alkalic volcanic rocks from their respective, distinct but connected, Tertiary intrusive caldera complexes, Custer County reports minimal occurrences of molybdenum (Cappa, 1998). The Iron Mountain mine (Rosita Hills) produced molybdenum (molybdenite and powellite) as a minor commodity after iron and silver (USGS MRDS, 2013). Eckel (1961) notes that wulfenite occurs at the Review mine of the Silver Cliff district. Molybdenum occurs in carbonatite dikes that intruded Precambrian gneiss in the Gem Park Alkalic Complex (shared with Fremont County), although no production is reported (USGS MRDS, 2013). Molybdenite is found as grains and aggregates in quartz veins and a rhyolite dike of the Tertiary Rito Alto stock at the Knight-Stacy claims; assays vary widely and show an average of 1 percent, but ranging from 0.01 to 3.47 percent, MoS_2 (Eckel, 1961; Ellis et al., 1983; U.S. Bureau of Mines, 1989). The Verde Creek Deposit produced some molybdenum as a secondary commodity from veins in Precambrian gneiss (USGS MRDS, 2013).

A buffer around these occurrences is M/C for molybdenum potential; the alkalic volcanic complexes, including the Gem Park, Silver Cliff, and Rosita Hills complexes, as well as the Rito Alto stock, are M/B. A buffer around the Rito Alto stock in Paleozoic sediments is L/B as veins and dikes could have intruded those units. Metamorphic and other igneous rocks are L/B.

4.11.8 Nickel

Nickel-bearing serpentine dikes associated with carbonatites occur in the Gem Park Alkalic Complex in northern Custer and southern Fremont Counties (Olson et al., 1977; Parker and Sharp, 1970). Production of 34 percent nickel ore (niccolite) was reported from the Gem mine in the Fremont County portion of the complex (Eckel, 1961). Elsewhere, nickel is found in the Big Stake Nickel Deposit in Precambrian mafic gneiss in the Rosita Hills district and near the boundary of Silver Cliff volcanic and Precambrian metamorphic rocks at the Skek City mine a couple of miles south of Rosita Hills (USGS MRDS, 2013). Nickel is also reported in gabbro and peridotite of the San Isabel pluton at the Wild Goose mine about 7 miles east of Rosita Hills (USGS MRDS, 2013; Vanderwilt, 1947). Small buffers around these occurrences are designated M/C for nickel potential. Precambrian metamorphic and igneous rocks elsewhere in the county are designated L/B.

4.11.9 Tungsten

There are no reported tungsten prospects in Custer County; however, the Precambrian metamorphic and granitic rocks are designated L/B since minor tungsten occurs in these rocks in nearby Fremont County.

4.11.10 Beryllium

Bertrandite occurs as a tertiary commodity at the Swartz Ranch (Iron Queen) prospects just north of Querida near the contact of the Rosita Hills volcanic and Precambrian metamorphic rocks (USGS MRDS, 2013). Although this is the only recorded occurrence of beryllium in Custer County, the Precambrian granitic rocks have been assigned a beryllium potential of L/B due to occurrences in the same rocks in other counties.

4.11.11 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Custer County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. About 1.9 million pounds of zinc were produced in Custer County between 1872 and 1958; sphalerite ore is commonly reported at past-producing zinc mines (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.11.12 Rare Earth Elements

In Custer County, the rare-earth minerals bastnaesite, synchisite ($CaCe(CO_3)_2F$), ancylite ($CeSr(CO_3)_2(OH)$), monazite, and REE-bearing thorite have been identified in carbonatites and thorium-bearing veins of the Gem Park and Democrat Creek alkalic intrusive complexes, shared with Fremont County (Armbrustmacher, 1979). Heinicke (1960) stated that more than 800 thorium prospects were developed in the greater Wet Mountain Alkalic Province by 1958, and it is likely that REEs occur in most of those. An enrichment of HREEs is noted within these complexes (Armbrustmacher, 1988). Armbrustmacher (1988) estimated 136,000 tons of REE (including 48,850 tons of HREE) reserves in the composite Wet Mountains Alkalic Province. The Gem Park and Democrat Creek complexes in Custer County are designated H/C for REE occurrence potential.

Thorium-REE veins filling fracture zones in Precambrian gneiss contain an estimated 64,200 tons of 0.46 percent thorite ore reserves, mostly in an area south to southeast of the Democrat Creek syenite complex in Custer County (Schwochow and Hornbaker, 1985; Van Gosen et al., 2009). Thorium-REE veins are a late-stage product of Cambrian alkalic magmatism related to the Democrat Creek intrusive complex (Armbrustmacher, 1988; Olson et al., 1977). Some of the more important deposits in Custer County include the Haputa Ranch, Beardsley, and Schwarz Ranch areas, where thorium-REE veins fill northwest-trending shear zones in Precambrian felsic and hornblendic gneisses (Armbrustmacher, 1988; Tweto, 1979a). Samples from shear zones at the Haputa Ranch prospect assayed up to 4.29 percent total REE oxides; the prospect harbors an estimated 3,325 tons of thorite ore (Armbrustmacher, 1988; Christman et al., 1953). Heinicke (1960) reports production of 440 tons of thorite ore from mineralized veins at the Beardsley lease in the Hardscrabble district. Analyses on samples from the Pine Tree claim yielded 5.06 percent total REE oxides, and the most common REEs include cerium, lanthanum, yttrium, and neodymium (Christman et al., 1959). A buffer around these occurrences in Precambrian Idaho Springs Formation gneiss in Custer County is designated H/C for REE occurrence potential.

4.11.13 Niobium-Tantalum

Pyrochlore and columbite occur in irregular masses in shear zones between carbonatite dikes and surrounding pyroxenite and Precambrian rocks at the Cambrian Gem Park alkalic complex, which spans Custer and Fremont Counties; no production is reported (Cappa, 1998; Meeves et al., 1966; Parker and Sharp, 1970). These complexes are designated L/C for niobium-tantalum occurrence potential. Columbite is reported from the G.W. and Antrim claims from a rhyolite porphyry dike extending from a Tertiary stock into Precambrian gneiss (Christman et al., 1959; USGS MRDS, 2013). Buffers along faults at this contact are assigned L/B for niobium-tantalum potential.

4.11.14 Tellurium

The Hardscrabble, Rosita Hills, and Querida district hosts numerous copper and gold occurrences and is known to contain some telluride minerals (Eckel, 1961). The occurrence potential for tellurium in these districts is designated M/C. Precambrian rocks in the remainder of the county are considered L/B.

4.11.15 Titanium

Titanium is hosted by carbonatites at the Mag Lode prospect in the Gem Park alkalic complex, shared with Fremont County (Armbrustmacher, 1988; Cappa, 1998). The Cambrian volcanic rocks of the composite Wet Mountains Alkalic Province, including the Gem Park and Democrat Creek portions in Custer County, are designated H/C for titanium occurrence potential. The abundance of accessory minerals, especially sphene, is diagnostic of the San Isabel Granite (Boyer, 1962). The San Isabel Granite is assigned L/B for titanium potential.

4.11.16 Uranium

Though only minor uranium production is known from Custer County, there are nearly 30 reported occurrences in the county. Ore from a Tertiary carbonaceous vein along a fault in Precambrian gneiss at the Floyd Watters Ranch mine averaged 0.11 percent U_3O_8 and yielded 17 pounds of U_3O_8 (Nelson-Moore et al., 1978). Numerous other uranium occurrences are associated with Tertiary metalliferous veins in faulted Precambrian metamorphic rocks in the Wet Mountains (Nelson-Moore et al., 1978). Buffers around the faults and/or occurrences are designated L/C for uranium occurrence potential, except the fault at the Floyd Watters Ranch location, which is assigned M/C.

The remainder of the minor production came from the Horn Peak claims and the King Midas and Bonanza claims, which produced from the Permian Sangre de Cristo Formation. Samples from the Horn Peak claims assayed up to 1.7 percent U_3O_8 (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from this unit is also reported in Huerfano County, and the Sangre de Cristo Formation is designated M/C for uranium potential.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale in northeasternmost Custer County is designated L/B for uranium occurrence potential.

Tertiary siliceous tuffs are source rocks for uranium leached and reprecipitated in nearby fractures and faults (Olson, 1988). Production of nearly 500 pounds of uranium is reported from a seam underlying Tertiary tuffs in Saguache County (Nelson-Moore et al., 1978). Tertiary tuffs in Custer County are designated L/B for uranium occurrence potential.

4.11.17 Thorium

Meeves et al. (1966) report production of 137 tons of thorite ore from pegmatites in Custer County through 1963. Forty-eight thorium occurrences are located in Custer County and most are hosted by alkalic veins in Precambrian metamorphic rocks (USGS MRDS, 2013). Quartz-barite-thorite veins and fracture zones contain an estimated 64,200 tons of 0.46 percent thoria ore reserves, mostly in an area south to southeast of the Democrat Creek syenite complex within Custer County (Schwochow and Hornbaker, 1985; Van Gosen et al., 2009). Thorium-bearing veins are a late-stage product of Cambrian alkalic magmatism related to the Democrat Creek intrusive complex (Armbrustmacher, 1988; Olson et al., 1977). Some of the more important deposits in Custer County include the Haputa Ranch, Beardsley, and Schwarz Ranch areas, where veins fill northwest-trending shear zones in Precambrian felsic and hornblendic gneisses (Armbrustmacher, 1988; Tweto, 1979a). The shear zones in the Haputa Ranch area contain 0.06 to 0.60 percent ThO_2 and harbor an estimated 3,325 tons of thorite ore, and stockpiled ore at the Schwarz Ranch assayed up to 7.0 percent ThO_2 (Armbrustmacher, 1988). Heinicke (1960) reports production of 440 tons of thorite ore from the Zabel-Beardsley lease in the Hardscrabble district from mineralized veins. Assays on samples from the Floyd Watters mine, which also produced small amounts of uranium and vanadium, contained 0.54 percent ThO_2 (Nelson-Moore et al., 1978). Buffers along faults in Precambrian crystalline rock in Custer County are designated H/D for thorium occurrence potential where producing mines are clustered and M/D elsewhere.

4.11.18 Vanadium

In Custer County, production of 8 pounds of V_2O_5 from 8 tons of up to 0.19 percent V_2O_5 ore is reported from a calcareous replacement of a lamprophyre dike along a fault in Precambrian gneiss at the Floyd Watters Ranch mine (Nelson-Moore et al., 1978). Another prospect (non-producing) occurs along a fault at the juncture of Precambrian migmatitic gneiss and Deer Peak rhyodacite (USGS MRDS, 2013). Buffers along these faulted locations are designated L/C for vanadium occurrence potential.

Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The undifferentiated Morrison Formation and Dakota Sandstone unit is designated M/B for vanadium occurrence potential.

Vanadium occurrences and some production are reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in this as well as Park and Fremont Counties; samples assayed up to 4.34 percent V_2O_5 (Nelson-Moore et al., 1978; Schwochow and Hornbaker, 1985; Wilmarth, 1959). The Minturn Formation is assigned L/C for vanadium occurrence potential.

Samples from mines in the Permian Sangre de Cristo Formation of Huerfano County host carnotite and assayed up to 4.0 percent V_2O_5 (Nelson-Moore et al., 1978). Several other Sangre de Cristo Formation prospects report high V_2O_5 grades as well, including the Parks Lode (2.6 percent) and Halls property (2.3 percent), although no production is recorded (Nelson-Moore et al., 1978). In Custer County, carnotite and tyuyamunite are reported from the King Midas and Bonanza claims, and about 5 pounds of vanadium were produced at the Beck Mountain mine (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for vanadium occurrence potential.

4.11.19 Fluorspar

Only minimal fluorspar production is reported from Huerfano County; however, average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks (Wallace, 2010). Aurand (1920) and Cox (1945) report production of green to brown fluorspar from a vein measuring up to 4 feet wide and 110 feet long near the contact of Precambrian hornblende gneiss and Tertiary intrusives east of the Antelope Creek district. The property was worked prior to 1920 and reportedly shipped over 1,000 tons of fluorspar averaging 80 percent CaF_2 (metallurgical grade) (Aurand, 1920; Brady, 1975). Precambrian igneous rocks are designated H/C, and Precambrian hornblende gneiss is assigned M/C in areas of known fluorite prospects and M/B elsewhere, for fluorspar occurrence potential throughout the county.

4.11.20 Diamond and Gemstones

Clear and wine-colored topaz crystals occur with garnet and quartz in concentric cavities in a transition zone between spherulites and Tertiary banded rhyolite within the Rosita Hills district of Custer County (Eckel, 1961). These mapped units are designated M/C for gemstone occurrence potential. Despite the lack of beryl-bearing pegmatites in Custer County, due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the northwest of the county, Precambrian felsic metamorphic rocks are designated L/B for gemstone potential (Lovering and Goddard, 1950).

4.11.21 Pegmatite Minerals

Meeves et al. (1966) report production of just 8 tons of scrap mica from pegmatites in Custer County. In northern Custer County, the Feldspar mine is listed as a past producer of feldspar as a tertiary commodity (after barite and lead) from a mineralized 1000-foot portion of the Ilse Fault in Precambrian felsic gneiss (USGS MRDS, 2013). Production of feldspar is also reported from a pegmatite in Precambrian felsic gneiss northwest of Westcliffe at the Lake View prospect (USGS MRDS, 2013). Precambrian felsic metamorphic rocks are designated M/B for pegmatite mineral potential due to these occurrences and others in the same rock types in other counties. Precambrian plutonic rocks are assigned L/B.

4.11.22 Industrial Abrasives

There is no reported production of industrial abrasives in Custer County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks, these rocks are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.11.23 Limestone and Dolomite

There are no limestone prospects in Custer County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential. The Pennsylvanian Minturn and Belden Formations host limestone prospects in other counties and are designated L/C for limestone potential.

4.11.24 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, although no industrial sand occurrences are reported in Custer County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica (Vanderwilt, 1947). The Dakota Sandstone is designated H/C for industrial sand occurrence potential.

4.11.25 Gypsum

Though no gypsum prospects are reported in Custer County, productive gypsum quarries in nearby western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation, equivalent to the Chubb evaporite member in South Park (Brill, 1952). The Minturn Formation occurs along the Arkansas River corridor in western Fremont County, and this unit extends into Custer County (Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential in Custer County.

Although no bedded gypsum is reported from within the Jurassic Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). Several gypsum quarries hosted by the Jurassic Ralston Creek Formation occur in nearby Pueblo and Fremont Counties (USGS MRDS, 2013). The Stevens Gypsum mine (Pueblo County), reportedly developed in the undivided Colorado Group, likely produced from the underlying Morrison and Ralston Creek Formations; production of 700 tons of gypsum per month at one point is reported (George, 1920; USGS MRDS, 2013). The undivided Jurassic Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential in Custer County.

Very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation or the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in northeastern Custer County.

4.11.26 Sand and Gravel

High-quality sand and gravel deposits in Custer County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, as well as glacial drift (Qd), are assigned H/C for potential (Arbogast et al., 2011).

Sedimentary units of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Custer County and elsewhere, the Fountain Formation and Dakota Sandstone host sand and gravel operations (W. D. Carter, 1968); these units are assigned L/C for sand and gravel potential. A cluster of sand and gravel permitted quarries occurs in the Tertiary Santa Fe Formation along tributaries to Grape Creek; a buffer around these occurrences is designated M/D for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.11.27 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Custer County, developed in Tertiary basalt and quartz latite of the dual alkalic caldera complexes in the Silver

Cliff and Rosita Hills districts. Dark, dense, fine-grained igneous rocks (traprock) like basalt satisfy the physical and chemical standards for high-quality crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Precambrian mafic rocks and Tertiary basalts, latites, and unwelded tuff are assigned H/C for crushed stone potential. Tertiary andesitic lavas and breccias may be too porous in part to meet the requirements of crushed stone aggregate (Knepper et al., 1999); Tertiary andesitic rocks are assigned M/B for crushed stone potential. The mafic plutons of the composite Wet Mountain Alkalic Complex, composed largely of syenite and diabase, meet the physical and chemical qualifications for crushed stone aggregate (Knepper et al., 1999). The Gem Park and Democrat Creek plutons are designated H/C for crushed stone aggregate occurrence potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the San Isabel pluton in Huerfano, Pueblo, and Custer Counties, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, weathered, and jointed Precambrian Boulder Creek plutons and satellites were classified as only ‘fair’ source rocks by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The San Isabel pluton and satellites are designated H/C, and the Boulder Creek Granite is designated M/C, for crushed stone aggregate potential. Precambrian felsic and hornblendic gneisses (Idaho Springs Formation) are assigned H/B for crushed stone aggregate occurrence potential.

The Fort Hays Member of the Cretaceous Niobrara Formation has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Minturn, Fountain, and Sangre de Cristo Formations, the Jurassic Morrison Formation, Cretaceous Dakota Sandstone, and the Tertiary Santa Fe Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in other counties. The Dakota Sandstone is designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.11.28 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay and contains slightly to highly expansive illite and montmorillonite; this shale member may be a suitable resource for Leca (Hansen and Crosby, 1982). The Pierre Shale is assigned H/C, and the Niobrara Formation is designated L/B, for lightweight aggregate occurrence potential.

The Pennsylvanian Minturn and the Tertiary Santa Fe Formations bear sporadic interbedded shale that may be suitable sources for Leca (Knepper et al., 1999); these units are assigned L/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in Precambrian metamorphic rocks and Cambrian alkalic plutonic rocks of Custer County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). There are several past DRMS-permitted vermiculite operations developed in these rocks. The relatively unweathered San Isabel pluton is designated L/B, and older, highly weathered felsic and hornblendic gneisses (derived from volcaniclastic host rocks), as well as the Cambrian Democrat Creek alkalic pluton, are designated M/C for lightweight aggregate potential. The Cambrian Gem Park alkalic pluton hosts numerous vermiculite occurrences and is designated H/D for lightweight aggregate potential. Precambrian mafic intrusives and biotite gneiss are assigned M/B for lightweight aggregate potential.

There are several DRMS-permitted lightweight aggregate (perlite, pumicite) operations developed in Tertiary basalt and quartz latite of the dual alkalic caldera complexes in the Silver Cliff and Rosita Hills districts; these rocks are designated H/D for lightweight aggregate potential. Also, significant outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity throughout the county may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.11.29 Clay

The best quality refractory clays in the RGFO region are found in the Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; numerous occurrences are noted throughout the RGFO region (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; USGS MRDS, 2013; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the underlying Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation, Purgatoire Formation, and Dakota Sandstone are designated H/D for clay occurrence potential in Custer County.

Several prospects developed in the Cretaceous Graneros Shale (Colorado Group), the Smoky Hills Member (Niobrara Formation), and the overlying Pierre Shale throughout the RGFO region have occasionally produced a high-quality fire clay, but most prospects produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds (Arbogast, 2011; Landis, 1959b; Schultz, 1978; USGS MRDS, 2013). The Pierre Shale is assigned H/C, and the Colorado Group and Niobrara Formation are assigned M/C, for clay potential.

Abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). The undifferentiated Minturn and Belden Formations are designated L/B for clay occurrence potential. A couple of clay prospects are developed in Quaternary alluvium near Silver Cliff and Westcliffe; a large bentonite deposit up to 30 feet thick was reported in this area (Patterson, 1968; USGS MRDS, 2013). The mapped alluvium unit is assigned L/C for clay potential.

4.11.30 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Custer County hosts granites, limestones, and sandstones that have potential to be quarried for dimension stone, including Precambrian Silver Plume-aged granite and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

Silver Plume-aged granite has been quarried for dimension stone in other counties, although where weathered, fractured, or highly jointed, granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The alkalic San Isabel pluton and satellites, which range from granite to granodiorite, are designated H/C for dimension stone potential; a small outcrop of older and more weathered Boulder Creek Granite in southwesternmost Custer County is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Significant production of high-quality dimension stone is reported from the Dakota Sandstone throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). This unit is designated H/D for dimension stone potential. The Pennsylvanian Minturn, Fountain, and Sangre de Cristo Formations host numerous sandstone and limestone beds throughout their extent; building stone production is reported from the Fountain Formation in other counties (Arbogast et al., 2011; Cappa and Bartos, 2007; Lindvall, 1968; Schwochow, 1981). The Minturn and Sangre de Cristo Formations are assigned M/B, and the Fountain Formation is assigned M/C, for dimension stone potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential.

Colorado Quarries, Inc. operates several building stone operations developed in dual Tertiary alkalic caldera complexes intruded into Precambrian metamorphic rocks in the Silver Cliff and Rosita Hills mining districts (Cappa, 1998; Cappa et al., 2007). The Tertiary units hosting the operations are designated H/D, and related volcanic rocks are assigned H/B, for dimension stone potential; other Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.12 Denver County

4.12.1 Coal

All of Denver County lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). There are no past-producing mines reported within the county. The Denver Coal

Region in Denver County is designated H/C for coal occurrence potential. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.12.2 Geothermal

Traditional / EGS Geothermal

The entirety of Denver County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Denver County contains no known wells or springs. All of Denver County is above the 100°F threshold for low temperature and co-produced resources, with the northeastern corner being designated H/C (within named COGCC fields) and rest being H/B (outside named fields).

4.12.3 Gold

Present-day Denver County was the site of some of the earliest discoveries of placer gold in Colorado, with the original discovery thought to be at the confluence of Cherry Creek and the South Platte River around 1859 (Davis and Streufert, 1990). The source of the gold is likely fossil placers from the Oligocene Castle Rock Conglomerate, which caps much of the Cherry Creek divide area where Cherry Creek and its tributaries originate; Big and Little Dry Creeks also likely eroded gold from the same source and fed it into the South Platte River (Desborough et. al., 1970; Parker, 1974). About 273 ounces of placer gold was recovered between 1929 and 1941 (Vanderwilt, 1947). The sediment load of lower Cherry Creek has likely been affected by the construction of the Cherry Creek Reservoir, and therefore has little gold potential. The South Platte River is designated M/C where it flows through the county, although urbanization will likely affect placer potential.

4.12.4 Silver

Just 17 ounces of placer silver is reported from gold placer operations along Cherry Creek in Denver County from 1932 to 1934 (Vanderwilt, 1947). Cherry Creek is designated L/B for silver occurrence potential.

4.12.5 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Denver County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.12.1 of this MPR) is designated L/B for germanium occurrence potential.

4.12.6 Uranium

Nelson-Moore et al. (1978) state that no uranium occurrences have been reported in Denver County; however, there is one uranium occurrence (Rodger Steel claim) in modern alluvium included in the USGS MRDS (2013). The Laramie Formation and Fox Hills Sandstone, known for uranium occurrences in Weld County, exist in the subsurface; a buffer around this claim is designated L/B for uranium occurrence potential.

4.12.7 Industrial Sand

Quaternary eolian sands in Denver County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in nearby Adams and Arapahoe Counties along Cherry, Sand, and Box Elder Creeks, and the South Platte River, all of which flow through Denver County (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose throughout the RGFO region (Arbogast et al., 2011). The Dawson Arkose is designated L/C for industrial sand potential.

4.12.8 Helium

Part of Denver County is designated L/C for helium occurrence potential due to its location in the Denver Basin.

4.12.9 Sand and Gravel

Del Rio (1960) estimates over 250 million tons of sand and gravel were available prior to the urbanization of metropolitan Denver County, primarily from extensive Quaternary deposits. High-quality sand and gravel deposits within Denver County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Denver County, the undifferentiated Tertiary Dawson Arkose, Denver

Formation, and Arapahoe Formation host sporadic sand and gravel operations in other counties; these units are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968).

4.12.10 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Denver County; however, well-cemented and unweathered sandstone units in the Tertiary Dawson Arkose may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999). The Dawson Arkose is assigned L/B for crushed stone aggregate occurrence potential.

4.12.11 Lightweight Aggregate

Often mapped together, the Arapahoe and Denver Formations and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C, and the undivided Denver Formation and Dawson Arkose (mapped as TKdl) are designated M/B, for lightweight aggregate potential.

4.12.12 Clay

The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). One producing pit is developed in the Dawson Arkose in Denver County (USGS MRDS, 2013). The Dawson Arkose is designated M/C for clay potential. A few sand and/or gravel pits also produce clay from the alluvium along the South Platte River in this and other counties; the alluvium mapped unit is designated L/C for clay potential.

4.12.13 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Denver County, the Tertiary Denver Formation and Dawson Arkose, although hosting sandstones in part, have no documented production of dimension stone. As sandstones, these units are designated M/B for dimension and building stone occurrence potential.

4.13 Douglas County

4.13.1 Coal

The eastern half of Douglas County lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 and Figure 3-1 of this MPR). Production of 27,367 tons of coal from the Cretaceous Laramie Formation at four past-producing mines in Douglas County was reported between 1864 and 2002 (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). Of an estimated 186.7 million tons of original coal resources in the county, only 54,700 tons are reportedly depleted, implying reserves of 186.6 million tons of coal (Brandt, 2015; Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Douglas County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.13.2 Geothermal

Traditional / EGS Geothermal

The majority of Douglas County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the southwestern corner is considered M/C because of moderate-high traditional favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Douglas County contains no known wells or springs. Almost all of the southwest quadrant of Douglas County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The rest of Douglas County is designated H/B for low temperature and/or co-produced geothermal resources.

4.13.3 Gold

Gold has been recovered from placers along Cherry Creek and its tributaries, which originate from the Cherry Creek divide in Douglas County (Davis and Streufert, 1990). Moderate potential areas specifically pointed out by Parker (1974) include Newlin Gulch (west of Parker) and Russellville Gulch (east of Castle Rock). Davis and Streufert (1990) also add Lemon Gulch and Happy Canyon, west of Cherry Creek near Parker, as a potential source of placer recovery. The gold is very fine and pure, and fossil placers of the Castle Rock Conglomerate are likely the source (Desborough et al., 1970; Parker, 1974). An MRDS (2013) placer gold occurrence is noted along Horse Creek, which drains the Pikes Peak batholith, near Deckers. Vanderwilt (1947) reports production of 712 ounces of placer gold between the years 1885 to 1941 in Douglas County.

Placer locations found along the Cherry Creek Divide, such as Newlin, Russellville, and Lemon Gulches, and Happy Canyon are assigned a gold occurrence potential of M/C based on historic activity. Big and Little Dry Creeks also start in Douglas County, and any portions of those streams in the county are considered M/C as well. The Pikes Peak batholith is assigned M/B due to minor gold occurrences here and in other counties (e.g., El Paso and Teller).

4.13.4 Silver

A total of 168 fine ounces of silver were produced from various placer deposits in Douglas County from 1885 to 1941 (Henderson, 1926; Vanderwilt, 1947). Cherry Creek and its tributaries were the main sources, and they have been designated L/B. The Pikes Peak batholith is designated M/B due to sporadic occurrences in nearby counties (e.g., Jefferson and Teller).

4.13.5 Copper-Lead-Zinc

Vanderwilt (1947) reported no production of any base metals from the county, but the USGS MRDS (2013) records 3 occurrences, one of which is listed as a past producer. Henderson (1926) estimates production of 37 million pounds of lead, 10.8 million pounds of zinc, and 6.2 million pounds of copper between the years 1879-1923 based on Denver Mint, Colorado State Bureau of Mines, and Mineral Resources reports. Chalcopyrite, chrysocolla, malachite, azurite, tenorite, and, at one location, smithsonite are reported in veins and disseminated near faults in Precambrian silicate gneiss and amphibolite (Scott, 1963). Assays from one of two unnamed prospects about 5 miles southwest of Kassler yielded results of 2.4 percent copper from a limonite gossan, 5.0 percent copper from a biotite-quartz gneiss, and 2.5 percent copper from a lime-silicate gneiss (Scott, 1963). One MRDS (2013) occurrence (Devils Head Copper) occurs in the Pikes Peak Granite. Hence, the Precambrian rocks of Douglas County are designated as M/B for copper-lead-zinc potential, except the Pikes Peak Granite which is L/B.

4.13.6 Iron

No iron production is reported for Douglas County, but late-stage syenite, fayalite, and mafic intrusions into the Precambrian Pikes Peak batholith host iron-rich minerals (Smith et al., 1999); these units are designated M/B for iron occurrence potential. Elsewhere, the Pikes Peak batholith is designated L/B for iron potential. Iron-bearing minerals (especially pyrite and magnetite) are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks are designated L/B for iron occurrence potential.

The Mississippian Leadville Dolostone hosts limonite, and several past producers are noted from other counties (Cappa and Bartos, 2007); this unit is designated L/B in Douglas County. Thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Douglas County.

4.13.7 Manganese

Nodular manganese oxide occurs in the upper Dawson Arkose at the R E Coulter and Leonard mines in eastern Douglas County (USGS MRDS, 2013; Vanderwilt, 1947). The area around each mine is designated M/C for manganese potential whereas the upper Dawson Arkose elsewhere in the county is assigned M/B. The White River Formation, which overlies the upper Dawson Arkose, is assigned L/B. Precambrian metamorphic rocks are assigned a potential of L/B throughout the county due to occurrences in similar rocks in neighboring counties (e.g., Jefferson and El Paso).

4.13.8 Molybdenum

In southwestern Douglas County, one occurrence of molybdenite is reported from the Sugarloaf syenite pluton, one of seven sodic plutons in or adjacent to the Pikes Peak batholith (USGS MRDS, 2013). A buffer around the Sugarloaf syenite is M/C; other Precambrian metamorphic and igneous rocks are designated L/B due to minor occurrences in other counties.

4.13.9 Nickel

Nickel is reported in trace amounts in an unnamed copper prospect situated in Precambrian gneiss and amphibolite (Scott, 1963; USGS MRDS, 2013). Precambrian metamorphic and igneous rocks throughout the county are designated L/B for nickel potential.

4.13.10 Tungsten

There are no known tungsten prospects in Douglas County; however, there are a few minor occurrences of tungsten in veins or stocks of the Pikes Peak Granite in other counties (e.g., Teller, El Paso, and Jefferson). Pikes Peak Granite is L/B for tungsten occurrence potential.

4.13.11 Beryllium

Beryl and gadolinite in association with fluorite are reported in at least 14 pegmatites of the Devils Head Pegmatite district, and some production was noted prior to 1963 (Meeves et al., 1966). The areas around the beryllium prospects are designated M/C for beryllium potential. The Pikes Peak batholith elsewhere in the county is designated M/B. Granitic rocks in the rest of the county are L/B.

4.13.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Douglas County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.13.1, as well as Figure 3-1, of this MPR) is designated L/B for germanium occurrence potential.

4.13.13 Rare Earth Elements

Meeves et al. (1966) report production of 500 pounds of rare-earth minerals from pegmatites in Douglas County through 1963. Allanite, bastnaesite, fergusonite, yttrian- and cerian-fluorite, samarskite, gadolinite, xenotime, and monazite are reported from the many pegmatites in the Pikes Peak batholith in the South Platte Pegmatite district, which spans Jefferson and Douglas Counties (Haynes, 1960; Simmons et al., 1999). District pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak Granite and quartz monzonite (Simmons and Heinrich, 1980). South Platte district pegmatites are super-enriched in REEs compared to most other pegmatites in the country (Simmons and Heinrich, 1980). Simmons et al. (1999) report production of “many tons” of samarskite ore from several pegmatites in the district. The greater South Platte Pegmatite district area, including the Devils Head pegmatite district, is designated H/D for REE occurrence potential.

The Pikes Peak composite batholith is comprises numerous late-stage peraluminous to peralkaline granitic plutons, all of which are enriched in REEs, especially LREEs (Gross and Heinrich, 1965; Persson, 2016; Simmons et al., 1999; Smith et al., 1999). The sodic West Creek syenite stock in southwestern Douglas County assayed up to 869 ppm total REE oxides, almost 4 times the normal crustal abundance (Smith et al., 1999). The pink Pikes Peak granite assayed up to 853 ppm total REE oxides (Smith et al., 1999). The Pikes Peak batholith outside the South Platte Pegmatite district is assigned M/C for REE occurrence potential.

4.13.14 Niobium-Tantalum

Euhedral fergusonite crystals, as well as microlite, pyrochlore, and samarskite, are reported from several of over 75 zoned pegmatites in the South Platte Pegmatite district of Jefferson County, which extends into southwestern Douglas County and encompasses the Devils Head Pegmatite district (Haynes, 1965; Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite (Simmons and Heinrich, 1980). Buffers along pegmatite zones in Pikes Peak Granite in the pegmatite districts of Douglas County are designated L/B for niobium-tantalum occurrence potential.

4.13.15 Tellurium

There are no reported occurrences of tellurium in Douglas County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.13.16 Titanium

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals, and several past producers are noted from El Paso and Teller Counties (Smith et al., 1999; USGS MRDS, 2013). Alkalic and mafic units in the Pikes Peak batholith of Douglas County are designated L/B for titanium potential.

Potential economic concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). This unit in Douglas County is designated L/B.

4.13.17 Uranium

There is no recorded production of uranium in Douglas County; however, several occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

A couple of occurrences occur in a shear zone between Precambrian granite and Paleozoic sedimentary rocks, although no production is recorded (USGS MRDS, 2013). A buffer around these occurrences is assigned L/B for uranium potential.

Several uranium prospects occur in Mesozoic sedimentary rocks in this and neighboring counties in the Jurassic undivided Morrison, Entrada, and Ralston Creek group and the Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from these units is reported in Pueblo County (Nelson-Moore et al., 1978). Part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. All these units in Douglas County are designated L/B for uranium potential.

4.13.18 Thorium

Thorium from monazite is found in pegmatites along faults in the Precambrian Pikes Peak batholith at several feldspar mines in Douglas County; no production is noted (USGS MRDS, 2013). Thorite and monazite are reported from pegmatites along faults in Pikes Peak Granite in the South Platte Pegmatite district spanning Jefferson and Douglas Counties (Simmons et al., 1999). Buffers along faults in Precambrian crystalline rocks in Douglas County are designated L/C for thorium occurrence potential.

4.13.19 Vanadium

There is no vanadium production reported in Douglas County; however, the Pallaro mine in Jefferson County, developed in the Cretaceous Dakota Sandstone, produced 256 pounds of V_2O_5 from 678 tons of 0.02 percent V_2O_5 ore (Nelson-Moore et al., 1978). Also, carnotite occurs in several other Dakota Sandstone prospects in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). The undifferentiated Morrison Formation, Entrada Sandstone, and Dakota Sandstone mapped unit is designated H/C for vanadium occurrence potential in Douglas County.

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation and underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.13.20 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, both of which are found in Douglas County (Wallace, 2010). The Pikes Peak composite batholith comprises the main granitic body plus numerous late-stage peraluminous to peralkaline granitic plutons, all of which host pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999; Tweto, 1987). Fluorite is a primary accessory mineral in all phases of the Pikes Peak composite batholith and related pegmatites; the composite batholith assayed anomalously high in fluorine abundance, averaging 2,140 to 3,500 ppm fluorine and ranging rarely up to 100,000 ppm (Wallace, 2010). Several fluorspar prospects are developed in the Douglas County portion of the batholith (USGS MRDS, 2013). Precambrian igneous rocks, including all phases of the Pikes Peak batholith, are designated H/C, and Precambrian biotite gneiss is assigned M/C, for fluorspar occurrence potential.

4.13.21 Diamond and Gemstones

The South Platte Pegmatite district has been mined for amethyst, milky and smoky quartz, and other pegmatite-hosted gems (Arbogast et al., 2011; Eckel, 1961). Excellent specimens of topaz, including the largest gem-quality crystal ever reported in Colorado, have been recovered from the Devils Head pegmatite (Scott, 1968b). Amazonite and smoky quartz are also found at the Devils Head location (Eckel, 1961). Fluorite, smoky quartz, and amazonite are reported from the Pine Creek and Watson Park Quarry group of mines (Eckel, 1961; USGS MRDS, 2013). The South Platte Pegmatite district is designated H/D for gemstone occurrence potential. Pegmatites hosting amazonite, smoky quartz, topaz, and amethyst occur sporadically throughout the Pikes Peak region (Arbogast et al., 2011, Pearl, 1972). Outside the South Platte Pegmatite district, the Pikes Peak batholith is designated M/C for gemstone potential.

Highly prized pink satin spar and alabaster occurs in the Permian-Triassic Lykins Formation at Perry Park (Eckel, 1961; Scott, 1968b); this unit in Douglas County is designated M/C for gemstone potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the nearby CMB, Precambrian biotite gneisses and schists are assigned M/B for gemstone potential (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

4.13.22 Pegmatite Minerals

Numerous pegmatites intrude the crystalline rocks of the Pikes Peak batholith in southwestern Douglas County in the South Platte Pegmatite district, shared with Jefferson County (Martin, 1993). In a study of Colorado pegmatites, Heinrich (1957) groups the pegmatites of Douglas County into the Pikes Peak-Florissant Pegmatite Province. At least a couple dozen mines and prospects have commercially produced feldspar and some mica in Douglas County (USGS MRDS, 2013).

Pikes Peak-related pegmatites are largest at the margins with metamorphic rocks of the Idaho Springs Formation (Clusters of pegmatites occur in the Pikes Peak batholith marginal to biotite gneiss of the Idaho Springs Formation in the South Platte Pegmatite district and are designated H/D for pegmatite occurrence potential. A zone of biotite gneiss marginal to the district with several occurrences and past producers is assigned H/C. Elsewhere in the county, Precambrian plutonic rocks are considered L/B except the Pikes Peak batholith which is designated M/C.

4.13.23 Industrial Abrasives

Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Numerous pegmatites in the South Platte Pegmatite district intrude the crystalline rocks of the Pikes Peak batholith in southern Jefferson and southwestern Douglas Counties (Martin, 1993). A buffer around these pegmatite clusters is designated H/C for industrial abrasive potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the west, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.13.24 Limestone and Dolomite

There is one limestone prospect in Douglas County, developed in the Permian Minnekahta and Forelle Limestones of the Lykins Formation; the Lykins Formation is designated L/C for limestone potential.

The undifferentiated Leadville, Williams Canyon, and Manitou Limestones have historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). The Leadville limestone group is designated H/C for limestone and dolomite occurrence potential in southwestern Douglas County.

The Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State. The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale (Colorado Group) is designated M/C for limestone and dolomite occurrence potential.

4.13.25 Industrial Sand

Small outcrops of Quaternary eolian sands in northern Douglas County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no permitted operations are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region, including one along Plum Creek in Douglas County (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in

Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Significant industrial sand production from these units is reported in Douglas and other counties (Schwochow, 1981). The Lykins Formation and Dakota Sandstone are designated H/D for industrial sand occurrence potential. Sporadic occurrences and production of industrial sand are reported from the Cambrian Sawatch Quartzite and Tertiary Dawson Arkose throughout the RGFO region, including one in Douglas County (Arbogast et al., 2011). The Sawatch Quartzite and Dawson Arkose are designated L/C for industrial sand potential.

4.13.26 Gypsum

Although no bedded gypsum is reported from within the Jurassic Morrison Formation in Douglas County, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). George (1920) reports gypsum beds up to 60 feet thick below the Morrison Formation at the Garden of the Gods and Glen Eyrie in neighboring El Paso County. Several gypsum quarries hosted by the Ralston Creek Formation occur in Pueblo and Fremont Counties (USGS MRDS, 2013). Highly prized pink satin spar and alabaster, as well as massive gypsum, reportedly occur in the underlying Permian-Triassic Lykins Formation at Perry Park (Eckel, 1961; Scott, 1968b). Morgan et al. (2005b) mapped the Perry Park area, concluding that the massive gypsum bed occurred in the Ralston Creek Formation, but they also described thin beds of gypsum in the Lykins Formation. George (1920) identified a massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8 mile section just above the Lykins Formation and below the Morrison Formation at Perry Park. The Perry Park gypsum was mined from 1898 to 1901, and it is estimated that massive anhydrite exists at depths below 30 feet (Schwochow, 1981; Withington, 1968). The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/D for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation as well (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in Douglas County.

4.13.27 Sand and Gravel

Del Rio (1960) reports production of over 700,000 tons of sand and gravel, primarily from alluvium, in Douglas County between 1953 and 1958. High-quality sand and gravel deposits within Douglas County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Douglas County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation, White River Formation, and Paleozoic Dakota, Fountain, and Lykins Formations, all of which host sporadic sand and gravel operations in this and other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968).

4.13.28 Crushed Stone Aggregate

There are numerous DRMS-permitted crushed stone aggregate operations in Douglas County, developed in Cambrian to Mississippian limestones and quartzites, which are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). Crushed stone quarries are also mapped in the limestone members of the Colorado Group, although limestone in the overlying Fort Hays Member of the Cretaceous Niobrara Formation may crop out in the area as well (Tweto, 1979a). The Niobrara Formation and Colorado Group may host suitable source rocks where the limestone is dense, well-consolidated, and free from abundant joints and fractures (Knepper et al., 1999; Langer and Knepper, 1995). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as a ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Colorado Group is designated H/D along a belt with numerous operations and M/B elsewhere for crushed stone aggregate occurrence potential. Cambrian to Mississippian limestones and quartzites, mapped as MC or DOC, are assigned H/D for crushed stone potential.

The Tertiary Wall Mountain Tuff occurs as prominent buttes throughout the county; dense, fine-grained igneous rocks like some tuffs satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Wall Mountain Tuff meets the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999). The Wall Mountain Tuff is assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The weathered and jointed Precambrian Boulder Creek Granite is classified as a "fair" source rock by Knepper et al. (1999). Arbogast et al. (2011) categorized the younger Pikes Peak Granite as a good-quality source for crushed stone aggregate, but Knepper et al. (1999) classified it as unsuitable due to the degree of weathering. Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Boulder Creek Granite is assigned M/C, and the Pikes Peak Granite is assigned M/B, for crushed stone aggregate potential. Precambrian biotite schist (Idaho Springs Formation) is assigned L/B for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Fountain and Permian-Triassic Lykins Formations, the Jurassic Morrison Formation, Cretaceous Dakota and Fox Hills Sandstones, and the Tertiary Dawson Arkose and White River Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone at its contact with the Colorado Group. The Dakota Sandstone is designated H/D along the belt of operations and L/C elsewhere, for crushed stone potential. The Fox Hills Sandstone is designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.13.29 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation, as well as the Tertiary White River Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The undivided Fox Hills Sandstone and Laramie Formation are designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Tertiary Denver Formation and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The Denver Formation and Dawson Arkose (mapped as TKdl or Tdu) are designated M/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in Precambrian igneous and metamorphic rocks of Douglas County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The moderately weathered Pikes Peak Granite is designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Sporadic outcrops of felsic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.13.30 Clay

There are numerous clay producers and prospects in Douglas County (USGS MRDS, 2013). The clay-bearing Permian-Triassic Lykins Formation, Jurassic Morrison Formation, the Cretaceous Dakota Sandstone, Colorado Group (including the Graneros Shale), Pierre Shale, Fox Hills Sandstone, and Laramie Formation, and the Tertiary Dawson Arkose and White River Formation together cover over half of Douglas County. Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the

Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The best quality refractory clays in the RGFO region are found in the Dry Creek Canyon Member of the Dakota Sandstone (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Several clay producers are developed in the undifferentiated Morrison Formation and Dakota Sandstone in Douglas County (USGS MRDS, 2013); this unit is designated H/D for clay occurrence potential.

There are two fire clay producers developed in the Colorado Group, although most prospects developed in the Graneros Shale throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Colorado Group is assigned M/D for clay potential.

The Cretaceous Pierre Shale, which crops out in the eastern part of Douglas County, hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). Shale interbeds of the underlying Fox Hills Sandstone and the overlying Tertiary White River Formation host clay suitable for brick making (Vanderwilt, 1947). The undifferentiated Laramie Formation and Fox Hills Sandstone are designated M/C, and the Pierre Shale is assigned H/C, for clay potential. The White River Formation, which hosts one clay pit in this county, is assigned L/B for clay potential.

The Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses; kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Both fire and common clay is produced from the Dawson Arkose in this county, numerous USGS MRDS (2013) and DRMS-permitted mines are noted in this unit in northern Douglas County. The Dawson Arkose is designated M/D in areas of production and M/C elsewhere for clay potential in Douglas County.

There are several clay prospects developed in the Lykins Formation along the Front Range of Douglas County; this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated M/C for clay occurrence potential. There is a clay pit developed along East Plum Creek, likely in the Piney Creek Alluvium; this unit is assigned L/C for clay potential near the occurrence.

4.13.31 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Douglas County hosts granites, sandstones, conglomerates, and volcanic rocks that have been quarried for dimension stone, including the Precambrian Pikes Peak Granite, Cambrian to Mississippian limestone and quartzite, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, the Cretaceous Dakota Sandstone, and the Tertiary Wall Mountain Tuff (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Precambrian Pikes Peak Granite has been quarried for dimension stone, although where weathered or highly jointed, this granite is more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak Granite is designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). These units are designated H/D for dimension and building stone occurrence potential; the Fountain Formation and Codell Sandstone capping the Colorado Group are assigned M/C for dimension stone potential. Other sandstone-bearing units in the county, but without documented production of dimension stone, include the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation, Dawson Arkose, and White River Formation. As sandstone-bearing units, these rocks are designated M/B for dimension and building stone occurrence potential.

Production of dimension stone is reported from the Sawatch Quartzite, Manitou Formation, and Leadville Limestone in several counties (e.g., Pueblo, Fremont, and Chaffee) from undifferentiated Cambrian through Mississippian limestones and quartzites that are mapped as MDO, OC, or MC (Del Rio, 1960; Schwochow, 1981; Tweto, 1979a). The Cambrian to Mississippian mapped unit, MC, in Douglas County is designated H/D for dimension stone potential.

The Wall Mountain Tuff is a welded, rhyolitic, ash-flow tuff that forms up to 35-foot caps on the Dawson Arkose forming buttes throughout Douglas County (Arbogast et al., 2011; Del Rio, 1960; Tweto; 1979a). The deposits have been quarried for high-quality dimension and building stone, and Del Rio (1960) estimated reserves at over 1 million tons. The Wall Mountain Tuff is designated H/D for dimension stone potential.

4.14 El Paso County

4.14.1 Coal

Over 16 million tons of coal were recovered between 1864 and 2002 from the north-central part of El Paso County, which lies within the southernmost Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR) (Brandt, 2015; Carroll and Bauer, 2002). Carroll and Bauer (2002) report production from the Cretaceous Laramie Formation at 74 historic mines in El Paso County. Currently, there is one terminated CDRMS coal permit in the county. Of an estimated 572 million tons of original coal resources under less than 3,000 feet of overburden in the county, roughly 32.3 million tons are depleted, implying reserves of 539.7 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in El Paso County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.14.2 Geothermal

Traditional / EGS Geothermal

The entirety of El Paso County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

El Paso County contains one known well, the Papeton Well, in north Colorado Springs (NREL, 2016). This location is designated as H/D for direct use. Almost all of the western half of El Paso County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The rest of El Paso County is designated as H/B for low temperature and/or co-produced geothermal resources.

4.14.3 Gold

There is no reported gold production for El Paso County; however, several gold occurrences are scattered throughout the Pikes Peak batholith in this and other (e.g., Teller and Douglas) counties, and so the batholith is designated M/B for gold occurrence potential. Mineralization (primarily fluorite with minor gold) in the St. Peters Dome (Cheyenne) district, adjacent to the Mt. Rosa alkalic intrusive center in the Pikes Peak batholith, may be related to the Tertiary intrusion of the Cripple Creek volcanic complex, which hosts the most productive gold deposits in Colorado (Cappa, 1998; Smith et. al., 1999; Stevens, 1949). Several gold occurrences are reported in this area on the USGS MRDS (2013), and a buffer around these occurrences and the Mount Rosa district is assigned M/C.

4.14.4 Silver

Though there is no reported production of silver in El Paso County, several occurrences are noted in the Windy Point granite, Mount Rosa intrusive complex, and Cheyenne district areas, all within the boundaries of the Pikes Peak batholith (USGS MRDS, 2013). The Pikes Peak batholith is designated M/B for silver occurrence potential.

4.14.5 Copper-Lead-Zinc

El Paso County had minimal base-metal production reported: 13,276 pounds of copper were produced from 1913 to 1914 in the Blair Athol district (Henderson, 1926). Deposits of the Blair Athol mine, northwest of Colorado Springs, occur as nodules of chalcocite rimmed in malachite and azurite along bedding planes or fractures in the Permian Lyons Sandstone (Lovering and Goddard, 1950). The rock unit that hosts this mine is designated M/C for minimal production. Several base-metal prospects occur east of the Teller County Mount Rosa district and in the Cheyenne (St. Peters Dome) district (USGS MRDS, 2013). Pegmatites from the Pikes Peak region are reported to contain galena and sphalerite (Heinrich, 1957). These areas are designated M/C. Outside of these areas, the Pikes Peak Granite and other Precambrian rocks are designated L/B.

4.14.6 Iron

About 40 tons of hematite and 20 tons of yellow ochre were produced at the Talca Gulch Iron mine near the contact of Pikes Peak Granite and Ordovician Manitou Limestone (Harrer and Tesch, 1959). A buffer around this producer is designated H/C for iron potential. Late-stage syenite, fayalite, and mafic intrusions into the Precambrian Pikes Peak batholith host iron-rich minerals, and a couple of past producers (Iron King mine in the Windy Point granite and Stove Mountain Minerals in the Mt. Rosa fayalite) are noted (Smith et al., 1999; USGS MRDS, 2013). Buffers around the producers are assigned M/C for iron potential; elsewhere, the mafic units are designated M/B for iron potential. In the rest of the county, the Pikes Peak batholith is designated L/B for iron occurrence potential.

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Magnetite ore averaging 43 percent iron was mined from Precambrian schist near Fountain Creek (Harrer and Tesch, 1959). A buffer around this prospect is assigned M/C; elsewhere Precambrian metamorphic rocks in the county are designated L/B for iron occurrence potential. Precambrian Silver Plume-related granites host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B.

Limonite and siderite concretions were mined in the Rusty Zone of the Cretaceous Pierre Shale in neighboring Pueblo County (Gilbert, 1897; Harrer and Tesch, 1959; Scott; 1969). The lower unit (Sharon Springs shale) of the Pierre Formation in El Paso County is designated H/C for iron occurrence potential. The Mississippian Leadville Dolostone hosts limonite, and several past producers are noted from other counties (Cappa and Bartos, 2007); this unit is designated L/B in El Paso County. Thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in El Paso County.

4.14.7 Manganese

Production of 42.2 percent manganese ore (wad) is reported in 1958 from the Rampart No. 1 claim, which occurs in the Windy Point Granite of the Pikes Peak batholith (Smith et al., 1999; USGS MRDS, 2013). Samples from the nearby Iron King mine contained 25 to 30 percent manganese oxide (USGS MRDS, 2013). Manganese oxide occurs in the upper Dawson Arkose at the Burgess claim and Blair Athol mine (Lovering and Goddard, 1950; USGS MRDS, 2013). Manganese occurs at an unnamed prospect in the Silver Plume quartz monzonite (USGS MRDS, 2013). Wolframite ($(FeMn)WO_4$) is reported from Park Lodes 1-4 in proximity to the Mount Rosa intrusive complex in the Pikes Peak batholith (USGS MRDS, 2013). The area around each mine is designated M/C for manganese potential whereas the upper Dawson Arkose elsewhere in the county is assigned M/B. The White River Formation, which overlies the upper Dawson Arkose, is assigned L/B. Precambrian metamorphic rocks are assigned a potential of L/B throughout the county.

4.14.8 Molybdenum

There are no known molybdenum prospects in El Paso County, but the Precambrian metamorphic and igneous rocks are designated L/B since minor tungsten occurs in the same rocks in other counties (e.g., Park and Teller).

4.14.9 Nickel

There are no known occurrences of nickel in El Paso County, but Precambrian metamorphic and igneous rocks throughout the county are designated L/B for nickel potential due to minor occurrences in similar rocks in nearby counties (e.g., Teller, Douglas, and Jefferson).

4.14.10 Tungsten

The Park Lodes 1-4 claims contain wolframite veins in the Pike Peaks granite associated with the Mount Rosa intrusive center (USGS MRDS, 2013). These occurrences are similar to the Teller

County Heavystone prospect within the same complex. The Mount Rosa area is M/C for tungsten occurrence potential; Pikes Peak Granite elsewhere is L/B.

4.14.11 Beryllium

Crystals of the beryllium silicate, phenakite, are found at Crystal Park (Eckel, 1961). The occurrence potential for beryllium in El Paso County is considered M/C around a cluster of beryllium-bearing pegmatites located at the contact of the Mount Rosa intrusive complex (St. Peters Dome and Crystal Park areas) and the Pikes Peak batholith (Heinrich, 1957; USGS MRDS, 2013). The remainder of the Pikes Peak batholith is assigned a beryllium potential of M/B. Granitic rocks elsewhere in the county are designated L/B.

4.14.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in El Paso County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.14.1 of this MPR) is designated L/B for germanium occurrence potential.

Sphalerite is reported from several zinc occurrences in the western and southwestern portion of the county (USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.14.13 Rare Earth Elements

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, including the sodic Mount Rosa intrusive complex in western El Paso County, all of which are enriched in REEs, especially LREEs (Gross and Heinrich, 1965; Persson, 2016; Simmons et al., 1999; Smith et al., 1999). Allanite, bastnaesite, cerianite, fergusonite, yttrium fluorite, xenotime, and monazite are reported from the many pegmatites of the Mount Rosa complex and St. Peters Dome area (Adams, 1968; Gross and Heinrich, 1966; Olson and Adams, 1962; Persson, 2016; Smith et al., 1999; Stevens, 1949). Samples from Mount Rosa dikes assayed upwards of 1,018 ppm total REE oxides, more than 4 times the normal crustal abundance (Smith et al., 1999). The pink Pikes Peak granite and potassic Windy Point granitic intrusion assayed up to 853 ppm and 980 ppm total REE oxides, respectively (Smith et al., 1999). The region around the Mount Rosa complex is designated H/C for REE occurrence potential; the composite Pikes Peak batholith elsewhere is assigned M/C.

4.14.14 Niobium-Tantalum

Euhedral fergusonite crystals, as well as microlite, pyrochlore, and samarskite, are reported from zoned pegmatites in the Pikes Peak batholith of Jefferson and Douglas Counties (Haynes, 1965; Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite

(Simmons and Heinrich, 1980). In El Paso County, niobium-tantalum minerals are reported from pegmatites in the Pikes Peak batholith in the St. Peters Dome area and around the perimeter of the peralkaline Mount Rosa intrusive center (Parker, 1968). Buffers along pegmatite zones in Pikes Peak Granite of El Paso County are designated L/B for niobium-tantalum occurrence potential.

4.14.15 Tellurium

There are no reported occurrences of tellurium in El Paso County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.14.16 Titanium

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals (Smith et al., 1999; USGS MRDS, 2013). Rutile occurs in veins and pegmatites of late-stage fayalite intrusions into the Pikes Peak batholith in the Mount Rosa–St. Peters Dome area, and a couple of past producers (Eureka Shaft and Stove Mountain Mineral) are noted (Eckel, 1961; Schwochow and Hornbaker, 1985; USGS MRDS, 2013). At the head of Fountain Creek, five carloads of titaniferous magnetite ore containing 2 percent TiO_2 were removed from a quartz monzonite porphyry (Fountain Creek Magnetite Deposit) (Harrer and Tesch, 1959; Tweto, 1979a). Buffers around the producers are assigned M/C for titanium occurrence potential; elsewhere, the alkalic and mafic units are designated L/B for titanium potential.

Economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone in El Paso County is designated L/B for titanium occurrence potential.

4.14.17 Uranium

In El Paso County, 277 pounds of U_3O_8 from 0.13 percent uranium ore was mined from the Cretaceous Dakota Sandstone at the Mike Doyle Carnotite Deposit (a.k.a. Lucky Ben Lease), located along Highway 115, south of Colorado Springs (Nelson-Moore et al., 1978). Additionally, records indicate that about 500 tons of ore containing uranium and thorium were apparently produced at the nearby St. Peters Dome No. 1 mine from mineralized veins in the Precambrian Mount Rosa alkaline granite (Nelson-Moore et al., 1978). The undivided Dakota Sandstone-Purgatoire Formation in southwestern El Paso County is designated H/C for uranium occurrence potential; the Mount Rosa intrusive complex is also assigned H/C for uranium potential. Late-stage Precambrian Windy Point alkalic intrusions into the Pikes Peak batholith are assigned L/B for potential.

Several uranium prospects occur in Mesozoic sedimentary rocks in this and neighboring counties in the Jurassic undivided Morrison, Entrada, and Ralston Creek group (Nelson-Moore et al., 1978; USGS MRDS, 2013). These units in El Paso County are designated L/B for uranium occurrence potential.

Part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in El Paso County are designated L/B for uranium potential.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.14.18 Thorium

Meeves et al. (1966) reports production of 39 tons of thorite from pegmatites in El Paso County through 1963. Thorium in monazite is found in veins and lenses in pegmatites along faults in the Precambrian Pikes Peak batholith at several mines in the St. Peters Dome area of El Paso County; some production is reported (Heinicke, 1960; Schwochow and Hornbaker, 1985; USGS MRDS, 2013). Buffers along faults in Precambrian crystalline rocks are designated M/C in the St. Peters Dome area and L/C elsewhere for thorium occurrence potential.

4.14.19 Vanadium

There is no vanadium production reported from El Paso County; however, carnotite occurs in the Dakota Sandstone at the Avery Ranch and Mike Doyle deposits (Nelson-Moore et al., 1978). Also, carnotite occurs in several Dakota Sandstone prospects in Fremont and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential. Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985).

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone throughout the county are designated L/B for vanadium occurrence potential.

4.14.20 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, both of which are found in El Paso County (Wallace, 2010). The Pikes Peak composite batholith comprises the main granitic body plus numerous late-stage peraluminous to peralkaline granitic plutons, all of which host pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999; Tweto, 1987). Fluorite is a primary accessory mineral in all phases of the Pikes Peak composite batholith and related pegmatites; the composite batholith averaged 2,140 to 3,500 ppm fluorine and ranged up to 100,000 ppm (Wallace, 2010). Several fluorspar prospects are developed in the El Paso County portion of the batholith near the Mount Rosa and St. Peters Dome areas (USGS MRDS, 2013). The St. Peters Dome district has produced green, purple, and some colorless fluorite intermittently since 1910; production in 1944-1945 amounted to 16,100 tons of ore and reserves are estimated at 65,000 tons of 35 percent CaF_2 (Brady, 1975; Del Rio, 1960; Eckel, 1961). The deposits occur in veins in a northeast-trending belt of Pikes Peak Granite about 1,200 feet wide by 1,700 feet long (Brady, 1975). The Mount Rosa and St. Peters Dome productive area is assigned H/D and Precambrian igneous rocks elsewhere, including all phases of the Pikes Peak batholith, are designated H/C for fluorspar occurrence potential; Precambrian biotite gneiss is assigned M/C.

4.14.21 Diamond and Gemstones

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, including the sodic Mount Rosa intrusive complex in western El Paso County, all of which host pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999). Gem-quality fluorite, topaz, quartz, amazonite, and zircon are reported from the numerous pegmatites of the Mount Rosa complex, St. Peters Dome, Stove Mountain, and Crystal Park areas (Eckel, 1961; Pearl, 1972; Persson, 2016; Scott, 1968b). A buffer around this region is designated H/D for gemstone occurrence potential. Pegmatites hosting amazonite, smoky quartz, topaz, and amethyst occur sporadically throughout the Pikes Peak region (Arbogast et al., 2011, Pearl, 1972). The Pikes Peak batholith outside the Mount Rosa area is assigned M/C for gemstone potential.

Abundant petrified wood specimens hosting agate and carnelian occur in the area of Austin Bluffs in Colorado Springs (Eckel, 1961); a buffer around this area is labeled M/C for gemstone potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the nearby CMB, Precambrian biotite gneisses and schists are assigned M/B for gemstone potential (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954). Pegmatites are known to occur in Silver Plume-aged plutons, and these units are assigned L/B for gemstone potential (Boos, 1954).

4.14.22 Pegmatite Minerals

In a study of Colorado pegmatites, Heinrich (1957) grouped the pegmatites of El Paso County into the Pikes Peak-Florissant pegmatite province and characterized them as generally small with a central quartz vug. Meeves et al. (1966) report production of 4 tons of scrap mica from pegmatites in El Paso County through 1963. The Johnny Feldspar mine, located in proximity to a contact between Boulder Creek and Silver Plume-aged granites, produced a few tons of feldspar (microcline) through 1942 (Hanley et al., 1950). An unnamed pegmatite intrudes Pikes Peak granite northwest of the Johnny Feldspar mine and is listed as a past producer of feldspar on the USGS MRDS (2013). The area around these occurrences is designated H/C for pegmatite occurrence potential. Elsewhere in the county, Precambrian biotite gneiss and schists are assigned M/B for potential. Precambrian plutonic rocks are considered L/B except the Pikes Peak batholith which is designated M/C.

4.14.23 Industrial Abrasives

There is no reported production of industrial abrasives in El Paso County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks in the county are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954). Buffers around two clusters of pegmatites near the Mount Rosa and St. Peters Dome areas are assigned H/C for industrial abrasive potential.

4.14.24 Limestone and Dolomite

There are several limestone quarries developed in Paleozoic limestone units in El Paso County, including the Leadville, Williams Canyon, and Manitou Limestones (USGS MRDS, 2013). The Leadville group of limestones has historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). These units are designated H/D for limestone and dolomite occurrence potential in areas of known quarries and H/C elsewhere. Undifferentiated Mesozoic and Paleozoic mapped units are assigned L/C.

The Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in

Colorado; both are found in the southwestern corner of the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential.

4.14.25 Industrial Sand

Widespread Quaternary eolian sands are composed of well-sorted and well-rounded quartz grains; significant past and present production is reported from eolian sands in El Paso County (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001). Eolian sands are designated H/D around permitted operations, and H/C elsewhere, for industrial sand occurrence potential in El Paso County. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). The Lykins Formation and Dakota Sandstone are designated H/C for industrial sand occurrence potential. Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose throughout the RGFO region, including in El Paso County (Arbogast et al., 2011). The Dawson Arkose is designated M/D around a cluster of permitted operations, and L/C in the rest of the county, for industrial sand potential.

4.14.26 Gypsum

Although no bedded gypsum is reported from within the Jurassic Morrison Formation in El Paso County, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). Darton (1906) reports a 30-foot-thick bed of gypsum below the Morrison Formation at the Garden of the Gods; George (1920) reports massive gypsum up to 60 feet thick below the Morrison Formation at nearby Glen Eyrie. These deposits were mined from 1875 to 1907 (Schwochow, 1981; Withington, 1968). Several gypsum quarries hosted by the Ralston Creek Formation occur in Pueblo and Fremont Counties (USGS MRDS, 2013). The Stevens Gypsum mine (Pueblo County), reportedly developed in the undivided Colorado Group, likely recovered gypsum from the underlying Morrison and Ralston Creek Formations; production of 700 tons of gypsum per month at one point is recorded (George, 1920; USGS MRDS, 2013). George (1920) identified a massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8 mile section just above the Permian-Triassic

Lykins Formation and below the Morrison Formation at Perry Park in Douglas County. The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/D for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation as well (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in western El Paso County.

4.14.27 Sand and Gravel

Del Rio (1960) reports production of over 5.3 million tons of sand and gravel, primarily from alluvium, in El Paso County between 1954 and 1958. High-quality sand and gravel deposits in El Paso County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In El Paso County, the undifferentiated Dawson Arkose, Denver Formation, and Arapahoe Formation, which host numerous occurrences in this and other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968). The Paleozoic Fountain Formation, Lykins Formation, Dakota Sandstone, and Lytle Sandstone Member of the Purgatoire Formation also host sporadic sand and gravel operations in this and other counties (W.D. Carter, 1968); these units are assigned L/C for sand and gravel potential.

4.14.28 Crushed Stone Aggregate

There are numerous DRMS-permitted crushed stone aggregate operations in El Paso County, developed in Cambrian to Mississippian limestones, sandstones, and quartzites, which are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). The Fort Hays Member of the

Cretaceous Niobrara Formation has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as "fair" source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential. Cambrian to Mississippian limestones, sandstones, and quartzites, mapped as Or, MC, or OC, are assigned H/D for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Cripple Creek pluton and satellites in El Paso, Fremont, Park, and Teller Counties, are deemed excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995); one past DRMS-permitted aggregate quarry is reported in the El Paso portion. The older, more weathered and jointed Precambrian Boulder Creek Granite is classified as a 'fair' source rock by Knepper et al., (1999). Arbogast et al. (2011) reports the younger Pikes Peak Granite would make good-quality crushed stone aggregate, but Knepper et al. (1999) classify it as unsuitable due to the degree of weathering. Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Cripple Creek pluton and satellites are designated H/C, the Boulder Creek Granite is assigned M/C, and the Pikes Peak Granite is assigned M/B, for crushed stone aggregate potential. Precambrian biotite schist (Idaho Springs Formation) is assigned L/B for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Fountain and Permian-Triassic Lykins Formations, the Jurassic Morrison Formation, the Cretaceous Dakota and Fox Hills Sandstones, and the Tertiary Dawson Arkose and White River Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are sporadic DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in other counties. The Dakota and Fox Hills Sandstones are designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.14.29 Lightweight Aggregate

In southwestern El Paso County, highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Purgatoire Formation and Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Purgatoire Formation, Dakota Sandstone, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Tertiary Denver Formation and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The Denver Formation and Dawson Arkose (mapped as TKdl or Tdu) are designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation, the Cretaceous Niobrara Formation, and the Tertiary White River Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are abundant in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are common in Precambrian igneous and metamorphic rocks of El Paso County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The moderately weathered Pikes Peak Granite is designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

4.14.30 Clay

There are numerous clay producers in a dozen Pennsylvanian through Tertiary shale-bearing rock units in El Paso County (USGS MRDS, 2013). The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone) and Glencairn Shale Member (Purgatoire Formation); numerous producers occur in this unit in nearby Douglas, Pueblo, and Fremont Counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). The undifferentiated Dakota Sandstone and Purgatoire Formation is designated H/D for clay occurrence potential.

Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation; a few producers in this unit are noted from other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). Most prospects developed in the Cretaceous Graneros Shale (Colorado Group), as well as the overlying Niobrara Formation, throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Morrison Formation, Colorado Group, and Niobrara Formation are assigned M/C for clay potential.

The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). Shale interbeds of the underlying Fox Hills Sandstone and the overlying Tertiary White River Formation host clay suitable for brick making (Vanderwilt, 1947). The Laramie Formation and Pierre Shale are designated H/C for clay potential. The White River Formation, which hosts 3 clay pits in this county, is assigned L/C in the area of production and L/B elsewhere, for clay potential. The Fox Hills Sandstone is assigned L/C, and the undivided Laramie Formation and Fox Hills Sandstone is assigned M/C, for clay potential.

The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses; kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Both fire and common clay is produced from the Dawson Arkose in Douglas County and numerous USGS MRDS (2013) and DRMS-permitted mines are noted in El Paso and Douglas Counties. The Dawson Arkose is designated M/D in areas of production and M/C elsewhere for clay potential.

There are several clay prospects developed in the Permian-Triassic Lykins Formation along the Front Range; this unit has also been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation, as well as undifferentiated Mesozoic-Paleozoic rocks, are designated M/C for clay occurrence potential.

4.14.31 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). El Paso County hosts granites, limestones, sandstones, and conglomerates that have been quarried for dimension stone, including the Precambrian Pikes Peak and Granites, Cambrian to Mississippian limestones and quartzite, Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Precambrian Pikes Peak and Silver Plume-aged granites have been quarried for dimension stone in the RGFO region, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak and Cripple Creek granitic plutons are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Production of dimension stone is reported from the Sawatch Quartzite, Manitou Formation, and Leadville Limestone in several counties (e.g., Pueblo, Fremont, and Chaffee) from undifferentiated Cambrian through Mississippian limestones and quartzites mapped as MDO, OC, or MC (Del Rio, 1960; Schwochow, 1981; Tweto, 1979a). The Cambrian to Mississippian mapped units, OC and MC, in El Paso County are designated H/D for dimension stone potential.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). These units are designated H/D for dimension and building stone occurrence potential; the Fountain Formation is assigned M/C for dimension stone potential. Other sandstone-bearing units in the county, but without documented production of dimension stone, include the Jurassic Morrison and Ralston Creek Formations, the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation, Dawson Arkose, and White River Formation. As sandstone-bearing units, these rocks are designated M/B for dimension and building stone occurrence potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential.

4.15 Elbert County

4.15.1 Coal

Most of Elbert County, except the eastern edge, lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). Carroll and Bauer (2002) report production of 109,628 tons of coal from the Laramie Formation at 12 past-producing mines in Elbert County through 2001. There are two terminated and one inactive CDRMS coal exploration permits in the county, indicating there is the continued potential for coal exploration. Of an estimated 787.8 million tons of original coal resources under 3,000 feet of overburden in the county, only 188 thousand tons are reportedly depleted, implying reserves of 787.6 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Elbert County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.15.2 Geothermal

Traditional / EGS Geothermal

The entirety of Elbert County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Elbert County contains no known wells or springs. The majority of Elbert County is designated as H/B because the estimated temperature is above the 100°F threshold for low temperature and co-produced resources but is outside named COGCC fields. The areas within named COGCC fields are designated as H/C.

4.15.3 Gold

The dry gulches near Elizabeth, Colorado in westernmost Elbert County are host to placer gold deposits likely sourced from the Oligocene Castle Rock Conglomerate along the Cherry Creek divide (Desborough et. al., 1970). The placer gold exhibits the same fineness as other Cherry Creek divide placers (e.g., Arapahoe, Denver, and Douglas Counties) (Desborough et al., 1970). Production of 132 ounces of placer gold was reported between 1926 and 1941 (Parker, 1974; Vanderwilt, 1947).

Gold Creek from near the western county line to just northeast of Elizabeth is designated as M/C for gold occurrence due to past production. There are likely other gulches nearby that have potential if they drain areas of gold-bearing Castle Rock Conglomerate, but their locations are uncertain.

4.15.4 Silver

There is no reported production of silver in Elbert County; however, silver was found at a small placer gold prospect along Gold Creek (USGS MRDS, 2013). A buffer around this occurrence is assigned a potential of L/B.

4.15.5 Iron

No iron production is reported in Elbert County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Elbert County.

4.15.6 Manganese

Psilomelane occurs as concretions, fracture fillings, and cement in the Tertiary upper Dawson Arkose at the Harris Manganese Deposit in westernmost Elbert County (Traver, 1947; USGS MRDS, 2013; Wells et al., 1952). The area around this past producer is designated M/C whereas the upper Dawson Arkose elsewhere in the county is assigned M/B for manganese occurrence potential. The White River Formation, which overlies the upper Dawson Arkose, is assigned L/B.

4.15.7 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Elbert County; however, the Denver Coal Region in the county (see section 3.1.1 and 4.15.1 of this MPR) is designated L/B for germanium occurrence potential.

4.15.8 Titanium

Fossil heavy-mineral placer deposits, including rutile and ilmenite, occur in subtidal, forebeach, backbeach, and washover fan deposits at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone (Arbogast et al., 2011; Pirkle et al., 2012). Radar Acquisitions Corp. (now CanAm Coal) reported a resource estimate of 14.2 million tons of material containing 2.3 percent ilmenite and 0.1 percent rutile (Carroll et al., 2002). The Fox Hills Sandstone in Elbert County is designated H/C for titanium occurrence potential.

4.15.9 Uranium

A single, minor uranium occurrence is known in Elbert County, which was detected by an airborne radiometric program. Shallow drilling at one anomaly yielded drill cuttings with low concentrations of uranium in the Cretaceous Laramie Formation near the Town of Limon. A large part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in Elbert County are designated L/B for potential.

4.15.10 Vanadium

There is no vanadium production reported in Elbert County; however, carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation and underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.15.11 Diamond and Gemstones

Numerous petrified logs hosting carnelian and agate occur in the region between Running and Cherry Creeks, as well as near the heads of Kiowa and Bijou Creeks, in southwestern Elbert County (Eckel, 1961). A buffer around this region is designated M/C for gemstone occurrence potential.

4.15.12 Industrial Sand

Quaternary eolian sands in Elbert County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and two DRMS-permitted operations are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in this (along East Bijou Creek) and other counties (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose throughout the RGFO region (Arbogast et al., 2011). The Dawson Arkose is designated L/C for industrial sand potential.

4.15.13 Helium

The north-central portion of Elbert County is designated L/C for helium due to its location near the Denver Basin.

4.15.14 Sand and Gravel

High-quality sand and gravel deposits in Elbert County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). This unit is designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, host a dozen quarries and are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Cretaceous and Tertiary sedimentary rocks host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in some areas (W. D. Carter, 1968); this unit is considered H/D for sand and gravel potential. The undifferentiated Dawson Arkose, Denver Formation, and Arapahoe Formation, as well as the Fox Hills Sandstone, all of which host sporadic sand and gravel operations in this and other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968). The White River Formation hosts several small gravel operations; this unit is assigned L/C for sand and gravel potential (USGS MRDS, 2013).

4.15.15 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Elbert County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone as well as the Tertiary Dawson Arkose, White River Formation, and Ogallala Formation, may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999). The Fox Hills Sandstone is designated L/C, and the Dawson Arkose, White River Formation, and Ogallala Formation are assigned L/B, for crushed stone aggregate occurrence potential.

4.15.16 Lightweight Aggregate

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie

Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Denver Formation and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The Denver Formation and Dawson Arkose are designated M/B for lightweight aggregate potential.

Suitable expandable clays may be found in the Tertiary White River Formation, which is composed of ashy claystones and sandstones (Knepper et al., 1999). The White River Formation is assigned L/B for lightweight aggregate occurrence potential.

4.15.17 Clay

There is one clay pit developed in the Laramie Formation and another in the Dawson Arkose in Elbert County (USGS MRDS, 2013). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). The Pierre Shale and Laramie Formation are designated H/C, and the Dawson Arkose is designated M/C, for clay potential.

Shale interbeds of the Cretaceous Fox Hills Sandstone and the Tertiary White River Formation host clay suitable for brick making; these units are designated L/C for clay potential (Vanderwilt, 1947). There are 3 clay pits developed in the alluvium along Kiowa Creek; the alluvial mapped unit along this creek is assigned L/C for clay potential.

4.15.18 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Elbert County, the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation, Dawson Arkose, White River Formation, and Ogallala Formation host sandstones in part but have no documented production of dimension stone. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the remaining sedimentary units are designated M/B, for dimension and building stone occurrence potential.

4.16 Fremont County

4.16.1 Coal

The Cañon City Coal Region (section 3.1.4 of this MPR) is completely contained in the southeastern part of Fremont County. Nearly 200 historic mines have produced 48 million tons of high-volatile C bituminous coal from the Upper Cretaceous Vermejo Formation (identified as and essentially correlated with the Laramie Formation by Washburne, 1910b) in the Cañon City Coal Region between 1864 and 2002 (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). Five terminated CDRMS coal exploration permits and six terminated, permanent cessation, or revoked CDRMS coal permits are noted in the county. As discussed in section 3.1.4, there is one coal permit for which CDRMS is awaiting the warranty package. That same company, Northfield Partners, LLC also has an active coal exploration permit; both permits are located in the Vermejo Formation between Brookside and Rockvale, southeast of Cañon City.

An estimated original coal resource of 295.3 million tons under less than 3,000 feet of overburden and depletion through 2002 of 85.6 million tons implies coal reserves of 209.7 million tons (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). Boreck and Murray (1979) estimated reserves at 107 million tons, whereas Brandt (2015) estimated reserves at 247 million tons. The Cañon City Coal Region is designated H/D for coal occurrence potential. RGFO management area coal occurrence potential is shown on Map 7-1 in section 7.

4.16.2 Geothermal

Traditional / EGS Geothermal

The majority of Fremont County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area along the southwestern border is considered M/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Several thermal springs and wells are found in Fremont County, mostly concentrated in the Cañon City/Penrose/Florence area (Barrett and Pearl, 1978; Zacharakis and Pearl, 1982; Cappa and Hemborg, 1995). The hottest is the Desert Reef well, with a temperature of 131^{o}F (NREL, 2016). The Desert Reef Hot Springs is an old oil well that was plugged back to a depth of 1,096 feet and now produces 129^{o}F water (Cappa and Hemborg, 1995). The Cañon City Hot Spring water was discharged from the contact between the Fremont Limestone and overlying Fountain Formation (Zacharakis and Pearl, 1982), but the pool was filled in and the well casing severely degraded when documented by Cappa and Hemborg (1995). Water from the Florence Artesian Well (a.k.a. Penrose Artesian Well) is 82^{o}F and is produced from an unknown depth, although the aquifer is thought to be the Dakota Sandstone (Barret and Pearl, 1978). The 1,800-feet deep well at the Fremont Natatorium produces 95^{o}F water (Zacharakis and Pearl, 1982). Two springs occur in very western Fremont County at Swissvale and Wellsville. The Swissvale Warm Spring is only 68 to 82^{o}F, and the water at the Wellsville Warm Spring is 82 to 91^{o}F (Barret and Pearl, 1978). Geothermometry models described by Barrett and Pearl (1978) suggest subsurface reservoir temperatures may be as high as 35 to 50^{o}C, but they note that the models may not be appropriate for use because some of the assumptions in the model were violated.

Ringrose (1980) ran temperature logs in 11 drill holes in the Cañon City area that were drilled specifically for determination of geothermal gradients. The gradients in these holes ranged from 2.17 to 4.92^{o}F/100ft, with the highest gradients located on the Brush Hollow Anticline. In 1981, Professor Gwinn, from Southern Methodist University, determined the gradients to be 1.24 to 4.67^{o}F/100ft and the heat flow ranged from 34 to 130 mW/m^2 (Zacharakis and Pearl, 1982).

Zacharakis and Pearl (1982) conducted an assessment of the geothermal resources of the Cañon City area that included several geophysical methods: electrical resistivity, telluric, audio-magnetotelluric, and seismic. They also performed soil mercury geochemical sampling in three areas: near the Penrose artesian thermal well, on the grounds of the Colorado Department of Corrections, and at the Cañon City Hot Spring. The geophysical studies provided some information useful for the geothermal assessment, but the mercury survey did not, due to anthropogenic disturbances. Zacharakis and Pearl concluded that geothermal resources of the area were “large”, and were chiefly a result of favorable geologic conditions and heating by radioactive decay. Gamma-rays logs indicated the presence of radioactive minerals in the Dakota Group, Morrison Formation, Fountain Formation, and Precambrian rocks, and high levels of dissolved radium-226 were detected in groundwater in the Dakota Group (Vinckier, 1982). The overlying Pierre Shale, which has low thermal conductivity, was proposed as a cap that effectively trapped the heat in the underlying formations.

Dixon (2004) evaluated bottom-hole temperatures in petroleum wells in the Cañon City Embayment. About 30 wells were included in the analysis. The hottest borehole temperature was about 189°F at a depth of 3,930 feet in the Jurassic Morrison Formation. Due to the limited amount of data and its scattering on a depth-versus-temperature plot, Dixon was unable to draw any conclusions from the data, but this report does contain a summary of bottom-hole temperatures for each well.

Fremont County contains four wells and two springs in the NREL (2016) database; all of these features are described above. These locations, and one noted current direct-use operation, are designated as H/D for direct use. The Desert Reef Hot Springs, with a temperature of >122°F, has a 5 mile buffer zone that is H/D potential, as the U.S. EERE (2004) and NREL (2016) deem this the distance sufficiently hot waters can be transported for direct use. Some historic springs and wells noted by Barret and Pearl (1978) and Zacharakis and Pearl (1982) are not included in the NREL database, and therefore fall into the classification for other low temperature resources in the county. The majority of the rest of Fremont County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. Areas along the Arkansas River from Spikebuck to Cotopaxi, in the southwestern corner of the county, and along Oak Creek in the south-central part of the county are designated H/B for low temperature and/or co-produced geothermal resources. Those areas that are greater than the 100°F threshold within named COGCC fields near Cañon City and Florence are considered H/C.

4.16.3 Gold

Despite its rich mining history, not much gold has been recovered in Fremont County. Production of about 4,400 ounces of gold is reported between the years 1881 and 1957 (Del Rio, 1960; Vanderwilt, 1947). Davis and Streufert (1990) estimate production of 7,000 ounces of mostly placer gold between 1881 and 1990. The most significant gold deposits occur in the Dawson Mountain and Grape Creek districts area in the northern end of the Wet Mountains. Gold has been mined from stratabound, exhalative sulfide deposits (Type 1) that occur in faulted Precambrian gneiss and schist in proximity to Boulder Creek-aged plutons (Sheridan et al., 1990). Zephyr Minerals Limited (Zephyr), a Canadian company, has ownership interest in several patented and unpatented gold claims located about 5 miles southwest of Cañon City near Dawson Mountain. In June 2013, Zephyr announced two of thirteen boreholes intercepted a 21-foot zone averaging 0.3 ounces per ton gold and another 15-foot zone averaging 0.65 ounces per ton. At the time of preparing this MPR (2018), Zephyr is in process of obtaining DRMS permits to mine.

Gold was produced from a couple of prospects in Laramide intrusive rocks (quartz monzonite of the Whitehorn stock) in the Whitehorn mining district (USGS MRDS, 2013). This area is designated H/C for occurrence potential and the rest of the Whitehorn stock in this region and further south is assigned M/B. Badger Creek drains the Whitehorn mining area and is assigned L/B for placer gold occurrence potential.

Placers have been (and still are) worked for fine gold along the lower terraces of the Arkansas River especially near Point Bar, Pleasant Valley near Wellsville, and the mouths of Texas and Badger Creeks (Davis and Streufert, 1990; Parker, 1974). These areas are designated M/C for gold occurrence potential; the rest of the Arkansas River in Fremont County is considered M/B. Placer gold may occur along Fourmile and Eightmile creeks since they drain the region containing the productive Cripple Creek lode gold mines of Teller County; these creeks are designated L/B for gold occurrence potential.

Stratabound exhalative deposits in Precambrian metamorphic rocks are known to be rich in base metals, and sometimes gold, in the RGFO region including Fremont County (Heinrich, 1981; Sheridan and Raymond, 1984a). Though Fremont County has not been a prolific producer of gold, Precambrian metamorphic rocks in the county all carry some potential for gold since it has been sporadically mined as a byproduct. The Cotopaxi mine has produced minor gold (162 ounces from 1944 to 1952) from polymetallic veins in an exhalative deposit, and a buffer around this mine is designated M/C (Sheridan et al., 1990). Limited gold production is reported from exhalative deposits (e.g., Isabel mine) along the Currant Creek fault zone near the contact of Precambrian biotite gneiss and Boulder Creek Granite and Silver Plume-aged (Cripple Creek) granite (USGS MRDS; 2013 Sheridan et al., 1990). The cluster of gold prospects along the Currant Creek fault zone is designated M/C. South of the Arkansas River, Precambrian felsic metamorphic rocks, which are in proximity to Boulder Creek-aged granite in heavily faulted terrane, are considered M/B for gold potential. North of the Arkansas River, similar rocks are designated L/B for gold potential.

4.16.4 Silver

The aggregate production of silver in Fremont County from 1881 to 1957 was 103,971 ounces (Del Rio, 1960; Vanderwilt, 1947). The greater Grape Creek and Greenhorn district area of Fremont County has historically produced silver and is considered H/D. These districts are “hot spots” within a widespread faulted Precambrian terrane that contains scattered stratabound exhalative deposits hosting precious- and base-metal ores (Sheridan et al., 1990).

The Cotopaxi mine has produced minor silver (about 1 ounce per ton) from polymetallic veins in an exhalative deposit, and a buffer around this mine is designated H/C (Sheridan et al., 1990). Limited silver production is reported from exhalative deposits (e.g., Isabel mine) along the Currant Creek fault zone near the contact of Precambrian biotite gneiss and Boulder Creek-aged and Silver Plume-aged granites (USGS MRDS; 2013 Sheridan et al., 1990). The cluster of silver prospects along the Currant Creek fault zone is designated M/C. Precambrian felsic gneisses and schists with silver occurrences and past producers are designated H/C; the same rocks elsewhere in the county are assigned M/B for silver due to the common occurrence of stratabound exhalative deposits scattered across that terrane.

Mineralized veins of the Laramide Whitehorn stock (quartz monzonite) host assorted precious and base metals (Vanderbilt, 1947). The Whitehorn intrusion is assigned an occurrence potential of M/C. The greater Paleozoic Wet Mountain alkalic igneous complex, comprising the Gem Park, Democrat Creek, and McClure Mountain alkalic complexes in south-central Fremont County, hosts minor deposits of silver in carbonatite dikes within mafic and ultramafic rocks (Cappa, 1998). The Wet Mountain alkalic complex is designated M/C for silver occurrence potential.

Several mines (e.g., Red Gulch and Acme) have produced minor silver from sediment-hosted copper deposits in the Pennsylvanian Minturn Formation where it contacts Precambrian felsic gneiss in the Red Gulch district area (USGS MRDS, 2013). Chalcocite ore at the Red Gulch mine contains up to 10 ounces of silver per ton (USGS MRDS, 2013). The Minturn here is designated M/C for silver potential. Anomalous “redbed-type” concentrations of silver are noted from the Minturn Formation throughout the RGFO region, and this unit is designated L/B for silver occurrence potential in the rest of the county where no prospects are noted.

4.16.5 Copper-Lead-Zinc

A diversity of geologic settings in Fremont County yielded a wide variety of mineral deposits, including base metals. Precambrian gneiss, Tertiary intrusives and extrusives, and sedimentary units from Cambrian to Upper Cretaceous are exposed in the county. Historic base-metal production in Fremont County stems from small districts scattered across the county. Production between 1881 and 1957 amounts to 881,655 pounds of copper, 969,277 pounds of lead, and 4.7 million pounds of zinc (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947).

The Grape Creek, Greenhorn, and Dawson mining district area, located southwest of Cañon City, are in the northern end of the Wet Mountains. Stratabound, exhalative sulfide mineralization (Type 1) occurs in Precambrian gneiss and schist within a matrix of pyrrhotite and/or pyrite (Sheridan et al., 1990). Principal ore minerals include chalcopyrite, galena, and sphalerite. Vanderwilt (1947) reports 344,900 pounds of zinc, 133,000 pounds of lead, and 17,900 pounds of copper were produced in the greater Dawson-Greenhorn-Grape Creek area between 1943 and 1945. Additionally, a 3.5 mile-long stratiform exhalite with base-metal mineralization was more recently located in this area (U.S. Bureau of Mines, 1989). The area around the past producing mines is assigned H/D for base-metal potential on the basis of historic mining activity, and a buffer of Precambrian metamorphic rocks around this area is H/C for occurrence potential. Precambrian gneiss with base-metal occurrences adjacent to this area is assigned M/C.

Henderson (1926) notes there was significant prospecting of zinc and silver-lead ores in the Currant Creek-Guffey district area. Lovering and Goddard (1950) add that high-grade zinc was produced chiefly from the Isabel mine. The Isabel mine deposit is characterized as a copper-zinc skarn (mostly sphalerite with some galena and chalcopyrite) in a host rock of amphibolite and biotite gneiss (Heinrich, 1981). Lovering and Goddard (1950) classify the deposit as a hypothermal replacement vein and report an association with a shattered, pegmatitic quartz seam that parallels foliation in the host rock. Sheridan et al. (1990) categorize this deposit as a Type 1 Precambrian stratabound, exhalative deposit and report production from 1946: 12,824 pounds of zinc, 1,723 pounds of lead, and 866 pounds of copper. Associated with exhalative sulfides, Type 3 Precambrian stratabound tungsten (scheelite) and copper deposits (tungsten-copper skarn) in calc-silicate gneisses have been mined at the Charlene claims in the nearby Guffey district (Heinrich, 1981; Sheridan et al., 1990). The Currant Creek-Guffey district area is considered H/D for occurrence potential of base metals.

The mineralized deposit of the Cotopaxi mine occurs in a lenticular amphibolite mass within a granite gneiss host rock (Lovering and Goddard, 1950). Heinrich (1981) classifies the deposit as a copper-zinc skarn and reports it is found in a roof pendant, 0.75 mile long and 0.5 mile wide, that lies just south of a granitic pluton and a few hundred feet west of the Precambrian Cotopaxi fault. The ore is categorized as a Type 1 exhalative sulfide deposit and contains (among other metals) sphalerite, gahnite, chalcopyrite, and some galena (Heinrich, 1981; Sheridan et al., 1990). Production is reported to have been substantial prior to 1907, but no data are available (Lovering and Goddard, 1950; Vanderwilt, 1947). Between 1943 and 1952, the Cotopaxi mine produced approximately 212,109 pounds of copper, 140,648 pounds of lead, and 3.5 million pounds of zinc, although data were lacking in some years (Sheridan et al,. 1990; Vanderwilt, 1947). The Cotopaxi district is identified as H/D.

Less than 10 miles north of Cotopaxi and adjacent to the Cotopaxi fault, sediment-hosted copper ore from the Red Gulch and Copper Prince mines occurs in the Pennsylvanian redbeds of the Minturn and Belden Formations near the contact with Precambrian gneiss (Tweto, 1979a; USGS MRDS, 2013). The mineralization, composed principally of chalcocite with minor malachite and azurite, is found in gray to greenish-gray sandstones or shales and is associated with nearby coal seams (Lovering and Goddard, 1950). Lindgren (1908) reported nodules of pure chalcocite up to two inches in diameter at the Red Gulch mine; Lovering and Goddard (1950) add that visible, coaly shale bedding within the nodules demonstrate the mineral replaced the coal seam. The area around this cluster of mines along the fault is designated H/C for base-metal occurrence potential. Like redbed-hosted base-metal deposits of other counties, other Paleozoic sediments in the county are designated H/B for occurrence potential.

Approximately 10 miles southeast of Cotopaxi, minor occurrences of copper as chalcocite, bornite, and chalcopyrite occur in pyroxenite in the Gem Park alkalic igneous complex (Cappa, 1998). The Gem Park, McClure Mountain, and Democrat Creek alkalic complexes make up the greater Wet Mountain alkalic complex of south-central Fremont County. Nodular ore was found in a 3- to 4-foot-wide carbonatite vein (USGS MRDS, 2013). The Wet Mountain alkalic complex is designated M/C for occurrence potential.

At least two prospects (Leek's Lode and Baker Gulch) exhibit Type 6 massive sulfide characteristics: these copper-bearing pegmatites may be indicative of concealed Type 1 stratabound exhalative deposits (Sheridan et al., 1990). Heinrich (1981) categorized these deposits as copper-zinc skarns developed in mineralized pegmatites. This area and the Precambrian gneisses surrounding the Wet Mountain complex as far northwest as the Red Gulch district are considered H/C for occurrence potential due to scattered historic mining activities throughout; other Precambrian rocks are L/B.

Elsewhere, Vanderwilt (1947) notes there are small veins that carry base metals in the Whitehorn stock in northwesternmost Fremont County, so the Whitehorn district is designated M/C; the Whitehorn Granodiorite elsewhere is M/B. The lower member of the Thirtynine Mile Andesite is designated L/B. In the rest of the county, Precambrian gneisses and schists are M/B.

4.16.6 Iron

The mafic-ultramafic rocks of the composite Wet Mountain Alkalic Province hosts several iron ore past producers (USGS MRDS, 2013). At the Iron Mountain mine within the McClure Mountain complex, numerous Cambrian dikes of pyroxenite and gabbro intrude Precambrian felsic gneiss, and discontinuous zones about 10 to 50 feet thick contain intergrown titaniferous magnetite and ilmenite (Becker et al., 1961; Harrer and Tesch, 1959; Shawe and Parker, 1967). An estimated 39,000 tons of ore averaging 48 to 50 percent iron were produced between 1872 and 1956 at the Iron Mountain mine (Harrer and Tesch, 1959). Iron is hosted by pyroxenite, gabbro, and syenite at the Mag Lode prospect in the Gem Park alkalic complex (Armbrustmacher, 1988; Cappa, 1998). The composite Wet Mountains Alkalic Province is designated H/C for iron occurrence potential.

Iron was produced as a tertiary commodity at the Cotopaxi mine, which is developed in a metamorphosed Precambrian sulfide deposit that hosts precious and base metals (Sheridan and Raymond, 1984a; Sheridan et al., 1990; USGS MRDS, 2013). Magnetite samples assayed 59 percent iron and hematite assayed 46.2 percent iron. A buffer around the Cotopaxi mine area is designated H/C. Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential where no occurrences are reported, L/C where minor or non-producing occurrences are noted, and M/C where some production is noted.

Precambrian Silver Plume-related granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B. Magnetite and hematite, as masses, and pyrite as veins, occur as replacements of mostly carbonates in a contact metamorphic zone where the Upper Cretaceous-Tertiary Whitehorn stock (Calumet granodiorite) intruded the Mississippian Leadville Dolostone in Chaffee County (Behre et al., 1936; Wrucke, 1974). The Whitehorn stock is designated L/B in Fremont County.

Limonite and siderite concretions in the Cretaceous Vermejo Formation about 12 feet above a coalbed contain an average 54 percent iron at the Cañon City Deposit north of Florence (Harrer and Tesch, 1959). The Vermejo Formation is assigned L/C for iron occurrence potential. The Mississippian Leadville Dolostone hosts limonite, and several past producers are noted from other counties (Cappa and Bartos, 2007); this unit is designated L/B throughout Fremont County.

4.16.7 Manganese

Psilomelane occurs as a replacement deposit in massive limestone about 2 miles northeast of Wellsville, where production of 39.42 percent manganese ore was reported from the Iron Mountain claims in Wells Canyon (Jones, 1920; Muilenburg, 1919). Other claims in the same area indicate that the replacement zone is widespread, and Muilenburg (1919) reports that one zone is "visible for 3,000 to 5,000 feet" with good-quality ore of 20 to 40 percent manganese oxide. Botryoidal masses of manganese oxides occur in fissures in limestone at the Ben Boyer claims south of the Iron Mountain claims (Jones, 1920). Psilomelane and pyrolusite fill fissures in the Pennsylvanian Belden Formation and replace aplite in veins at the Galpin and Vreeland claims near Wellsville, although no production is reported (Jones, 1920; USGS MRDS, 2013). An area around Wellsville is designated H/C for manganese occurrence potential.

Past production of manganese from Precambrian metamorphic rocks is reported from the Dell prospect in northeastern Fremont County (USGS MRDS, 2013). Production of manganese from Oligocene Thirtynine Mile volcanic rocks is also reported from an unnamed mine in central Fremont County (USGS MRDS, 2013). Anomalous concentrations of manganese are reported from replacement carbonatites in the Wet Mountain Alkalic Complex (Armbrustmacher, 1988). The Thirtynine Mile Andesite, as well as the area around the Dell prospect, is designated M/C for manganese potential. Tertiary intrusives and other igneous and metamorphic rocks are assigned L/B.

4.16.8 Molybdenum

There are several occurrences of molybdenite in proximity to the Cambrian Wet Mountain Alkalic Complex, comprising the Gem Park (shared with Custer County), McClure Mountain, and Democrat Creek alkalic complexes, in south-central Fremont County (USGS MRDS, 2013). Reported production of over 3 percent MoO_2 is reported from quartz veins in Precambrian gneiss at or near the Red Mountain prospect (USGS MRDS, 2013). Production of 3.7 to 4.3 percent MoO_2 is also reported at the Copper Girl mine, where molybdenum occurs between chalcopyrite bands (Eckel, 1961; USGS MRDS, 2013). Flakes of molybdenite up to 0.5 inch in diameter are reported from the Liberty Bond claim; an assay showed 0.5 percent MoO_2 (Eckel, 1961; USGS MRDS, 2013). The Precambrian metamorphic and Cambrian intrusive rocks of the Wet Mountain Alkalic Complex area are designated M/C for molybdenum potential; the same metamorphic rocks in the rest of the county are assigned L/B. Tertiary intrusives are assigned M/B; other igneous rocks are designated L/B for molybdenum potential.

Minor molybdenum is reported from the Cotopaxi mine, where sulfide mineralization occurs in a roof pendant of Idaho Springs Formation within Boulder Creek Granite (Heinrich, 1981; USGS MRDS, 2013). The area around this occurrence is designated M/C for molybdenum occurrence potential whereas the Boulder Creek Granite elsewhere in the county is assigned L/B.

4.16.9 Nickel

Nickel-bearing serpentine dikes associated with carbonatites occur in the Gem Park Alkalic Complex in northern Custer and southern Fremont Counties (Olson et al., 1977; Parker and Sharp, 1970). Production of 34 percent nickel ore (niccolite) was reported from the Gem mine in the Fremont County portion of the complex (Eckel, 1961). Occurrence potential for nickel is considered M/C in the Gem Park Alkalic Complex. Precambrian metamorphic and igneous rocks elsewhere in the county are designated L/B due to minor occurrences in similar rocks in nearby counties (e.g., Custer and Chaffee).

4.16.10 Tungsten

There are over a dozen tungsten occurrences in Fremont County, some of which are past producers. Small, wolframite-bearing veins in the Precambrian Boulder Creek Granite (as mapped by USGS) were found along Eight Mile Creek in Phantom Canyon in the Tungsten (Wilbur) district, and production at the Bond Ranch mine amounted to 1,800 pounds of 58 percent WO_3 during World War I (Belser, 1956). Due to historic production, the Tungsten district is H/D. Just north of this district, a similar prospect with wolframite-bearing veins in Boulder Creek Granite occurs but no production is reported (Belser, 1956; USGS MRDS, 2013); this area is designated M/C.

In Central Fremont County, the Oliver prospect near the head of Copper Creek also reported production (4 tons of 2 percent WO_3) during World War II: mineralized amphibolite lenses containing scheelite are found in Precambrian gneiss and schist (Belser, 1956). The Knisley mine to the southwest had minor reported production in the 1970s or 1980s (Sheridan et al, 1990). Sheridan et al. (1990) classify these deposits as Type 3, stratabound exhalative deposits. Due to production, the area around the Oliver prospect and Knisley mines are H/D. Several other prospects are reported in this region, although no production is reported for them (USGS MRDS, 2013); these areas are considered M/C.

The Currant Creek-Tallahassee Creek-Guffey district area hosts several tungsten deposits, all in the same mapped Precambrian rock, identified as Idaho Springs Formation by Heinrich (1981). The Venture No. 1 claim consists of a 10-foot-wide by 800-foot-long mineralized deposit containing scheelite in the Idaho Springs Formation, but no production was recorded (Heinrich, 1981). A 3- to 13-foot-wide by 1,500-foot-long mineralized zone, characterized as tungsten skarns by Heinrich (1981), contains flakes, grains, and crystals of tungsten in gneiss at the Charlene claims. The Four Claim Group hosts a coarse-grained skarn with disseminated tungsten grains and crystals (Heinrich, 1981). Sheridan et al. (1990) classify these three prospects as Type 3, stratabound exhalative deposits. Similar tungsten deposits occur in the same rocks of the Park County portion of the Guffey district. These closely grouped occurrences within the same rock type suggest high potential of tungsten occurrence, and the area is designated H/D.

Tungsten occurs with copper in Precambrian igneous rocks at the Copperhead mine in northwestern Fremont County and past production is reported (USGS MRDS, 2013). Scheelite occurs with molybdenum and base-metal sulfides in Precambrian granite at the Cotopaxi mine, although no production of tungsten is reported (USGS MRDS, 2013). The areas around these deposits are designated M/C. In the rest of the county, areas of early Precambrian metamorphic (Idaho Springs Formation) and igneous (Boulder Creek Granite) are designated M/B for tungsten occurrence potential.

4.16.11 Beryllium

Through 1963, production of beryl from pegmatites in Fremont County amounted to 1.1 million pounds, chiefly from one of the top pegmatite producers in Colorado, the Devil’s Hole pegmatite of the Eightmile Park district (Eckel, 1960; Meeves et al., 1966; Vanderwilt, 1947). A cluster of large beryllium-bearing pegmatites occur in the vicinity of the contact of Precambrian granodiorite of the Boulder Creek batholith facies and metamorphic rocks in the greater Eightmile Park district (Tweto, 1979a). Production of 57 tons of beryl ore is reported from the Mica Lode pegmatite through 1950 (Hanley et al., 1950; Heinrich, 1948). A buffer around the contact along the gorge between these rocks is considered H/D for beryllium potential.

A few smaller clusters of beryllium-bearing pegmatites along contacts of Precambrian granodiorite or quartz monzonite with metamorphic rocks occur further west and also in the Tungsten district. These areas are designated H/C for beryllium potential. Beryl was mined from the Rowe pegmatites along Mac Gulch where Precambrian quartz diorite of the Boulder Creek batholith facies and gneiss occur in the Guffey-Micanite district (shared with Park County) (Del Rio, 1960; Hanley et al., 1950; Sterrett, 1923; USGS MRDS, 2013). The Guffey-Micanite district area is considered H/D due to past production from pegmatites such as the Meyers Ranch (just over the border in Park County), an estimated beryl reserve of 38 to 150 tons, as well as favorable geological and structural features (Hanley et al., 1950). Due to the preponderance of pegmatites in Precambrian granitic rocks throughout the RGFO, beryllium occurrence potential is considered L/B in these rocks.

4.16.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Fremont County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Approximately 4.7 million pounds of zinc were produced in Fremont County between 1881 and 1957; sphalerite ore is commonly reported at past-producing zinc mines (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

The Cañon City Coal Region lies in the southeastern part of Fremont County (see sections 3.1.4 and 4.16.1 of this MPR), and nearly 48 million tons of high-volatile C bituminous coal were produced from the Vermejo Formation (Carroll and Bauer, 2002). This coal region is designated L/B for germanium potential.

4.16.13 Rare Earth Elements

In Fremont County, the rare-earth minerals bastnaesite, synchisite, ancylite, monazite, and thorite have been identified in carbonatites and thorium-bearing veins of the composite Wet Mountain Alkalic Province (Armbrustmacher, 1979). Heinicke (1960) states that more than 800 thorium prospects were developed in the greater province area by 1958, and it is likely that REEs occur in most of those. An enrichment of HREEs is noted within the three intrusive complexes (Armbrustmacher, 1988). Armbrustmacher (1988) estimated 136,000 tons of REE (including 48,850 tons of HREE) reserves are located in the composite Wet Mountains Alkalic Province. The McClure Mountain, Gem Park, and Democrat Creek complexes are designated H/C for REE occurrence potential.

Thorium-and REE-bearing veins occur along faults and shear zones in Precambrian Idaho Springs Formation gneiss and are a late-stage product of Cambrian alkalic magmatism related to the Wet Mountain Alkalic Province (Armbrustmacher, 1988; Olson et al., 1977). Samples from the Homestake claims, where bastnaesite, fergusonite, and monazite are reported in veins of a shear zone, assayed up to 6.51 percent total REE oxides; samples from the nearby Dreamer's Hope claim assayed only 0.46 percent total REE oxides (Christman et al., 1953; Christman et al., 1959). East of the Democrat Creek intrusive complex, samples from thorium-bearing veins along a fault in Precambrian gneiss assayed up to 2.01 percent total REE oxides (Christman et al., 1953). Precambrian biotite gneiss surrounding the Wet Mountain Alkalic Province is designated H/C for REE potential.

Gadolinite masses as large as 20 pounds are found at the Pine Ridge pegmatite about 7 miles north of Cotopaxi near a contact of Precambrian granodiorite and gneiss (Eckel, 1961; Tweto, 1979a; USGS MRDS, 2013). Euxenite, gadolinite, xenotime, monazite, and allanite are hosted by veins along a fault that cuts the Slide Rock Mountain soda granite stock at the Benton prospect, southwest of Cotopaxi (Parker, 1963). Xenotime and monazite are reported from veins along a contact between Precambrian Boulder Creek and Cripple Creek granites at the Olhio prospect south of the Guffey-Micanite district (Haynes, 1960; Olson and Adams, 1962). Buffers around these and similar occurrences are assigned L/C for REE occurrence potential.

4.16.14 Niobium-Tantalum

Meeves et al. (1966) reports production of 3,574 pounds of niobium-tantalum minerals from pegmatites in Fremont County through 1963.

Tweto (1979a) mapped a shear zone between Precambrian Boulder Creek granodiorite and Idaho Springs Formation gneiss on the north rim of the Royal Gorge with numerous beryl-bearing pegmatite deposits. Several pegmatite prospects also host columbite and tantalite, and specific gravity analyses of samples at the Meyers mine indicate a content of 56.5 percent Nb_2O_5 and 22.1 Ta_2O_5 (Hanley et al., 1950). Production of 615 pounds of columbite-tantalite is reported from the Mica Lode (Hanley et al., 1950). Readily accessible columbite-tantalite reserves in this pegmatite zone are estimated at 2,500 pounds and as much as 5.6 tons at depth (Meeves et al., 1966). The occurrence potential along this contact for niobium-tantalum pegmatite hosted deposits is H/D.

To the west and southwest of the Royal Gorge, clusters of pegmatites along faults in Precambrian Boulder Creek Granite, Silver Plume Granite, and Idaho Springs Formation gneiss are reported by the USGS MRDS (2013). About 200 pounds of columbite and tantalite were recovered from a tabular, northward-trending pegmatite at the Devil’s Hole (Zingheim) deposit 4 miles northwest of Cotopaxi (Hanley et al., 1950). Roughly 50 tons of columbite reserves were estimated to remain in 1950 (Hanley et al., 1950). Buffers around these pegmatite zones where known occurrences are clustered are designated H/C for niobium-tantalum occurrence potential; pegmatite zones in the same rocks adjacent to known producers are assigned M/C.

Pyrochlore and columbite occur in irregular masses along shear zones between carbonatite dikes and surrounding Precambrian rocks at the Cambrian Gem Park, McClure Mountain, and Democrat Creek alkalic intrusive complexes, but no production is reported (Cappa, 1998; Meeves et al., 1966; Parker and Sharp, 1970). These complexes are designated L/C for niobium-tantalum occurrence potential.

In the Guffey-Micanite district, shared with Park County, the northeast-trending Meyers Ranch pegmatite (Park County) contained up to 48.3 percent Nb_2O_5 and 26.5 percent Ta_2O_5, and the deposit yielded one ton of columbite-tantalite ore (Hanley et al., 1950; Scarbrough, 2001).

Several beryl-bearing pegmatite prospects are noted along Mac Gulch in the Fremont County portion of this district on the USGS MRDS (2013), but none report niobium-tantalum minerals. A buffer along this area is assigned L/B for niobium-tantalum potential.

Two pegmatite prospects along faults in the Phantom Canyon area host columbite (Hanley et al., 1950; Parker, 1953; USGS MRDS, 2013). Buffers along these faults are designated L/C for niobium-tantalum occurrence potential.

4.16.15 Tellurium

There is no reported production of tellurium in Fremont County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.16.16 Titanium

Two specific locations in Fremont County are known to contain commercial concentrations of titanium; both are within the Cambrian mafic-ultramafic composite Wet Mountain Alkalic Province (USGS MRDS, 2013). At the Iron Mountain mine within the McClure Mountain complex, numerous dikes of pyroxenite and gabbro intrude Precambrian felsic gneiss, and discontinuous zones about 10- to 50-feet thick were mined for titaniferous magnetite and ilmenite with 13.5 to 14.1 percent TiO_2 (Becker et al., 1961; Harrer and Tesch, 1959; Shawe and Parker, 1967). The deposit was mined sporadically during the years 1872 to 1956, and an estimated 39,000 tons of ore were produced (Harrer and Tesch, 1959). Titanium is also hosted by carbonatites at the Mag Lode prospect in the Gem Park alkalic complex (Armbrustmacher, 1988; Cappa, 1998). The Cambrian volcanic rocks of the composite Wet Mountains Alkalic Province are designated H/C for titanium occurrence potential.

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals, and several past producers are noted from El Paso and Teller Counties (Smith et al., 1999; USGS MRDS, 2013). Alkalic and mafic units related to the Pikes Peak batholith in northeastern Fremont County are designated L/B for titanium potential.

4.16.17 Uranium

Nelson-Moore et al. (1978) report production of 464,203 pounds of uranium through 1971 from 94,000 tons of 0.25 percent uranium ore from Fremont County. Ninety percent of the uranium was recovered from Tertiary units in the Tallahassee Creek Uranium district: the Eocene Echo Park Formation is overlain by Wall Mountain Tuff and subsequently cut by the Oligocene Tallahassee Creek Conglomerate, all of which is overlain by the lower unit of the Thirtynine Mile Andesite (Nelson-Moore et al., 1978). The district is located north of the Arkansas River and between Cañon City and South Park. Interest in this area was prompted by strong surface radiometric anomalies conducted in 1954, which led to exploration drilling and the discovery of about fifteen small ore bodies (Chenoweth, 1980). The Wall Mountain Tuff and lower unit of the Thirtynine Mile Andesite are the likely sources of the uranium, which leached into the underlying Echo Park Formation and Tallahassee Creek Conglomerate, respectively (Hon, 1984). Primarily uraninite but also autunite, coffinite, and schoepite ($(UO_2)_8O_2(OH)$), a rare alteration product of uraninite, are all reported from mineralized lenticular masses in these units (Hon, 1984; Nelson-Moore et al., 1978).

In 1977, Rampart Exploration Company, contracted by Cyprus Mines Corporation discovered two significant uranium ore bodies when drilling in the Tallahassee Creek Uranium district: the Hansen orebody in the Echo Park Formation and the Picnic Tree orebody in the Tallahassee Creek Conglomerate (Chapin et al., 1982). Cyprus Mines drilled over 1,000 test holes at the Hansen deposit, completed three favorable feasibility studies, and obtained a DRMS permit to mine the deposit in 1981 (Permit No. M1979-213HR), but the project was tabled due to low uranium prices and the permit was terminated. Hon (1984) describes the Hansen deposit as being similar to basal-type sedimentary uranium deposits, and he reports that most deposits in the Tallahassee Creek Conglomerate appear to be related to altered volcanic ash near the top of the formation. The bentonitic altered volcanic ash strata have characteristics of solution-front movement and evidence of physical injection into surrounding units (Hon, 1984).

Black Range Minerals Limited (acquired by Western Uranium Corporation in 2015) acquired rights to many of the uranium deposits in the Tallahassee Creek district and conducted additional exploration drilling during the past several years (http://www.blackrangeminerals.com/mines-projects.html). The Hansen/Taylor project includes the Hansen, Taylor, Boyer, Noah, and Picnic Tree deposits in Fremont County and the High Park deposit in adjacent Teller County. Exploration revealed the Echo Park Formation is the primary host of approximately 90 million pounds of uranium, located at a depth of 150 to 190 meters, making it one of the largest uranium deposits in the United States (Western Uranium, 2018). The Eocene Echo Park Formation and overlying Oligocene Wall Mountain Tuff, Tallahassee Creek Conglomerate, and the lower unit of the Thirtynine Mile Andesite are designated H/D for uranium occurrence potential in the area of production and H/B elsewhere in the county.

The Permian-Pennsylvanian Sangre de Cristo Formation hosts uranium occurrences in Fremont and other counties. Though only occurrences (carnotite) are reported from the Sangre de Cristo Formation in Fremont County, production of up to 0.36 percent U_3O_8 ore is reported from Huerfano County and up to 1.7 percent U_3O_8 ore from Custer County (Nelson-Moore et al., 1978). The Sangre de Cristo Formation in Fremont County is designated M/C for uranium occurrence potential.

Numerous uranium prospects occur in the Jurassic Morrison or Ralston Creek Formations in the RGFO region; however, reported production from these units is limited to one mine, in Fremont County. Uraninite and coffinite were recovered from carbonaceous layers in association with a coal seam in the Morrison Formation at the Dilley Lease claim; assays ranged up to 0.3 percent

U_3O_8, and production amounted to 232 pounds of uranium (Nelson-Moore et al., 1978). The undivided Morrison and Ralston Creek Formations are designated H/C for uranium occurrence potential.

Significant production of uranium ore is reported from the Dakota Sandstone in neighboring Pueblo and El Paso Counties (Nelson-Moore et al., 1978). Carnotite and tyuyamunite ($Ca(UO_2)_2(VO_4)_2$) were identified from uranium ore, ranging from 0.34 to 0.92 percent U_3O_8, and recovered from mineralized nodules, concretions, vugs, and fractures of the Dakota Sandstone in Fremont County; production of 2,326 pounds of uranium is reported (Nelson-Moore et al., 1978). The undivided Dakota Sandstone and Purgatoire Formation mapped unit is designated H/C for uranium occurrence potential.

Faults, shear zones, pegmatites, and metalliferous veins in Precambrian igneous and metamorphic rocks host uraninite and occasional autunite, coffinite, and torbernite throughout the RGFO region (Nelson-Moore et al., 1978). In Fremont County, samples from these units assayed up to 0.36 percent U_3O_8 (Nelson-Moore et al., 1978). Buffers along faults where prospects occur or around individual prospects are designated L/C for uranium occurrence potential. Production of 193 pounds of uranium from 102 tons of 0.09 percent U_3O_8 is reported from a shear zone spanning a contact between the Precambrian Idaho Springs Formation and Tertiary tuff at the Lightning group of mines southwest of Cotopaxi; a buffer around these prospects is assigned M/C for uranium potential.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.16.18 Thorium

Twenty-three thorium occurrences are recorded in Fremont County, most of which are associated with the three intrusive complexes of the Wet Mountains Alkalic Province (USGS MRDS, 2013). According to Armbrustmacher (1988), the thorium in this province occurs in quartz-barite-thorite veins and fracture zones in Precambrian and Paleozoic rocks, carbonatite dikes, and red syenite dikes, the latter which hosts anomalous concentrations of thorium. The quartz-barite-thorite veins and fracture zones, some up to 15 meters thick, contain the largest thorium resources; reserves of 64,200 tons of 0.46 percent thoria ore are estimated to exist in the greater Wet Mountains Alkalic Province area of Fremont and Custer Counties (Christman et al., 1959; Schwochow and Hornbaker, 1985; Van Gosen et al., 2009). Hundreds of thorium-bearing veins filled tabular fracture zones during late-stage Cambrian alkalic magmatism at the McClure Mountain, Gem Park, and Democrat Creek intrusive complexes (Armbrustmacher, 1988; Olson et al., 1977). Peripheral to the Democrat Creek syenite complex, the Tuttle Ranch claims average 0.60 percent ThO_2 in veins within a shear zone in Precambrian rocks, and reserves are estimated at 1,165 tons ThO_2 ore (Armbrustmacher, 1988). Buffers around faults in Precambrian crystalline rock in the greater Wet Mountain Alkalic Province are designated H/D for thorium occurrence potential where producing mines are clustered and M/D elsewhere.

Two types of carbonatite dikes exist in the Wet Mountains Alkalic Province: replacement and primary magmatic carbonatites (Armbrustmacher, 1988). Primary magmatic carbonatites typically host more economically viable deposits than replacement types; in the Wet Mountains Province, they average 0.17 percent ThO_2, and reserves of 131 tons of ThO_2 are estimated (Armbrustmacher, 1988). In Fremont County, primary magmatic carbonatite hosts are most closely associated with the McClure Mountain intrusive complex (Van Gosen et al., 2009). The intrusive complexes of the composite Wet Mountains Alkalic Province of Fremont County are designated H/D for thorium occurrence potential.

A few thorium occurrences in Fremont County lie beyond the limits of the Wet Mountains Alkalic Province and occur in association with pegmatites, shear zones, and fractures in Precambrian rocks. One occurrence (Benton prospect) occurs in pegmatite within the Sangre de Cristo Formation; monazite and euxenite are reported (USGS MRDS, 2013). Less than 3 miles north of the Benton prospect, the Bill and Bud 2 and 4 prospect is reported as a past thorium producer from pegmatites in the Precambrian Boulder Creek Granite (USGS MRDS, 2013). In the Eight Mile Park pegmatite district along the Royal Gorge northwest of Cañon City, thorite is hosted by an irregular, northwest-trending ore body in Precambrian migmatitic gneiss in association with granodiorite and a northeast-trending fault at the School Section mine (Eckel, 1961; USGS MRDS, 2013). Buffers around faults in Precambrian crystalline rocks of this area are assigned M/D for thorium potential; faults in the northeastern portion of the county near the Teller County border (and Cripple Creek district) are designated L/C.

4.16.19 Vanadium

Much of the historical vanadium production in the RGFO management area came from the Tallahassee Creek Uranium district in Fremont County (Nelson-Moore et al., 1978). About 2,222 pounds of V_2O_5 at the Picnic Tree deposit, 1,342 pounds at the Thome claims; and 801 pounds at the Knob Hill mine were recovered from the Tallahassee Creek Conglomerate (Nelson-Moore et al., 1978). Significant uranium, and presumably associated vanadium, reserves are reported from the Tallahassee Creek Conglomerate and underlying Echo Park Formation (Nelson-Moore et al., 1978; Western Uranium, 2018). The Tallahassee Creek Conglomerate and Echo Park Formation are designated H/C for vanadium occurrence potential.

Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, the Cretaceous Dakota Sandstone hosts carnotite at several prospects in this and El Paso, Pueblo and Jefferson Counties; production of 256 pounds of vanadium was reported at a Jefferson County mine (Nelson-Moore et al., 1978). Carnotite and tyuyamunite is reported in the

Dakota Sandstone at the Brandt claims (Fremont County) (Nelson-Moore et al., 1978; USGS MRDS, 1978). The undifferentiated Morrison Formation, Entrada Sandstone and Dakota Sandstone mapped unit is designated M/B for vanadium occurrence potential in Fremont County; the Dakota Sandstone elsewhere is assigned L/B.

The Permian Sangre de Cristo Formation of Huerfano and Custer Counties host carnotite and tyuyamunite, and samples from several mines assayed up to 4.0 percent V_2O_5; 5 pounds of vanadium were produced at the Custer County Beck Mountain mine (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for vanadium occurrence potential in Fremont County.

Vanadium occurrences and some production are reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in this as well as Park and Custer Counties; samples assayed up to 4.34 percent V_2O_5 (Nelson-Moore et al., 1978; Schwochow and Hornbaker, 1985; Wilmarth, 1959). In the Red Gulch area of Fremont County, several vanadium-bearing copper-silver deposits occur in or in association with coal seams in the Minturn Formation (USGS MRDS, 2013). The Minturn Formation is assigned L/C for vanadium occurrence potential.

Anomalous concentrations of vanadium are reported from the composite Wet Mountains Alkalic Province, especially from the primary magmatic carbonatites (Armbrustmacher, 1988; Shawe and Parker, 1967). Samples from the Iron Mountain titaniferous magnetite deposit assayed up to 0.45 percent V_2O_5 (USGS MRDS, 2013). The Cambrian Gem Park, McClure Mountain, and Democrat Creek intrusive complexes are designated L/C for vanadium occurrence potential.

Vanadium is reported from Tertiary volcanic breccia, tuffs, and phonolite dikes in this and Teller County, although no production is reported (Nelson-Moore et al., 1978). Also, roscoelite is associated with gold tellurides in Tertiary volcanic rocks at the Cripple Creek gold mine (Cappa, 1998; Lovering and Goddard, 1950). Tertiary tuffs, phonolites, and other intrusives in Fremont County near the border with Teller County are assigned L/B for vanadium occurrence potential. An area around the Lightning group of mines with similar geology, but heavily faulted with recorded uranium production and vanadium occurrences, is designated L/C for vanadium potential.

4.16.20 Fluorspar

Only minimal fluorspar production is reported from Fremont County; however, average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks (Wallace, 2010). A small tonnage of 90 percent (ceramic grade) CaF_2 was produced from veins in Precambrian biotite gneiss at the Blue Spar deposit in the Cotopaxi district (Brady, 1975). A few other prospects are developed in Precambrian Boulder Creek Granite (USGS MRDS, 2013). Precambrian igneous rocks are designated H/C and Precambrian biotite gneiss is assigned M/C for fluorspar occurrence potential. Precambrian hornblende gneiss is assigned M/B for fluorspar potential.

4.16.21 Diamond and Gemstones

Beryl, garnet, tourmaline, chalcedony, azurite, chrysocolla, and rose quartz crystals are reported from numerous pegmatites developed near the contact of Boulder Creek Granite and Idaho Springs gneiss in the Royal Gorge (Eight Mile Park district) area of Fremont County (Heinrich, 1948; Pearl, 1972). Abundant black tourmaline crystals up to 3 inches in diameter and eight inches long have been recovered at the School Section pegmatite (Heinrich, 1948). Masses of granular spessartite up to 6 feet wide, as well as euhedral crystals up to an inch wide, are reported from the Mica Lode and other pegmatites (Heinrich, 1948). Beryl crystals up to 18 inches in diameter occur at the Meyers Quarry pegmatite (Heinrich, 1948). Hanley et al. (1950) report production of 57 tons of mostly fine-grained beryl ore through 1949 at the Mica Lode; large yellow euhedral crystals also occur. A beryl crystal measuring 2 feet in diameter and 3.5 feet long was reported from the R. H. Magnuson prospect (Hanley et al., 1950). The greater Eight Mile Park area is designated H/D for gemstone occurrence potential. The Idaho Springs Formation just to the south of this area is assigned M/C for gemstone potential.

Hanley et al., (1950) report production of 300 tons of beryl and 200 tons of rose quartz through 1942 from the Devils Hole pegmatite, which is developed in Precambrian felsic gneiss and schist near a contact with a Silver Plume-aged pluton about 6 miles north of Texas Creek. Greenish-blue to pale-blue euhedral beryl crystals up to 2 feet in diameter and 4 feet long have been collected; aquamarine is also reported (Eckel, 1961; Hanley et al., 1950; Pearl, 1972; Sterrett, 1909). The rose quartz was described as “flawless, gem-quality” by Eckel (1961). The Devils Hole pegmatite region is designated H/D for gemstone potential.

Clusters of feldspar- and beryl-bearing pegmatites are found throughout the greater Guffey-Micanite district, shared with Park County (Martin, 1993; Meeves et al., 1966). Gem-quality crystals of beryl, garnet, black tourmaline, and rose quartz have been recovered (Heinrich, 1957). The Meyers Ranch pegmatite (Park County) produced an estimated 25 tons of beryl between 1930 and 1950, (Hanley et al., 1950; Scarbrough, 2001). Bright-blue to yellow euhedral beryl crystals up to 10 inches in diameter were recovered from this northeast-trending pegmatite (Hanley et al., 1950). The greater Guffey-Micanite district is designated H/C for gemstone occurrence potential.

From the early 1900s and continuing until today, gem-quality amethyst crystals up to 2 inches thick and 3 inches long have been mined from an area 1 mile south of Twelvemile Park from veins and pods in pegmatite of Precambrian felsic metamorphic rock (Sterrett, 1909). A buffer around this area is designated H/C for gemstone occurrence potential.

Abundant pinkish- to deep-red almandine crystals up to 3 inches in diameter are found embedded in Precambrian biotite gneiss at the Grape Creek and Serpent prospect southwest of Cañon City (Eckel, 1961). A buffer around this prospect is designated H/C for gemstone occurrence potential.

Peridot (gem-quality olivine) crystals have been recovered from Tertiary vesicular basalt that caps several mesas near Badger and Herring Creeks in southwestern Park and northwestern Fremont Counties (Arbogast et al., 2011; Cappa, 2007). This mapped unit is designated M/C for gemstone occurrence potential.

Crystals of beryl, fluorite, and topaz are reported from pegmatite mines developed near a contact between Boulder Creek Granite and Idaho Springs gneiss in the Phantom Canyon area of the Tungsten district (Hanley et al., 1950; USGS MRDS, 2013). A buffer around these prospects is designated M/C for gemstone occurrence potential

Zoned pegmatites are known to occur in Silver Plume-aged plutons (Boos, 1954, Boos and Aberdeen, 1940); correlative plutons in Fremont County are assigned L/B for gemstone potential. The Precambrian Boulder Creek Granite and Cretaceous Whitehorn stock, which are relatively devoid of pegmatites, are designated L/A for gemstone occurrence potential, outside areas of known prospects which are assigned M/C (Boos, 1954).

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the northwest of Fremont County, Precambrian felsic metamorphic rocks in the northern half of Fremont County are designated L/C, and biotite gneisses and schists are assigned L/B, for gemstone occurrence potential outside areas of known prospects, which are assigned M/C (Lovering and Goddard, 1950). Precambrian metamorphic rocks south of the Royal Gorge area are devoid of beryl-bearing pegmatites, and so are designated L/B for gemstone potential (Meeves et al., 1966). The lower occurrence potential of gemstones in Precambrian metamorphic rocks of Fremont County compared to other counties (e.g., Boulder or Clear Creek) is due to the relative lack of known gemstone, beryl, and fluorite prospects and commercially developed pegmatites in these rocks outside the east-west-trending belt of pegmatites in the central part of the county.

4.16.22 Pegmatite Minerals

Meeves et al. (1966) report production of 30,000 pounds of sheet mica and 50,438 tons of scrap mica from pegmatites of Fremont County through 1963. Numerous past producers of feldspar and mica are found throughout central Fremont County surrounding the greater Eightmile Park, Red Gulch, and Cotopaxi mining districts and an area east of the Grape Creek district (USGS MRDS, 2013). The southern Eightmile Park district area, which spans a contact zone between Precambrian Boulder Creek granodiorite and felsic gneiss, hosts the greatest concentration of feldspar- and mica-bearing pegmatites in the county (Tweto, 1979a; USGS MRDS, 2013).

Approximately 169,000 tons of feldspar (microcline) and 34,700 tons of scrap mica were produced from pegmatites at the Mica Lode mine in this district through 1942 (Hanley et al., 1950).

Elsewhere, roughly 17,000 tons of feldspar and 1,675 tons of scrap mica have been produced from pegmatites at the boundary of Precambrian felsic gneiss and Silver Plume-aged quartz monzonite at the Devils Hole Beryl mine northwest of the Red Gulch district (Hanley et al., 1950). Martin (1993) estimates production of several thousand tons of feldspar and several hundred tons of mica from the Guffey-Micanite district (shared with Park County). The Fremont County portion of the district reportedly produced 2,000 tons of feldspar and 175 tons of scrap mica between 1934 and 1942 (Hanley et al., 1950). Several past producers of feldspar and mica occur in Boulder Creek-aged granite near Precambrian felsic gneiss east of the Grape Creek district (USGS MRDS, 2013).

Clusters of feldspar- and mica-bearing pegmatites in central Fremont County including the greater Eightmile Park, Red Gulch, and Cotopaxi districts are designated H/D for pegmatite mineral occurrence potential. The small cluster east of the Grape Creek district is designated H/C. In the rest of the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; elsewhere they are M/B. Biotite gneisses and schists are assigned M/B. Precambrian plutonic rocks are considered L/B.

4.16.23 Industrial Abrasives

Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Numerous garnet-bearing pegmatites occur near the contact of Boulder Creek Granite and Idaho Springs gneiss in the Royal Gorge (Eight Mile Park district) area of Fremont County (Hanley et al., 1950; Heinrich, 1948). Masses of granular spessartite up to 6 feet wide, as well as euhedral crystals up to an inch wide, are reported from the Mica Lode and other pegmatites in this district (Heinrich, 1948). A buffer around the contact zone between igneous and metamorphic rocks where pegmatites are clustered is designated H/D for industrial abrasive occurrence potential.

Clusters of pegmatites in Precambrian metamorphic rocks are found throughout the greater Guffey-Micanite pegmatite district, which spans the Fremont and Park County border (Hanley et al., 1950; Martin, 1993; Meeves et al., 1966). Garnet is reported as large crystals (up to 2 inches long) or masses at several of the pegmatites, including the Rosemont, Rose Dawn, and Star Girl (Hanley et al., 1950). A buffer around these pegmatite clusters is designated H/C for industrial abrasive potential.

West of the Eight Mile Park district, sporadic occurrences of pegmatites occur in Precambrian felsic gneiss; garnet is occasionally reported (Hanley et al., 1950; USGS MRDS, 2013). Abundant almandine crystals up to 3 inches in diameter are found embedded in Precambrian biotite gneiss at the Grape Creek and Serpent prospect southwest of Cañon City (Eckel, 1961). Buffers around these pegmatite clusters are designated H/C for industrial abrasive occurrence potential. Garnet is listed as a primary commodity at the Knob Hill prospect, developed near the contact of Precambrian granite and gneiss near Howard (Hanley et al., 1950). A buffer around this area is assigned H/D for industrial abrasive potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the west, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.16.24 Limestone and Dolomite

There are several limestone quarries developed in Paleozoic limestone units in Fremont County, including the Leadville, Williams Canyon, and Manitou Limestones (USGS MRDS, 2013). The Leadville group of limestones has historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). High-purity dolomite was mined near Cañon City from a 130-foot section of massive beds in the Fremont Limestone (D. A. Carter, 1968). These units are designated H/D for limestone and dolomite occurrence potential in the area of known occurrences and H/C elsewhere. Undifferentiated Ordovician mapped units which may host limestone are assigned H/B for limestone potential.

The Cretaceous Greenhorn Limestone hosts operating mines throughout the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; both are found in the eastern half of the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential.

The Pennsylvanian Minturn and Belden Formations and the correlative Sangre de Cristo Formation each host one limestone occurrence and are designated L/C for limestone potential.

4.16.25 Industrial Sand

Small outcrops of Quaternary eolian sands in southeastern Fremont County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in the RGFO region, including along the Arkansas River; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Several DRMS-permitted industrial sand operations occur in the Dakota Sandstone in Fremont County. The Lykins Formation and Dakota Sandstone are designated H/C for industrial sand occurrence potential.

4.16.26 Gypsum

Fremont County hosts some of the most important gypsum deposits in the RGFO management area. Gypsum mining in western Fremont County began in 1903 when the Colorado Portland Cement Company opened the first quarry to supply gypsum to its cement plant near Florence (Schwochow, 1981). The Colorado DRMS has issued eight permits to mine gypsum in the county, including four that are still active: the Coaldale Quarry (Holcim, Inc.), Maverick Placer (U.S. Soil Conditioning Company), Salt Canyon Project, and Thorson mine. The USGS MRDS (2013) includes 16 gypsum prospects in the county. The permitted mines and the MRDS occurrences cluster in two areas: one in the northeastern part of the county and a second in the western part.

Gypsum quarries in western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation, equivalent to the Chubb Member in South Park (Brill, 1952). Minturn Formation gypsum is known from the Swissvale, Badger Creek, Howard, and Coaldale areas of the Arkansas River corridor, as well as Red Gulch (Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). In some places of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere in Fremont and other counties, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). George (1920) described the gypsum deposit at Coaldale as being the most extensively worked deposit in the State at that time. The Minturn Formation is designated M/C for gypsum occurrence potential.

Although no bedded gypsum is reported from within the Jurassic Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965;

Witherington, 1968). Darton (1906) reports a 30-foot-thick bed of gypsum below the Morrison Formation at the Garden of the Gods in El Paso County; George (1920) reports massive gypsum up to 60 feet thick below the Morrison Formation at nearby Glen Eyrie. These deposits were mined from 1875 to 1907 (Schwochow, 1981; Withington, 1968). The Stevens Gypsum mine, just over the border in Pueblo County, is developed in the undivided Colorado Group, but likely recovered gypsum from the underlying Morrison and Ralston Creek Formations; production of 700 tons of gypsum per month at one point is reported (George, 1920; USGS MRDS, 2013). The permitted Thorson mine and Salt Canyon Project in Fremont County are developed in the Ralston Creek Formation (Wobus et al., 1979, 1985). George (1920) identified a massive gypsum layer ranging up to 75 feet thick along a traceable 8-mile section just above the Permian-Triassic Lykins Formation and below the Morrison Formation at Perry Park in Douglas County. Lindsey et al. (1986d) report Lykins Formation gypsum deposits just southeast of the Beaver Creek Wilderness Area. The Morrison and Ralston Creek Formations, as well as the underlying Lykins Formation, are designated H/D for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation as well (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in Fremont County.

4.16.27 Sand and Gravel

High-quality sand and gravel deposits in Fremont County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011).

Sedimentary units of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Fremont and other counties, the Pennsylvanian-Permian Fountain Formation and Cretaceous Dakota Sandstone host sand and gravel operations (W. D. Carter, 1968); these units are assigned L/C for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.16.28 Crushed Stone Aggregate

There are numerous DRMS-permitted crushed stone aggregate operations in Fremont County, developed in Cambrian to Mississippian limestones and quartzites, as well as the Fort Hays Member of the Cretaceous Niobrara Formation (Arbogast et al., 2011; Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense carbonate rocks, like the Cambrian to Mississippian limestones, sandstones, and quartzites, are excellent sources of crushed stone aggregate being relatively hard and free from fractures with no deleterious chemical constituents, whereas the Niobrara Formation and Colorado Group overall were only classified as 'fair' source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated H/D along a belt of aggregate operations and M/C elsewhere, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential. Cambrian to Mississippian limestones, sandstones, and quartzites, mapped as Or or MDO, are assigned H/D for crushed stone potential.

Dense, fine-grained volcanic rocks like basalt (traprock) satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz, which is detrimental to cement-making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Significant production of high-quality crushed stone from Tertiary volcanic rocks is reported from other counties in the RGFO region (Arbogast, 2011). Tertiary andesitic lavas and breccias (mapped as Tpl) may be too porous with abundant deleterious constituents in part to meet the requirements of crushed stone aggregate (Knepper et al., 1999). Tertiary volcanic rocks are assigned H/C for crushed stone potential, except rocks of the lower member of the Thirtynine Mile Andesite, mapped as Tpl, which are assigned M/B. The mafic plutons of the composite Wet Mountain Alkalic Complex, composed largely of syenite and diabase, meet the physical and chemical qualifications for crushed stone aggregate (Knepper et al., 1999). The McClure Mountain, Gem Park, and Democrat Creek plutons are designated H/C for crushed stone aggregate occurrence potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Cripple Creek pluton, in Fremont County, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed, Precambrian Boulder Creek plutons and satellites were classified as only 'fair' source rocks by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver

Plume-aged granites are designated H/C, and the Boulder Creek Granite is assigned M/C, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Paleozoic Fountain, Sangre de Cristo, Minturn, and Lykins Formations, Mesozoic Dakota Sandstone and Morrison, Trinidad, and Vermejo Formations, as well as the Cenozoic Raton, Poison Canyon, and Santa Fe Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in Fremont and other counties. The Dakota Sandstone is designated M/C, and remaining sedimentary rocks are assigned L/B, for crushed stone potential.

4.16.29 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential. The Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay and contains slightly to highly expansive illite and montmorillonite; this shale member may be a suitable resource for Leca (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B for lightweight aggregate occurrence potential.

Various Pennsylvanian to Tertiary sedimentary units, including the Minturn, Lykins, Trinidad, Vermejo, Raton, Poison Canyon, Dry Union, and Santa Fe Formations in Fremont County, bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in metamorphic rocks and Cambrian alkalic plutonic rocks of Fremont County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). There are several past vermiculite DRMS-permitted operations developed in these rocks (Del Rio, 1960). The relatively unweathered Cripple Creek and Whitehorn Granodiorite plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks, as well as the Cambrian McClure Mountain and Democrat Creek alkalic plutons, are designated M/C, for lightweight aggregate potential. The Cambrian Gem Park alkalic pluton hosts numerous occurrences and is designated H/D for lightweight aggregate potential.

Significant outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.16.30 Clay

Considerable clay has been mined from Fremont County since the 1890s; production of 645,000 tons of clay is reported between 1951 and 1958 (Del Rio, 1960; Waagé, 1953). There have been numerous clay producers in a dozen Pennsylvanian through Tertiary shale-bearing rock units (USGS MRDS, 2013). The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone) and Glencairn Shale Member (Purgatoire Formation); many prospects occur in these units in this and other counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation, Dakota Sandstone, and Purgatoire Formation are designated H/D for clay occurrence potential; the Morrison Formation alone is assigned M/C for clay potential.

Most prospects developed in the Graneros Shale (Colorado Group), as well as the overlying Niobrara Formation, throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). Several Fremont County clay quarries produce from the Colorado Group and Niobrara Formation; these units are assigned M/D in areas of reported mines and M/C elsewhere for clay potential.

The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay potential.

In Fremont County, the Cretaceous to Tertiary Trinidad, Vermejo, and Raton Formations of southern Colorado are correlative with the Fox Hills Sandstone, Laramie Formation, and Dawson Arkose, respectively, of northern Colorado. Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Tertiary Dawson Arkose commonly hosts mica clay in sandstone pockets or lenses; kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Several USGS MRDS (2013) clay occurrences are reported from the southern Colorado equivalent rocks in Fremont County. The Trinidad, Vermejo, and Raton Formations are designated M/D around known mines and M/C elsewhere, for clay occurrence potential.

There are several clay prospects developed in the Permian-Triassic Lykins Formation along the Front Range; this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated M/C for clay occurrence potential. Bentonite is mined from altered Tertiary igneous rocks (ash-flow beds) southeast of Howard (Patterson, 1968; USGS MRDS, 2013); this unit is assigned M/D for clay potential. Abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). The undifferentiated Minturn and Belden Formations are designated L/B for clay occurrence potential. A few clay operations occur in fault zones of Precambrian rocks; buffers around these occurrences are designated L/C for clay potential.

4.16.31 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Fremont County hosts rock units of all ages that have been quarried for dimension stone, including Precambrian Silver Plume-aged granite, Cambrian to Mississippian quartzites, sandstones, and limestones, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, the Cretaceous Dakota Sandstone, and Tertiary sedimentary and igneous rocks (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Silver Plume Granite has been quarried for dimension stone in Fremont and other counties, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). Silver Plume-aged granite, including the Cripple Creek pluton, are designated H/C for dimension and building stone occurrence potential. The older and more weathered Boulder Creek Granite is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Significant production of high-quality dimension stone is reported from the Ordovician Manitou Limestone and Harding Sandstone and the Mississippian Leadville Limestone throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Partially metamorphosed and marbleized Leadville Limestone is quarried in Pueblo, Fremont, and Chaffee Counties, and Pueblo County 'Beulah marble' adorns the Colorado State Capital building (Arbogast et al., 2011; Schwochow, 1981). In Fremont County, several DRMS-permitted quarries have been worked for building stone in these units near Wellsville and Cañon City (Arbogast et al., 2011). Keller and Widmann (2002) describe the deposit near Wellsville as the most significant 'travertine' deposit in Colorado, having been used in many buildings. Undifferentiated Ordovician through Mississippian limestones, quartzites, and sandstones (mapped as OR or MDO) are designated H/D for dimension and building stone occurrence potential.

The correlative Pennsylvanian Minturn, Fountain, and Sangre de Cristo Formations host numerous sandstone and limestone beds throughout their extent; building stone production is reported from the Fountain Formation in other counties (Arbogast et al., 2011; Cappa and Bartos, 2007; Lindvall, 1968; Schwochow, 1981). The Fountain Formation in Fremont County is the only conglomerate quarried for dimension stone in the RGFO region (Lindvall, 1968; Schwochow, 1981). The Fountain Formation is assigned M/C for dimension stone potential; the Minturn and Sangre de Cristo Formations are assigned M/B.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Sharps (1963) described over 30 sandstone quarries in the Lyons Sandstone of Larimer and Boulder Counties that provided dimension and building stone material to the University of Colorado-Boulder campus. In Fremont County, Siloam Stone, Inc. has been quarrying high-quality dimension and building stone from the Dakota Sandstone near Cañon City since 1973. The Lykins Formation, as well as the Lyons and Dakota Sandstones are assigned H/D for dimension stone potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential. Production of good-quality dimension stone is reported from the overlying, undivided Cretaceous Vermejo and Trinidad Formations (Lindvall, 1968); this unit is assigned M/C for dimension stone potential. The basal, massive, locally conglomeratic sandstone unit of the Tertiary Raton Formation is well-cemented and unweathered in part, and it holds potential for use as dimension or building stone (Johnson, 1958; 1961). The overlying Poison Canyon Formation is partially composed of massive, unweathered, buff to red arkosic sandstone that also holds potential for use as building stone (Johnson, 1958; 1961). Though no dimension stone production is documented for the Raton and Poison Canyon Formations, as sandstone-hosting units they are designated M/B for dimension and building stone potential.

The Wall Mountain Tuff is a welded rhyolitic ash-flow tuff that occurs as isolated remnants in Fremont County (Arbogast et al., 2011; Del Rio, 1960; Scarbrough, 2001; Tweto, 1979a). The deposits have been quarried in Douglas County for high-quality dimension and building stone (Del Rio, 1960). The Wall Mountain Tuff is designated H/D for dimension stone potential; other Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.17 Gilpin County

4.17.1 Geothermal

Traditional / EGS Geothermal

The entirety of Gilpin County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Gilpin County contains no known springs or wells. The majority of Gilpin County is considered M/B for low temperature and/or co-produced geothermal resources because it is below the 100°F temperature threshold for low temperature and co-produced resources. The northeastern corner of the county is considered H/B because it is above the threshold.

4.17.2 Gold

Gilpin is the second smallest county in Colorado but has the second highest gold production. Early lode mining was restricted to oxidized ore, which normally reached 40 to 100 feet below the surface. Fissure fillings include pyritic gold that, where unweathered, is rather low grade, but tenor was enhanced by oxidation. The construction of the Hill smelter in Blackhawk in 1868 enabled extraction of metals from the unoxidized sulfide ores. Later, the completion of the railroad from Denver to Blackhawk spurred production again. Though production of gold exceeded 4.5 million ounces in Gilpin County, mostly from the greater Central City district, mining diminished early in the 20th century and has occurred only sporadically since 1914 (Davis and Streufert, 1990).

In Colorado, lode gold was first discovered in the greater Central City district area of Gilpin County, contiguous with the Idaho Springs district in Clear Creek County. Folded and faulted Precambrian biotite and felsic gneisses and schists dominate the greater district area and are intruded by Precambrian Boulder Creek granodiorite and Laramide hypabyssal porphyritic dikes and stocks (Davis and Streufert, 1990; Sims, 1982). Gold-bearing polymetallic and pyritic quartz veins fill Laramide-related fractures primarily in the felsic gneisses and secondarily in the biotite gneisses (Davis and Streufert, 1990). Production also stemmed from mineralized breccia pipes, gold-silver telluride veins, and placer deposits draining the region (Davis and Streufert, 1990). Exemplifying the richness of this district's ore, the After Supper and Sleepy Hollow mineralized vein system, which crosses North Clear Creek near Blackhawk, produced on average 2 ounces, and as much as 34 ounces, of gold per ton (Lovering and Goddard, 1950). The San Juan mine of the Quartz Hill subdistrict, on the western end of the Central City district, produced 2 to 12 ounces of gold per ton from a network of veins in a brecciated stockwork known as The Patch (Lovering and Goddard, 1950). The greater Central City district, including its constituent subdistricts, Eureka, Nevada, Enterprise, Russell Gulch, Pleasant Valley, Gregory, and Quartz Hill, is designated H/D for gold occurrence potential.

The North Gilpin district is a large area comprising the gold-producing subdistricts of Pine, Kingston, Apex, Illinois-Perigo, Gamble Gulch, and Union. The greater North Gilpin district is credited with production of 225,000 ounces of gold by Davis and Streufert (1990) and is designated H/D for gold occurrence potential.

Gilpin County is attributed with production of 47,874 ounces of placer gold between 1859 and 1957 (Parker, 1974). Placer activity occurred in nearly all the gulches that drain the gold-producing districts of Gilpin County. Parker (1974) discusses the probability of remaining placer reserves in Gilpin County projecting that gold remains to be recovered in the South Boulder Creek drainage basin in the northern part of the county. Therefore, portions of the Kansas, Phoenix, and Wisconsin districts, as well as the Ralston Creek headwaters in the Mountain House district, are assigned an occurrence potential of H/C due to the historic occurrence of placer gold and proximity to lode deposits of the CMB. The drainage region just east of the high potential districts, including the historically productive Clear Creek, is assigned H/C; further east the designation is reduced to M/B. A portion of western Gilpin County with no USGS MRDS (2013) gold occurrences is assigned H/B due to proximity to the CMB and favorable geology.

4.17.3 Silver

Gilpin County has been a large silver producer since the late 1850s from the same mines and geologic units as the gold production. Production of 11,170,972 ounces of silver is reported from Gilpin County from 1895 to 1957, primarily from the greater Central City district area (Del Rio, 1960; Sims et al., 1963a). The geology of the deposits, discussed above in the gold section (4.17.2) of this county's MPR, is virtually the same throughout Gilpin County: primarily pyritic quartz, and secondarily lead-silver, vein deposits in Precambrian felsic and biotite gneisses, and to a lesser extent, in Tertiary intrusives (Davis and Streufert, 1990; Sims et al., 1963a). A few gold and silver telluride veins are found in the Russell Gulch area (Sims et al., 1963a). Silver grade from samples at over a dozen mines in the Central City district ranged as high as 67.1 ounces of silver per ton (Sims et al., 1963a). The After Supper-Sleepy Hollow mineralized vein system, which crosses North Clear Creek near Blackhawk, averaged 10 ounces per ton of silver, reaching as high as 492 ounces per ton (Lovering and Goddard, 1950). The most influential structural controls on ore value are vein intersections or junctions where increased brecciation accommodates more heavily concentrated ores (Sims et al., 1963a). The greater Central City district area is designated H/D for silver occurrence potential.

The silver-bearing pyritic quartz veins of north-central Gilpin County host numerous scattered occurrences and minor past producers of silver, contributing just an estimated 5 percent of total production for the county, which still amounts to over 550,000 ounces of silver between 1895 and 1957 (Del Rio, 1960; Sims et al., 1963a). Where producers are concentrated the area is designated H/D for silver potential; areas where producers are more scattered are assigned M/C. Precambrian felsic gneisses with no occurrences are labeled M/B due to favorable geology.

4.17.4 Copper-Lead-Zinc

Like its southern neighbor, Clear Creek County, Gilpin County lies within the Front Range Precambrian core complex and almost entirely within the CMB. Precambrian gneisses, schists, and granodiorite are in part intruded by Tertiary bodies. Mineralization is restricted primarily to veins related to Laramide intrusions (Cappa et al., 2000). Gilpin County produced 26.7 million pounds of copper, 39.7 million pounds of lead, and 1.8 million pounds of zinc between 1859 and 1958 (Del Rio, 1960; Henderson, 1926; Sims et al., 1963a; Vanderwilt, 1947). The greater Central City district area was far more productive due to the larger size and increased occurrence of polymetallic veins (Vanderwilt, 1947). Vanderwilt (1947) makes special mention of an unusual northern district deposit (Evergreen mine) within and adjacent to monzonite porphyry dikes that was mined for copper (chalcopyrite and bornite). Precambrian rocks around the historic mining districts within the CMB are H/D. Rocks to the east and west of the districts with fewer MRDS (2013) occurrences are H/C.

4.17.5 Iron

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Iron (magnetite) was produced from pegmatites in Precambrian metamorphic rocks (Idaho Springs Formation) at the Dory Hill mine in the Mountain House district of Gilpin County (USGS MRDS, 2013). A buffer around this occurrence is designated L/C for iron occurrence potential. Precambrian metamorphic rocks elsewhere in the county are designated L/B for iron occurrence potential.

4.17.6 Manganese

No known production of manganese is reported from Gilpin County. However, manganese carbonates are associated with silver-and gold-bearing veins in Precambrian metamorphic and Tertiary igneous rocks throughout the county. Rhodochrosite is abundant in the Franklin, Moose, Bellman, and Gem mines near Gilson and Russell Gulches (Eckel, 1961). Precambrian metamorphic and Tertiary igneous rocks are designated L/C for manganese occurrence potential.

4.17.7 Molybdenum

The Nye (or Wilma) mine in the Apex district produced some high-grade molybdenum ore in the years 1964-65 from pyritic quartz veins and silicified shear zones in Tertiary quartz monzonite porphyry, as well as the Precambrian gneiss wallrock (King, 1964; USGS MRDS, 2013). Molybdenite is reported from an unknown mine in the Eureka district (shared with Clear Creek County) as well as in polymetallic veins in Precambrian gneiss in proximity to Tertiary intrusives at the Anchor and Front Neck mines of the Russell Gulch-Pleasant Valley (Central City) districts (USGS MRDS, 2013). Powellite is reported from pods in schist 2 miles southeast of Black Hawk (Eckel, 1961). Buffers around these occurrences are designated M/C for molybdenum potential. Tertiary intrusives are designated M/B; other metamorphic and igneous rocks are L/B.

4.17.8 Nickel

Nickel in pitchblende is reported from uranium mines near Blackhawk in the Central City district (Sims et al., 1963). Precambrian metamorphic and igneous rocks in the county are designated L/B due to minor occurrences in similar rocks in nearby counties (e.g., Jefferson, Clear Creek, and Boulder).

4.17.9 Tungsten

A dozen MRDS (2013) occurrences of tungsten, some of which are designated as past producers, are listed for Gilpin County. Production during WW I from two lode claims near the head of Silver Creek in Pine Mountain mining district was reported by Burlingame (1934) and may be synonymous with Black Metals mine as reported by MRDS (2013). Seams and vugs of ferberite occur within a pegmatite dike alongside massive porphyry, and a tested sample yielded 2.36 percent WO_3 (Burlingame, 1934). Several small mines with minor tungsten production are reported by Cobb (1960) and MRDS (2013) including the Star, Melvin Tungsten, Chihuahua, Little Rebel, Manchester, Nugget, and Glendale mines. Cobb (1960) reports 5,000 units (an estimated 79,000 pounds) of tungsten were produced from the Manchester mine from veins in granite and schist. Cobb (1960) notes there are numerous showings of scheelite in tactites (skarns) throughout the Front Range in schists and gneisses, including southeast of Blackhawk; USGS MRDS (2013) lists the Lake Fork Gulch and Foster Ranch occurrences in this area.

Lemmon and Tweto (1962) report pods of ferberite are found in copper-silver-gold veins in the Blackhawk district, especially the Chihuahua mine.

Due to recorded production, the area around the Manchester and Nugget mines in northeastern Gilpin County are designated H/D. The rest of the eastern half of the county, including areas around the other mines and occurrences with minimal production, is designated M/C. The western half of the county is L/B as similar host rocks occur but no occurrences are reported.

4.17.10 Beryllium

Zoned beryl-bearing pegmatites are found in the granitic rocks of southeastern Gilpin County within the Clear Creek district that also spans northeastern Clear Creek and western Jefferson Counties (Heinrich, 1957; Meeves et al., 1966). This small area is designated M/C for beryllium occurrence potential. Numerous unzoned pegmatites, where beryl occurs as a minor accessory mineral, occur in other areas of the county (Heinrich, 1957). Granitic rocks throughout the county are assigned L/B for beryllium occurrence potential.

4.17.11 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Gilpin County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Production of 1.8 million pounds of zinc is recorded between 1859 and 1958 in Gilpin County; sphalerite ores from mineralized veins in Precambrian granitic rocks are commonly reported from the many zinc mines (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around clusters of known zinc mines or individual mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.17.12 Rare Earth Elements

Within the Clear Creek Pegmatite Province, spanning southeastern Gilpin, northeastern Clear Creek, and western Jefferson Counties, REE mineralization is present within beryl-bearing pegmatites or veins in Precambrian Idaho Springs Formation gneiss (Adams, 1968; Haynes, 1960; USGS MRDS, 2013). In Gilpin County, monazite and xenotime are reported at the Jasper Cuts, Illinois Gulch, Fourmile Gulch, Russel Gulch, Dory Hill, and Dolores prospects (Haynes, 1960; Olson and Adams, 1962; Sims et al., 1963). Samples from the Jasper Cuts area are more concentrated in HREEs than LREEs and contained up to 5 percent monazite and xenotime combined; one sample assayed almost 8 percent total REE oxides (Sims et al., 1963). Trace yttrium is also reported in pitchblende concentrates in the area (Sims et al., 1963). A buffer around the Clear Creek Pegmatite Province area is designated M/C for REE occurrence potential. Trace REEs are found in Tertiary intrusive stocks of Boulder and Gilpin Counties (Gable, 1984). Tertiary stocks are assigned L/B for REE potential.

4.17.13 Niobium-Tantalum

There is no niobium-tantalum production noted for Gilpin County; however, columbite is reported from pegmatites in Idaho Springs schist at the Dory Hill site (Heinrich, 1957; USGS MRDS, 2013). A buffer along the fault around this prospect is designated L/B for niobium-tantalum occurrence potential.

4.17.14 Tellurium

Gold-telluride veins are reported from mines in the Idaho Springs-Central City district, shared with Clear Creek County (Eckel, 1961). Due to these reports and numerous past producers of gold and copper, the occurrence potential for tellurium in the greater Central City district is designated H/C. Precambrian rocks with numerous gold or copper mines elsewhere in the county are assigned M/B. Precambrian rocks in the remainder of the county are assigned L/B.

4.17.15 Titanium

There is no recorded production of titanium in Gilpin County; however, titanium is reported to be concentrated (relative to continental crust averages) in diorite, gabbro, and other mafic rocks (Force, 1976a). A Precambrian mafic intrusion of gabbro and diorite composition in central Gilpin County is designated L/B for titanium occurrence potential.

Also, potential economic concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). This unit in Gilpin County is designated L/B.

4.17.16 Uranium

The first report of pitchblende (uraninite) in the United States came from the Quartz Hill district of Gilpin County at the Wood mine in 1871 (Sims et al., 1963). Over 112,000 pounds of U_3O_8 was recovered from Gilpin County mines between 1871 and 1960, mostly from the greater Central City-Quartz Hill-Russell Gulch district area (Sims et al, 1963; Sims and Sheridan, 1964). Most uranium in Gilpin County occurs in veins and pegmatites in the Precambrian Idaho Springs Formation. The Quartz Hill district, bordering Clear Creek County, is particularly noted for the high grade of uraninite; early ores from the Wood mine assayed up to 60 percent U_3O_8 (Sims et al., 1963). One specimen at the nearby German and Belcher mines weighed 240 pounds and contained 88 percent U_3O_8 (Lovering and Goddard, 1950). Though the uranium ore is of high grade where found in this district, it occurs in small, highly disseminated lenses or pods, and it can therefore only be economically mined as a secondary commodity to other metals (Lovering and Goddard, 1950; Sims and Sheridan, 1964). Due to the significant production, the greater

Central City, Quartz Hill, and Russell Gulch district area is designated H/D for uranium occurrence potential.

Numerous uranium occurrences, including the highly productive Schwartzwalder mine, are found along northwestward-trending Tertiary fault systems or breccia reefs in Boulder and Jefferson Counties, some of which extend into Gilpin County (Nelson-Moore et al., 1978; Sims and Sheridan, 1964). A couple of uranium occurrences and anomalous radioactivity (e.g., the Priscilla claims), but no production, are reported along these breccia reefs in Gilpin County (Nelson-Moore et al., 1978; Sims and Sheridan, 1964). Buffers along these major faults are designated M/B for uranium occurrence potential in Gilpin County. Elsewhere in the county, numerous base- or precious-metal mines report uranium occurrences or radioactive anomalies; buffers around these occurrences are assigned L/C for uranium potential.

4.17.17 Thorium

There are no reported occurrences of thorium in Gilpin County; however, thorium is reported from veins and pegmatites along mainly northwest-trending faults in Precambrian crystalline rocks in surrounding counties. Northwest-trending faults, as well as several northeast-trending dikes, in Precambrian crystalline rocks are designated L/B for thorium occurrence potential.

4.17.18 Vanadium

In Gilpin County, minor sporadic vanadium occurs in Tertiary polymetallic veins, pegmatites, and bostonite porphyry dikes intruded in Precambrian Idaho Springs Formation gneiss (Nelson-Moore et al., 1978). The only production reported is 5 pounds of vanadium recovered from 16 tons of 0.02 percent V_2O_5 ore at the Carrol (Spur-Daisy) mine (Nelson-Moore et al., 1978). Buffers along mapped Tertiary dikes throughout the county are designated L/C for vanadium occurrence potential.

4.17.19 Fluorspar

No commercial fluorspar production is reported from Gilpin County; however, three polymetallic prospects host green, purple, or rare colorless fluorite as gangue in fissure veins that occur in the Precambrian Idaho Springs biotite gneiss (Aurand, 1920; Brady, 1975; USGS MRDS, 2013). Also, the CMB in Gilpin County is cut by northeast-trending porphyry dikes and northwest-trending faults and boasts numerous pegmatites, all in rocks known to host fluorite elsewhere (Goddard,1947). Average content of fluorine (ppm) in Central Colorado measured highest in Precambrian igneous rocks, followed by Precambrian metamorphic and Tertiary intrusive rocks (Wallace, 2010). Precambrian igneous rocks are designated H/C, Precambrian biotite gneiss and Tertiary intrusives are assigned M/C, and hornblende gneiss is assigned M/B for fluorspar potential throughout the county.

4.17.20 Diamond and Gemstones

There are two mines (Little Melvin Lode and Carr mine) developed in polymetallic veins near contacts of Precambrian felsic and biotite gneisses that report gemstones as a primary commodity in the Apex and Gregory mining districts (USGS MRDS, 2013). Rhodochrosite is reported as abundant in several mines of the greater Central City district near the head of Gilson Gulch (Eckel, 1961). Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks are designated M/C, and biotite gneisses and schists are assigned M/B, for gemstone occurrence potential (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

4.17.21 Pegmatite Minerals

Zoned beryl-bearing pegmatites are reported in the granitic rocks of southeastern Gilpin County (Heinrich, 1957; Meeves et al., 1966). Numerous unzoned pegmatites occur in other areas of the county, but there are no reports of production and just one occurrence of anomalous feldspar or mica at the Dory Hill mine (Heinrich, 1957; USGS MRDS, 2013). Nonetheless, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B.

4.17.22 Industrial Abrasives

There is one past producer of garnet (Ellis Lode) noted for Gilpin County; the mine is located in the contact zone of Precambrian Boulder Creek granite and Idaho Springs biotite gneiss (USGS MRDS, 2013). Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks are designated M/C for industrial abrasive potential in Gilpin County (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.17.23 Sand and Gravel

There is no sand and gravel production reported for Gilpin County; however, Quaternary glacial drift (Qd) and Tertiary gravels (Tgv) are assigned H/C for potential (Arbogast et al., 2011; USGS MRDS, 2013). Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.17.24 Crushed Stone Aggregate

Tertiary intrusive rocks occur sporadically throughout Gilpin County; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Laramide intrusive rocks meet the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999) and are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The moderately weathered and jointed Precambrian Boulder Creek Granite is classified only as a ‘fair’ source rock by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Boulder Creek Granite is assigned M/C for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

4.17.25 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in the Precambrian granitic igneous and metamorphic rocks comprising the mountains of Colorado (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the igneous and metamorphic rocks of Gilpin County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The highly weathered Boulder Creek Granite is designated M/B for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

4.17.26 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Gilpin County hosts Precambrian igneous rocks that have potential to be quarried for dimension stone, including the Boulder Creek and related granites, although abundant fractures and joints make it more suitable for crushed rock (Arbogast et al., 2011;

Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981). The Boulder Creek Granite is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. Scattered outcrops of Tertiary intrusives are assigned L/B for dimension stone potential.

4.18 Huerfano County

4.18.1 Coal

The RGFO portion of the Raton Mesa Coal Region (see section 3.1.2 of this MPR), which falls entirely within Huerfano and Las Animas Counties, is host to over 380 historic coal mines (Boreck and Murray, 1979; Carroll and Bauer, 2002). In Huerfano County, 75.7 million tons of coal were recovered from 121 mines developed in the lower units of the Upper Cretaceous Vermejo Formation, which is correlated with the Laramie Formation of the Denver Basin (Brandt, 2015; Carrol and Butler, 2002; Landis, 1959). There are three non-active CDRMS coal exploration permits and four non-active CDRMS coal permits.

All of the past production in Huerfano County has been from mines located around the perimeter of the Raton Basin, likely leaving the deeper center mostly unmined. Of an estimated 12.4 billion tons of original coal resources under less than 3,000 feet of overburden and a realistic recoverability of 35 percent, about 4.3 billion tons of coal remain in the RGFO portion of the Raton Mesa Coal Region, which includes both Huerfano and Las Animas Counties (Brandt, 2015). The RGFO portion of the Raton Mesa Coal Region is designated H/D for coal occurrence potential. RGFO management area coal occurrence potential is shown on Map 7-1 in section 7.

4.18.2 Geothermal

Traditional / EGS Geothermal

The majority of Huerfano County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). Areas in the southwest and west are considered M/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Huerfano County contains no known springs or wells. About half of Huerfano County lies outside named COGCC fields and is above the 100°F temperature threshold for low temperature and co-produced resources, and is therefore considered H/B. Areas in the western portion within named fields are designated H/C. The rest of the county is M/B due to being below the temperature threshold.

4.18.3 Gold

Vanderwilt (1947) reports 168 ounces of gold recovered from the West Spanish Peak intrusive, as well as from streams draining that area. Budding and Kluender (1983) report 0.026 ounces per ton of gold from samples at the Bulls Eye mine. Placer gold is reported from Wahatoya Creek, flowing from the Spanish Peaks north toward the Cucharas River at La Veta (Vanderwilt, 1947). The area around the Spanish Peaks is designated H/C for gold occurrence potential. Wahatoya Creek is designated M/B.

Zimbelman (1989) reports anomalous gold in samples collected from the north face of Blanca Peak. Scott (1986) notes 40 ounces of gold were recovered from the Courthouse Vein system, but estimates 4 million tons of 0.4 ounces per ton gold may be contained in the large quartz veins. The mafic host rocks and southern hornblende gneiss are designated H/C in the Blanca Peak region.

4.18.4 Silver

Production of 1,176 ounces of silver was reported from the West Spanish Peak area of the La Veta district of Huerfano County prior to 1908 (Vanderwilt, 1947). Polymetallic quartz veins in a diorite porphyry of the West Spanish Peak intrusive complex host silver (tetrahedrite) (U.S. Bureau of Mines, 1989). Budding and Kluender (1983) identified mineralization in veins along a shear zone and in the contact metamorphic aureole around the Spanish Peak intrusive. Samples from the Bullseye mine averaged 2.2 ounces per ton of silver (Budding and Kluender, 1983). The area around West Spanish Peak and the La Veta district is designated M/C for silver occurrence potential.

Zimbelman’s detailed geochemistry study in 1989 indicates moderate potential of silver occurrence on the north face of Blanca Peak associated with northwest-trending faults. Assays reported in Ellis et al. (1983) show silver from quartz veins in Precambrian gneiss and granite on Carbonate Mountain. Samples from a Blanca Peak vein yielded 2 ounces per ton of silver (USBM, 1989). Precambrian felsic metamorphic rocks within the Sangre de Cristo range along western Huerfano County, including the Blanca Peak region, are assigned M/C for silver occurrence potential. Similar rocks in the northern portion of the county (Greenhorn Mountain area) are considered M/B for potential due to favorable geology and the presence of several occurrences of silver in the USGS MRDS (2013) database. Anomalous “redbed-type” concentrations of silver are noted from the Pennsylvanian Minturn Formation, and this unit is designated L/B for silver occurrence potential.

4.18.5 Copper-Lead-Zinc

Only a small amount of base metals have been produced in Huerfano County, 92 pounds of copper and 1,067 pounds of lead, all in 1908 in the La Veta district (including Huerfano A district of Dunn (2003)) (Vanderwilt, 1947). Past minor workings of mineralized veins within the contact zone of the West Spanish Peak Tertiary intrusive and sedimentary rocks is noted by Budding and Kluender (1983). The most significant working was at the Bullseye mine where a mineralized vein (gold, silver, lead, zinc, copper, and antimony) can be traced for half a mile (Budding and Kluender, 1983). Based on past production and workings, the La Veta district, including the area between the Spanish Peaks, is designated H/D for base-metal occurrence potential.

Johnson (1984) records mineralized lenses, with occurrences of copper and zinc, in redbeds of the lowest Sangre De Cristo Formation and upper Minturn Formation in the Blanca Peak and Carbonate Mountain areas (Blanca district), and other USGS MRDS (2013) base-metal occurrences are reported in these formations. One stratiform layer can be traced for eight miles (Johnson, 1984). Paleozoic sedimentary units are assigned H/B for base-metal occurrence potential. In the Blanca district, mafic host rocks and hornblende gneiss are designated H/C and other Precambrian rocks are M/B.

Minor production of lead and zinc in 1941 was reported in the Grayback district (also known as Russell district) of northern Costilla County (Vanderwilt, 1947). The Tertiary intrusive north of the Grayback district occurs in an area roughly corresponding to the Huerfano B district of Dunn (2003) and is designated M/C. The Malachite district lies along the Huerfano River southwest of Gardner in the Sangre de Cristo Mountains, although possibly further southwest than Vanderwilt (1947) reports. Here, Paleozoic redbeds of the Sangre de Cristo Formation (H/B) contain disseminated copper, although no production is recorded (Vanderwilt, 1947). The Greenhorn Mountain area in the northern part of the county has designations of M/B for Precambrian gneiss, L/B for Tertiary intrusives, and H/B for Paleozoic redbeds.

4.18.6 Iron

Harrer and Tesch (1959) report scattered limonite and siderite concretions from the Laramie Formation (called the Vermejo Formation in the Raton Basin by Harbour and Dixon (1959)). Samples taken from near Walsenburg contained 27.86 percent iron. This unit is designated L/C for iron occurrence potential. Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential. Precambrian Silver Plume-related granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B.

4.18.7 Manganese

There are no reported occurrences of manganese in Huerfano County; however, Precambrian igneous and metamorphic rocks, as well as Tertiary igneous rocks, are designated L/B for manganese potential due to occurrences in these same rocks in nearby counties (Custer and Chaffee).

4.18.8 Molybdenum

Molybdenum is reported just twice in Huerfano County. Quartz veins in Precambrian gneiss contain minor amounts of molybdenum in the Chimney Gulch and Blanca Peak areas (U.S. Bureau of Mines, 1989). Molybdenite in quartz veins in pegmatite is reported at the Mosca Pass prospect (Eckel, 1961; USGS MRDS, 2013). A small buffer around these areas is designated M/C. Tertiary intrusives are designated M/B; Precambrian rocks are L/B.

4.18.9 Nickel

Anomalous concentrations of nickel are reported from igneous and metamorphic rocks near Greenhorn Mountain in northern Huerfano County (Toth et al., 1983). Precambrian metamorphic and igneous rocks throughout the county are designated L/B due to this occurrence and others in similar rocks in nearby Custer County.

4.18.10 Tungsten

A cluster of tungsten-bearing deposits occurs in westernmost Huerfano County, in the West Blanca district about one mile northeast of Blanca Peak (USGS MRDS, 2013). The Courthouse Vein System is composed of polymetallic veins in Precambrian gneisses which were primarily mined for gold and silver (USGS MRDS, 2013). An assay showed just 0.01 percent WO_3 (USGS MRDS, 2013). This area is M/C for tungsten potential. Precambrian metamorphic and granitic rocks elsewhere are L/B.

4.18.11 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Huerfano County; however, 262.6 million tons of coal was produced in the Raton Mesa Coal Region (see sections 3.1.2 and 4.18.1 of this MPR), shared with Las Animas County; this coal region is designated L/B for germanium occurrence potential.

4.18.12 Tellurium

Mineral descriptions in Eckel (1961) for the Hawkins adit in the Blanca district and the area of the Courthouse Vein System include tellurides. Due to known occurrence of calaverite, sylvanite, and hessite in the Blanca and West Blanca districts, and the Courthouse Vein System, these areas are considered M/C. Precambrian rocks in the remainder of the county are assigned L/B.

4.18.13 Titanium

There is no recorded production of titanium in Huerfano County; however, the abundance of accessory minerals, especially sphene, is diagnostic of the San Isabel Granite (Boyer, 1962). The small portions of the San Isabel Granite in northern Huerfano County are assigned L/B for titanium potential.

4.18.14 Uranium

About 517 tons of ore were produced from mines in Huerfano County, but only 33 pounds of uranium were recovered (Nelson-Moore et al., 1978). The reported ore production came from several deposits located in the Eocene Farasita Conglomerate, mapped with the Huerfano Formation in the northern part of the county (Nelson-Moore et al., 1978; Tweto, 1979a). Samples assayed up to 0.28 percent U_3O_8 at the Anal No. 1 mine (USGS MRDS, 2013). A buffer around these prospects and mines is designated M/C for uranium occurrence potential; elsewhere in the county, the Huerfano Formation, including the Farasita Conglomerate, is assigned L/B.

About 40 tons of 0.07 percent U_3O_8 ore were produced from the Permian Sangre de Cristo Formation at the City Slicker claim (Nelson-Moore et al., 1978). Carnotite, autunite, and tyuyamunite are reported from numerous other mines and prospects in the Sangre de Cristo Formation, and samples assayed up to 0.36 percent U_3O_8 (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for uranium occurrence potential.

A sample from the lower Pierre Shale (Sharon Springs Member?) near the contact with the Niobrara Formation measured 0.4 percent U_3O_8 in Las Animas County (USGS MRDS, 2013). A buffer along the contact between these units in Huerfano County is designated L/B.

Several uranium prospects and occurrences occur in Mesozoic sedimentary rocks in this and other counties in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Coffinite is disseminated in the Dakota Sandstone / Purgatoire Formation near a contact with the Sangre de Cristo Formation and a Tertiary intrusive stock in the Badito Cone area, and samples from stratiform lenses at two mines assayed up to 0.13 percent U_3O_8 (Nelson-Moore et al., 1978; USGS MRDS, 2013; Wright and Everhart, 1960). Production from these units is reported in Pueblo County (Nelson-Moore et al., 1978). A buffer around these mines is designated M/C for uranium occurrence potential; elsewhere in the county these units are assigned L/B.

Tertiary siliceous tuffs are source rocks for uranium leached and reprecipitated in nearby fractures and faults (Olson, 1988). Production of nearly 500 pounds of uranium is reported from a seam underlying Tertiary tuffs in Saguache County (Nelson-Moore et al., 1978). Tertiary tuffs in Huerfano County are designated L/B for uranium occurrence potential.

4.18.15 Thorium

A single thorium occurrence, Stumbling Stud mine (Badito Cone), is known in Huerfano County at the southern end of the Wet Mountains. Mineralization occurs in Tertiary phonolite dikes in the Cretaceous Dakota Sandstone (USGS MRDS, 2013). Uranium and vanadium are the primary commodities of interest at this deposit, and thorium is listed as a tertiary commodity. This occurrence, as well as faults in Precambrian metamorphic rocks in the Wet Mountains, are designated L/C for thorium occurrence potential.

4.18.16 Vanadium

In Huerfano County, Nelson-Moore et al. (1978) report production of 6 pounds of 0.55 percent V_2O_5 at the Anal No. 1 mine in the Oligocene Farisita conglomerate of the Huerfano Formation. Vanadium occurs with uranium in limonite-stained lenses here and at a couple of other nearby prospects (USGS MRDS, 2013). The Huerfano Formation is designated L/B for vanadium occurrence potential.

Samples from the Dallas Dottie site, developed in the Permian Sangre de Cristo Formation, contained carnotite and assayed up to 4.0 percent V_2O_5 (Nelson-Moore et al., 1978). Several other Sangre de Cristo Formation prospects report high V_2O_5 grades as well, including the Parks Lode (2.6 percent), Halls property (2.3 percent), Muleshoe (2.0 percent), and Santa Rosa (1 to 2 percent), although no production is recorded (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for vanadium occurrence potential.

Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). In Huerfano County, samples from the Stumbling Stud (Badito Cone) mine, developed in a Tertiary alkalic dike intruded into an undifferentiated Jurassic Morrison Formation and Cretaceous Dakota Sandstone unit, assayed up to 0.07 percent V_2O_5; 510 tons of ore of 0.009 percent V_2O_5 were reportedly mined (Nelson-Moore et al., 1978; Toth et al., 1983). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The undifferentiated Morrison Formation and Dakota Sandstone are designated M/B for vanadium occurrence potential; the Dakota Sandstone elsewhere is designated L/B.

Vanadium is reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in Park, Fremont, and Custer Counties; samples assayed up to 4.34 percent

V_2O_5 (Nelson-Moore et al., 1978; Schwochow and Hornbaker, 1985; Wilmarth, 1959). The Minturn Formation is assigned L/C for vanadium occurrence potential.

4.18.17 Fluorspar

No commercial fluorspar production is reported from Huerfano County; however, average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks (Wallace, 2010). Precambrian igneous rocks are designated H/C and Precambrian hornblende gneiss is assigned M/B for fluorspar occurrence potential throughout the county.

4.18.18 Pegmatite Minerals

There are no known occurrences of pegmatites or reported production of feldspar or mica in Huerfano County. Nonetheless, Precambrian felsic metamorphic rocks are designated M/B for pegmatite mineral potential due to occurrences in the same rock types in other counties. Precambrian plutonic rocks are assigned L/B.

4.18.19 Industrial Abrasives

There is no reported production of industrial abrasives in Huerfano County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks elsewhere in the RGFO management area, these rocks are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.18.20 Limestone and Dolomite

There is only one limestone prospect in Huerfano County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; both are found throughout the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential. The Pennsylvanian Minturn and Belden Formations host limestone prospects in other counties and are designated L/C for limestone potential.

4.18.21 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, which crops out Huerfano County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). No permitted industrial sand operations are reported in Huerfano

County, but samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica (Vanderwilt, 1947). The Dakota Sandstone is designated H/C for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

4.18.22 Gypsum

Though no gypsum production or mines are reported from Huerfano County, several gypsum quarries hosted by the Jurassic Ralston Creek Formation occur in nearby Pueblo and Fremont Counties (USGS MRDS, 2013). No bedded gypsum is reported from within the Morrison Formation, but there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). The Stevens Gypsum mine (Pueblo County), developed in the undivided Colorado Group, likely produced from the underlying Morrison and Ralston Creek Formations; production of 700 tons of gypsum per month at one point is reported (George, 1920; USGS MRDS, 2013). The undivided Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential in Huerfano County.

Productive gypsum quarries in western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation along the Arkansas River corridor near the Swissvale, Badger Creek, Howard, and Coaldale areas, and this unit extends into Huerfano County (Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential throughout Huerfano County.

4.18.23 Helium

The Sheep Mountain and Oakdale fields in western-central Huerfano County are relatively small structural traps noted for low-BTU gas containing mostly carbon dioxide; the field extents as shown by Worrall (2004) are designated as L/C because of the small amount of drilling and relatively low helium contents.

4.18.24 Sand and Gravel

Numerous USGS MRDS (2013) and DRMS-permitted sand and gravel operations occur in Quaternary deposits in Huerfano County. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Glacial drift (Qd) is assigned H/C for sand and gravel occurrence potential.

The Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation host sporadic sand and gravel operations in this and other counties (W. D. Carter, 1968); these units are assigned L/C for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in various sedimentary rock units throughout the county along rivers their tributaries; buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.18.25 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Huerfano County, likely developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Precambrian mafic intrusives and Tertiary basalt occur throughout the county; dark, dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Precambrian mafic rocks and Tertiary basalt are assigned H/C for crushed stone potential. Tertiary andesitic lavas and breccias may be too porous in part to meet the requirements of crushed stone aggregate (Knepper et al., 1999); Tertiary andesitic rocks, mapped as Tpl, are assigned M/B for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the San Isabel pluton in Huerfano, Pueblo, and Custer Counties, are deemed excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed, Precambrian Boulder Creek plutons and satellites were classified as only ‘fair’ source rocks by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The San Isabel pluton and satellites are designated H/C, and the Boulder Creek Granite is designated M/C, for crushed stone aggregate potential. Precambrian felsic and hornblendic gneisses (Idaho Springs Formation) are assigned H/B for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Paleozoic Minturn and Sangre de Cristo Formations, the Mesozoic Morrison Formation, Dakota Sandstone, Trinidad Sandstone, and Vermejo Formation, and the Cenozoic Raton, Poison Canyon, Cuchara, and Santa Fe Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several past DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in nearby counties. The Dakota Sandstone is designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.18.26 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Purgatoire Formation and Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential. The Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay and contains slightly to highly expansive illite and montmorillonite; this shale member may be a suitable resource for Leca (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B for lightweight aggregate occurrence potential.

The Pennsylvanian Minturn Formation and other Cretaceous to Tertiary sedimentary units, including the Trinidad, Vermejo, Raton, Poison Canyon, Cuchara, Huerfano, and Santa Fe Formations, bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

The lightweight aggregate, vermiculite, forms from the weathering of micas, which commonly occurs in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). The lightly weathered San Isabel granite to granodiorite is designated L/B, the older and more weathered Boulder Creek Granite is assigned M/B, and felsic and hornblendic gneisses (derived from volcaniclastic host rocks) are designated M/C, for lightweight aggregate potential. Outcrops of mostly felsic tuffs and breccias derived from Tertiary volcanic activity may host perlite, scoria, or pumice (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.18.27 Clay

The best quality refractory clays in the RGFO region are found in the Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; there are several clay prospects in these units in nearby Las Animas County and numerous others throughout the RGFO region (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; USGS MRDS, 2013; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the underlying Jurassic Morrison Formation; several USGS MRDS (2013) prospects in this unit occur in this and other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Purgatoire Formation, Dakota Sandstone, and Morrison Formation are designated H/D for clay occurrence potential; the Morrison Formation as mapped alone is assigned M/C for clay potential.

Several prospects developed in the Cretaceous Graneros Shale (Colorado Group), the Smoky Hills Member (Niobrara Formation), and the overlying Pierre Shale throughout the RGFO region have produced a high-quality fire clay, but most prospects produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds (Arbogast, 2011; Landis, 1959b; Schultz, 1978; USGS MRDS, 2013). The Pierre Shale is designated H/C, and the Colorado Group and Niobrara Formation are assigned M/C, for clay potential.

The Cretaceous to Tertiary Trinidad, Vermejo, and Raton Formations of southern Colorado are correlative with the Fox Hills Sandstone, Laramie Formation, and Dawson Arkose, respectively, of northern Colorado. Abundant kaolinite with significant montmorillonite occur in shale of the Cretaceous Laramie Formation and shale interbeds of the underlying Fox Hills Sandstone host clay suitable for brick making (Spence, 1980; Vanderwilt, 1947). The Tertiary Dawson Arkose commonly hosts mica clay in sandstone pockets or lenses; kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Several USGS MRDS (2013) clay occurrences are reported from the southern Colorado equivalent rocks in other counties (Fremont and Las Animas). The Trinidad, Vermejo, and Raton Formations are designated L/B for clay occurrence potential.

Common shale layers occur in the Tertiary Cuchara and Huerfano Formations (Tweto, 1979a). The Cuchara and Huerfano Formations are designated L/B for clay occurrence potential.

4.18.28 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Huerfano County hosts rock units of all ages that have been quarried for dimension stone, including Precambrian granites, Paleozoic and Mesozoic sandstones and limestones, and Tertiary sedimentary and igneous rocks (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Silver Plume Granite has been quarried for dimension stone in other counties, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). Silver Plume-aged granite, including the San Isabel pluton and satellites, are designated H/C for dimension and building stone occurrence potential. The older and more weathered Boulder Creek Granite is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. Tertiary intrusive rocks are assigned L/B for building stone potential.

The Pennsylvanian Minturn and Sangre de Cristo Formations host numerous sandstone and limestone beds throughout their extent; building stone production is reported from the correlative Fountain Formation in nearby Fremont County (Arbogast et al., 2011; Cappa and Bartos, 2007; Lindvall, 1968; Schwochow, 1981). The Minturn and Sangre de Cristo Formations are assigned M/B for dimension and building stone occurrence potential. Significant production of high-quality dimension stone is reported from the Dakota Sandstone throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981).

The Dakota Sandstone is assigned H/C for dimension stone potential; the underlying Jurassic Morrison Formation is assigned M/B for dimension stone potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in the RGFO region (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential. Production of good-quality dimension stone is reported from the overlying, undivided Cretaceous Vermejo and Trinidad Formations (Lindvall, 1968); this unit is assigned M/C for dimension stone potential.

The basal, massive, locally conglomeratic sandstone unit of the Tertiary Raton Formation is well-cemented and unweathered in part, and it holds potential for use as dimension or building stone (Johnson, 1958; 1961). The overlying Poison Canyon Formation is composed in part of massive, unweathered buff to red arkosic sandstone that also holds potential for use as building stone (Johnson, 1958; 1961). The Cuchara Formation caps the Tertiary sedimentary units in part of the county; the Cuchara Formation hosts thin-bedded to massive, red, pink, and white, well-cemented sandstone beds which hold potential for use as dimension or building stone (Johnson, 1958; 1961). Though no dimension stone production is documented for the Raton, Poison Canyon, or Cuchara Formations, as sandstone-hosting units they are designated M/B for dimension and building stone potential.

4.19 Jefferson County

4.19.1 Coal

The northeastern corner of Jefferson County lies within the Denver Basin of the Denver Coal Region (see section 3.1.1 of this MPR). There are 52 historic coal mines in Jefferson County, and production of 6.7 million tons of coal from the Cretaceous Laramie Formation is reported from 26 past-producing mines between 1864 and 2002 (Brandt, 2015; Carroll and Bauer, 2002). Past production occurred along the edge of the basin where the layers are upthrust by the Golden Faults of the Front Range system. Of an estimated 806.6 million tons of original coal resources under less than 3,000 feet of overburden in the county, roughly 13.4 million tons are depleted, implying reserves of 793.2 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Jefferson County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.19.2 Geothermal

Traditional / EGS Geothermal

The entirety of Jefferson County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Jefferson County contains no known springs or wells. About ¾ of Jefferson County lies outside named COGCC fields and is above the 100°F temperature threshold for low temperature and co-produced resources, and is therefore considered H/B. A few small areas within named fields are designated H/C. The rest of the county is M/B due to being below the temperature threshold.

4.19.3 Gold

Jefferson County has been credited with production of 14,566 ounces of gold, primarily placer, between 1885 and 1958 (Del Rio, 1960; Vanderwilt, 1947). The chief source of gold in Jefferson County has been Clear Creek and Ralston Creek placers, which were discovered as early as 1859 and produced for many years. Alluvial placers recovered from sand and gravel operations along Clear Creek east of Golden accounted for most of the State's placer gold production from 1951 to 1974 (Parker, 1974). The gold source for the Clear Creek placers is most likely the lodes in Gregory and Russell Gulches and other lodes of the Central City district in Gilpin County (Parker, 1974; Tweto, 1979a). Clear Creek and Ralston Creek are designated M/C for gold occurrence potential. Several gold occurrences are scattered throughout the Pikes Peak batholith in this and other counties, and so the batholith is designated M/B for gold occurrence potential. In the western half of the county, buffer zones around known occurrences of placer or lode gold are designated M/C. An area devoid of gold occurrences, where streams drain from significant gold occurrences in neighboring Clear Creek and Gilpin Counties, is designated M/B.

4.19.4 Silver

Jefferson County is attributed with 14,375 ounces of lode and placer silver production from 1885 through 1958 (Del Rio, 1960; Vanderwilt, 1947). Several prospects and mines are noted in pegmatites of faulted Precambrian felsic metamorphic rocks of the Idaho Springs Formation in the northern half of the county (USGS MRDS, 2013). Production of 3,100 ounces of silver was reported from the Malachite mine from 1940 to 1941, and another 850 ounces was reported in 1946 (Sheridan et al., 1990; Vanderwilt, 1947). Sheridan et al. (1990) classify the Malachite deposit as a Type I Precambrian stratabound exhalative deposit. The Malachite deposit occurs in faulted Precambrian felsic gneiss, and samples yielded 0.4 to 0.9 ounces of silver per ton (Tweto, 1979a; USGS MRDS, 2013). About 0.72 ounces of silver per ton are reported from the nearby

Union Pacific Shaft (USGS MRDS, 2013). A grab sample at the Mena uranium mine, where silver is a tertiary commodity, assayed at 43.6 ounces of silver per ton; a sample from the North Star mine assayed at 6.42 ounces per ton (Sheridan et al., 1967; USGS MRDS, 2013). The Precambrian felsic metamorphic rocks in Jefferson County are designated M/C for silver occurrence potential where known past producers are located and M/B elsewhere. The Pikes Peak batholith is designated M/B for silver occurrence potential due to sporadic silver occurrences in this and nearby Douglas and Park Counties.

4.19.5 Copper-Lead-Zinc

Jefferson County production of base metals between 1885 and 1958 is reported at 560,195 pounds of copper, 11,063 pounds of lead, and 2,000 pounds of zinc (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). The western two-thirds of the county is underlain by Precambrian igneous and metamorphic rocks, some of which host small Type 1 (metamorphosed to upper amphibolite facies) stratabound exhalative sulfide deposits (Sheridan et al., 1990). The Creswell, Hosa Lodge, F.M.D., and Malachite mines plus the Cook and one unnamed prospect are of this type. All are noted for copper (chalcopyrite) and zinc (sphalerite), whereas lead (galena) is also noted at the Creswell, Hosa Lodge, and Cook sites (Sheridan et al., 1990). The F.M.D. and Malachite deposits occur as ‘massive sulfides’ in a pyrite-pyrrhotite matrix (Eckel, 1961; Sheridan et al., 1990; Vanderwilt, 1947). Gahnite, commonly found in the Type 1 upper amphibolite facies of these deposits, is found with galena at the Creswell mine (Eckel, 1961; Sheridan and Raymond, 1984a). The stratabound exhalative sulfides of Sheridan et al. (1990) and the surrounding gneisses are designated H/D for base-metal occurrence potential. The gneiss and quartzite in the Ralston Butte district are also designated H/D as they host the Schwartzwalder mine and Buckman property, among others, with noted copper minerals (Nelson-Moore et al., 1978). Northwest of these areas, Precambrian rocks associated with the CMB (see neighboring Clear Creek and Gilpin Counties) are assigned H/C for base-metal potential. Other Precambrian gneisses are assigned M/B, whereas granites, including the Pikes Peak Granite, are assigned L/B.

4.19.6 Iron

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Several USGS MRDS (2013) iron occurrences are noted in Jefferson County, and Precambrian metamorphic rocks are designated L/B for iron occurrence potential. Late-stage syenite, fayalite, and mafic intrusions into the Precambrian Pikes Peak batholith host iron-rich minerals (Smith et al., 1999); these units are designated M/B for iron occurrence potential. Elsewhere, the Pikes Peak batholith is designated L/B for iron potential. Precambrian Silver Plume-aged granites (Indian Creek pluton) host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported from this unit in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-aged granite in Jefferson County is assigned L/B.

Thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Jefferson County. Siderite, hematite, and limonite are also reported from a prospect worked in the Cretaceous Colorado Group shales (Benton or Carlile) (Herrer and Tesch, 1959; USGS MRDS, 2013); this unit is assigned L/C for iron occurrence potential.

4.19.7 Manganese

Minor manganese oxides and carbonates are reported from the Ralston Buttes district of northern Jefferson County (e.g., Schwartzwalder and Mena uranium mines) in Precambrian metamorphic rocks (USGS MRDS, 2013). Pyrolusite crystals occur in quartz pegmatites in proximity to quartz monzonite of the Buffalo Park intrusive center of the Pikes Peak batholith at the Dazie Bell and Oregon No. 3 mines (USGS MRDS, 2013; Smith et al., 1999). Precambrian igneous and metamorphic rocks throughout Jefferson County are designated L/C for manganese potential.

4.19.8 Molybdenum

Molybdenite is found in veins or pegmatites in Precambrian gneiss at several uranium mines in the Ralston Buttes district in the northern part of Jefferson County (USGS MRDS, 2013). An assay at the Mena mine found 0.1 percent molybdenum (USGS MRDS, 2013). Two other occurrences are found in polymetallic veins in Precambrian gneiss and a third occurs in the potassic Redskin stock of the Pikes Peak batholith in southern Jefferson County (USGS MRDS, 2013). The areas around these occurrences are designated M/C. Other Precambrian metamorphic and igneous rocks are L/B.

4.19.9 Nickel

Nickeliferous pyrrhotite is reported in a gabbro dike intruded in Precambrian amphibole schist (Idaho Springs Formation) at the Malachite mine in the Evergreen (Malachite) mining district (Lindgren, 1908). Nickel-bearing pitchblende occurs in Idaho Springs amphibole schist at the past-producing (copper and uranium) Mena mine (USGS MRDS, 2013). Several prospects (Osiris property and Osirio mines) in the Princeton-Crosson district (shared with Park County) in Precambrian amphibole schist near the boundary with the Pikes Peak Granite, are recorded as past-producers of nickel, although no data are available (USGS MRDS, 2013). Precambrian metamorphic and igneous rocks throughout the county are designated L/B due to these occurrences and others in similar rocks in nearby counties.

4.19.10 Tungsten

Only two occurrences of tungsten are noted by the USGS MRDS (2013), and no production is reported. Scheelite shows in pegmatite within the Idaho Springs Formation at the Genesee Mountain Scheelite claims (Eckel, 1961; USGS MRDS, 2013). Another, unnamed, prospect is composed of scheelite in veins along a contact between Precambrian hornblende gneiss and calc-silicate gneiss (Sheridan et al., 1967). The favorable host rock (Idaho Springs Formation gneiss) but lack of production accounts for the M/C designation around the two occurrences. The Idaho Springs Formation elsewhere in the county is L/B.

4.19.11 Beryllium

Through 1963, production of beryl from pegmatites in Jefferson County amounted to 108,152 pounds (Meeves et al., 1966). Numerous pegmatites hosting beryl, chrysoberyl, and bertrandite crystals, some as much as 1000 pounds, occur around the greater Clear Creek Pegmatite Province that extends into Jefferson County (Del Rio, 1960; Hawley and Wobus, 1977; USGS MRDS, 2013). About 18.9 tons of 12.1 percent BeO from beryl-bearing pegmatites have been produced from the Bigger Mica mine in central Jefferson County (Hanley et al., 1950; USGS MRDS, 2013). Pegmatites occur in Precambrian granitic and gneissic host rocks. Buffers around the beryl prospects are designated H/C for beryllium potential. Pegmatites of the South Platte Pegmatite district at the northern extent of the Pikes Peak batholith reportedly contain minimal occurrences of beryl. This district and the Pikes Peak batholith are assigned M/B due to the abundance of pegmatites throughout the area and beryllium occurrences in the same rocks in other counties (e.g., Douglas). Precambrian granitic rocks elsewhere in the county are L/B.

4.19.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Jefferson County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.19.1 of this MPR) is designated L/B for germanium occurrence potential.

The county produced 2,000 pounds of zinc from 1859 to 1958; sphalerite is commonly reported (Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.19.13 Rare Earth Elements

Meeves et al. (1966) report production of 15,545 pounds of rare-earth minerals from pegmatites in Jefferson County through 1963. Allanite, bastnaesite, fergusonite, yttrian- and cerian-fluorite, samarskite, gadolinite, xenotime, and monazite are reported from the many pegmatites in the Pikes Peak batholith in the South Platte Pegmatite district, which spans Jefferson and Douglas Counties (Haynes, 1960; Simmons and Heinrich, 1980; Simmons et al., 1999). South Platte district pegmatites are super-enriched in REEs compared to most other pegmatites in the country (Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite (Simmons and Heinrich, 1980). Euhedral fergusonite crystals and samarskite nodules up to 75 pounds are reported from several of over 75 zoned pegmatites in the South Platte district; an estimated ton of samarskite and fergusonite was recovered from the Oregon No. 3 mine in Jefferson County (Haynes, 1965; Simmons and Heinrich, 1980; Simmons et al., 1999). Over 16 tons of REE ore was recovered from the Deep Hole (Madonna #2) mine, 50 tons of gadolinite ore was mined from the White Cloud claims, and 100 tons of REE ore were recovered from the Big Bear # 2 mine (Simmons and Heinrich, 1980). The greater South Platte Pegmatite district area is designated H/D for REE occurrence potential.

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, all of which are enriched in REEs, especially LREEs (Gross and Heinrich, 1965; Persson, 2016; Simmons et al., 1999; Smith et al., 1999). The sodic Sugarloaf syenite stock in southern Jefferson County assayed up to 1,214 ppm total REE oxides, more than 5 times the normal crustal abundance (Smith et al., 1999). The pink Pikes Peak granite assayed up to 853 ppm (Smith et al., 1999). Outside the South Platte Pegmatite district, the Pikes Peak batholith is designated M/C for REE potential.

Within the Clear Creek Pegmatite Province in northern Jefferson, southeastern Gilpin, and northeastern Clear Creek Counties, REE mineralization is present within beryl-bearing pegmatites or veins in Precambrian Idaho Springs Formation gneiss (Adams, 1968; Haynes, 1960; USGS MRDS, 2013). In Jefferson County, allanite, euxenite, fergusonite, gadolinite, monazite, and xenotime are reported from at least a dozen pegmatite mines, although no production is reported (Adams, 1968; Haynes, (1960); Olson and Adams, 1962; USGS MRDS, 2013). A buffer around the Clear Creek Pegmatite Province is designated M/C for REE occurrence potential.

4.19.14 Niobium-Tantalum

Meeves et al. (1966) report production of 4,327 pounds of niobium-tantalum minerals from pegmatites in Jefferson County through 1963. Euhedral fergusonite crystals, as well as microlite and samarskite, are reported from several of over 50 zoned pegmatites in the South Platte Pegmatite district (Haynes, 1965; Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite (Simmons and Heinrich, 1980). Samarskite nodules up to a foot in diameter and 75 pounds were retrieved at the Oregon #3 prospect; an estimated ton of samarskite and fergusonite was recovered (Simmons and Heinrich, 1980). Buffers along pegmatite zones in the South Platte Pegmatite district are designated M/D for niobium-tantalum occurrence potential.

In the northwest quarter of Jefferson County, the Clear Creek Pegmatite Province is home to thousands of pegmatites hosted by Precambrian Idaho Springs Formation gneiss and Boulder Creek Granite (Boos, 1954). Columbite, tantalite, microlite, pyrochlore, and euxenite are all reported from various pegmatites of the Clear Creek Pegmatite Province (Hanley et al., 1950; Heinrich, 1957). Specific gravity measurements on some samples from this district indicate a content of 34 percent Nb_2O_5 and 48 percent Ta_2O_5 (Hanley et al., 1950). Buffers along pegmatite zones of the Clear Creek Pegmatite Province are designated M/C for niobium-tantalum occurrence.

4.19.15 Tellurium

There are no reported occurrences of tellurium in Jefferson County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.19.16 Titanium

Concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). Samples up to 4.2 percent rutile are reported from a unit which is 11 to 100 feet thick, and sphene and ilmenite occur in the surrounding units (Sheridan et al, 1968.) Sheridan et al. (1968) determined that the concentration and purity of the rutile deems this occurrence worthy of further investigation as an ore of titanium. This geologic unit, in the Clear Creek-Jefferson County border area, is designated H/C for titanium occurrence potential; elsewhere this unit is assigned L/B.

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals, and several past producers are noted from El Paso and Teller Counties (Smith et al., 1999; USGS MRDS, 2013). Alkalic and mafic units in the Pikes Peak batholith are designated L/B for titanium potential.

4.19.17 Uranium

Much of the total historic uranium production within the RGFO region is from the Ralston Buttes uranium district of Jefferson County. Nearly all of it, about 10.5 million pounds by 1978, came from the underground Schwartzwalder mine located in the Ralston Creek-Golden Gate area about 7 miles northwest of downtown Golden (Nelson-Moore et al., 1978). The uranium deposit at Schwartzwalder is reported to be the largest single uranium deposit in Colorado and the largest vein-type uranium deposit in the United States (Nelson-Moore et al., 1978; Wallace, 1983). Another 210,827 pounds of U_3O_8 were produced by twelve other mines in the county by 1971 (Nelson-Moore et al., 1978).

Fred Schwartzwalder, an amateur prospector, discovered uranium mineralization in the late 1940s, although production did not commence until 1953 (Chenoweth, 1980; Sims et al., 1963). By the time the mine had closed in March 2000, it had produced about 17 million pounds of U_3O_8, averaging 0.35 to 0.79 percent U_3O_8 ore, with reserves of another 16 million pounds (CGS, 2006; Nelson-Moore et al., 1978; USGS MRDS, 2013). At the Schwartzwalder mine, uraninite and some coffinite were deposited by hydrothermal fluids that precipitated the ore in veins and breccia fillings within a complex fault zone (Rogers breccia reef) formed in Precambrian metamorphic rocks during the Laramide Orogeny (Caine et al., 2011; Nelson-Moore et al., 1978; Sheridan et al., 1967; Wallace, 1983).

Over 113,000 pounds of U_3O_8 were recovered from 0.24 percent U_3O_8 ore at the Wright Lease (a.k.a. Foothills mine) located near the community of Idledale. The Ascension mine, in the Hurricane Hill breccia reef, and the Grapevine mine near Idledale each produced over 20,000 pounds of U_3O_8 from 0.29 to 0.32 percent ore (Nelson-Moore et al., 1978). Most of the production at these mines, including that at the Schwartzwalder, was recovered from deposits concentrated along 3 major, northwest-trending fault systems or breccia reefs developed in the Precambrian Idaho Springs Formation (Nelson-Moore et al., 1978). Buffers along the Rogers and Hurricane Hill breccia reef systems are designated H/D for uranium occurrence potential where production is noted and H/B elsewhere in the county. Buffers along the Livingston and Junction Ranch breccia reefs, where anomalous radioactivity but no production is reported, as well as other northwest-trending fault systems in the southern half of the county are designated H/B for uranium potential (Sheridan et al., 1967).

Two mines recovered uranium from sedimentary rocks in the foothills of the Front Range. Over 4,000 pounds of uranium were recovered from uraninite-bearing, siliceous material in fractures of the Laramie Formation coal bed worked at the Old Leyden mine. An estimated reserve of 17,000 tons of 0.2 percent U_3O_8 ore are reported at the Old Leyden mine (Nelson-Moore et al., 1978). The undifferentiated Laramie Formation and Fox Hills Sandstone mapped unit around the Old Leyden mines is designated H/D for uranium occurrence potential; elsewhere in the county this unit is assigned L/B. The Dakota Sandstone hosted the uranium produced at the Mann Ranch group of mines (~15,600 pounds of U_3O_8 from 0.27 percent ore) and the Pallaro mine (~2,700 pounds of U_3O_8). Mineralization in this area was localized by northwest-trending faults (Nelson-Moore et al., 1978). The area around this group of mines is designated H/D for uranium potential; elsewhere in the county the undifferentiated Cretaceous Dakota Sandstone and Jurassic Morrison / Ralston Creek Formations are assigned L/B.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.19.18 Thorium

Monazite and thorite occur in beryllium-bearing pegmatites along northwest-trending faults in Precambrian Idaho Springs Formation gneiss at three feldspar mines in Jefferson County (Schwochow and Hornbaker, 1985; USGS MRDS, 2013). Thorite, monazite, and minor thorogummite and samarskite are reported from pegmatites along northwest-trending faults in Pikes Peak granite in the South Platte Pegmatite district spanning Jefferson and Douglas Counties (Simmons et al., 1999; USGS MRDS, 2013). Thorium is listed as a tertiary commodity at these mines, although no production information is provided. Buffers along faults in Precambrian crystalline rocks in Jefferson County are designated L/C for thorium occurrence potential.

4.19.19 Vanadium

Several vanadium occurrences are located in Jefferson County, but production is reported for only one mine. The Pallaro (Morrison or Four Corners) mine, developed in the Cretaceous Dakota Sandstone, yielded 256 pounds of vanadium from 678 tons of 0.02 percent V_2O_5 ore (Nelson-Moore et al., 1978). Also, carnotite occurs in several other Dakota Sandstone prospects in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). The undifferentiated Morrison Formation, Entrada Sandstone, and Dakota Sandstone mapped unit is designated H/C for vanadium occurrence potential in Jefferson County.

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation and underlying Fox Hills Sandstone of this (e.g., Old Leyden Coal mine) and Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are reported in uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

Vanadium is reported from several uranium prospects developed in northwest-trending brecciated fault zones in the Precambrian Idaho Springs Formation, although no production is noted (Nelson-Moore et al., 1978; USGS MRDS, 2013). Buffers along breccia reef faults in Precambrian crystalline rocks are designated L/C for vanadium occurrence potential.

4.19.20 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, both of which are found in Jefferson County (Wallace, 2010). The Pikes Peak composite batholith comprises the main granitic body plus numerous late-stage peraluminous to peralkaline granitic plutons, all of which host pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999; Tweto, 1987). Fluorite is a primary accessory mineral in all phases of the Pikes Peak composite batholith and related pegmatites; the composite batholith assayed anomalously high in fluorine abundance, averaging 2,140 to 3,500 ppm fluorine and ranging up to 100,000 ppm (Wallace, 2010). Numerous fluorspar prospects are developed in the Jefferson County portion of the batholith; a few others are located in metamorphic rocks near Evergreen (USGS MRDS, 2013). Near Evergreen, 2 well-defined polymetallic veins up to 5 feet thick host purple and green fluorspar; the Augusta mine, developed in Precambrian biotite gneiss, produced over 1,000 tons of fluorspar from these veins (Aurand, 1920; Brady, 1975). Precambrian igneous rocks, including all phases of the Pikes Peak batholith, are designated H/C, Precambrian biotite gneiss is assigned M/C, and hornblende gneiss is assigned M/B for fluorspar occurrence potential.

4.19.21 Diamond and Gemstones

Countless pegmatites, some of which host gemstones, are known from the Clear Creek Pegmatite Province in western Jefferson County. Beryl, aquamarine, amethyst, amazonite, garnet (spessartite), several quartz varieties, and topaz have been recovered from numerous pegmatites (Boos, 1954; Eckel, 1961). The Santa Fe Mountain, Snyder, and Floyd Hill (Ajax) pegmatites are noted for aquamarine and massive rose quartz occurrences (Eckel, 1961; Scott, 1968a). Green to blue euhedral crystals of beryl up to 1.7 feet wide by 7.5 feet long and black tourmaline crystals up to 3 inches long have been recovered at the Bigger group of mines at Bald Mountain (Hanley et al., 1950). Massive, banded green and purple fluorite occurs at the Augusta mine near Evergreen (Eckel, 1961; Pearl, 1972). Beryl, garnet, topaz, tourmaline, and zircon crystals are known from the Guy Hill (Ramstetter Ranch) pegmatite area (Eckel, 1961). Abundart spessartite and almandine crystals are found in Precambrian garnetiferous gneiss at the Schwartzwalder uranium mine and elsewhere in the Ralston Buttes locale (Eckel, 1961). Crossing the Jefferson-Clear Creek county line is a unique west-trending gneissic mineral belt about 7,000 feet long and up to 100 feet thick; significant amounts of rutile and topaz are found (Sheridan et al, 1968). The Clear Creek Pegmatite Province and greater Ralston Buttes district are designated H/D for gemstone occurrence potential and a buffer to the south and west are assigned M/C.

The South Platte Pegmatite district has been mined for amethyst, milky and smoky quartz, and other pegmatite-hosted gems (Arbogast et al., 2011; Eckel, 1961). Fluorite, quartz, and topaz crystals are reported from the Oregon, Luster Lode, Patsy, White Cloud, and other groups of mines (Haynes, 1965; USGS MRDS, 2013; Wallace, 2010). The South Platte Pegmatite district is designated H/D for gemstone occurrence potential. Pegmatites hosting amazonite, smoky quartz, topaz, and amethyst occur sporadically throughout the Pikes Peak region (Arbogast et al., 2011, Pearl, 1972). Outside the South Platte Pegmatite district, the Pikes Peak batholith is designated M/C for gemstone potential.

Petrified palm wood hosting agate is found at Green and Table Mountains, and fossilized dinosaur bones hosting agate, jasper, and carnelian are commonly recovered from the Jurassic Morrison Formation (Eckel, 1961). Buffers around these areas and rocks are labeled M/C for gemstone occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the nearby CMB, Precambrian felsic metamorphic rocks outside of the Clear Creek Pegmatite Province are designated M/C for gemstone occurrence potential; biotite gneisses and schists are assigned M/B for gemstone potential (Lovering and Goddard, 1950). Zoned pegmatites are also known to occur in Silver Plume-aged plutons, and the correlative Indian Creek plutons in Jefferson County are assigned L/B for gemstone potential (Boos, 1954; Boos and Aberdeen, 1940). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

4.19.22 Pegmatite Minerals

Meeves, et al. (1966) report production through 1963 of 2,000 pounds of sheet mica and 540 tons of scrap mica in Jefferson County. The South Platte Pegmatite district of central Jefferson County and western Douglas County hosts over 50 pegmatites in the northern Pikes Peak pluton marginal to biotite gneiss of the Idaho Springs Formation. The Raleigh Peak pegmatites are composed of large, complex, concentrically zoned feldspar-rich pegmatites (Martin, 1993; Simmons and Heinrich, 1980). Production between the 1920s and the 1980s is estimated at several hundred thousand tons of potassium feldspar (Martin, 1993).

The Clear Creek Pegmatite Province covers northeastern Clear Creek and west-central Jefferson Counties and hosts numerous feldspar- and mica-bearing pegmatites in felsic and biotite gneisses and schists of the Precambrian Idaho Springs Formation (Heinrich, 1957; Martin, 1993). About 6,000 tons of feldspar were produced at the Burroughs Feldspar mine between 1942 and 1944 (Baillie, 1962). Over 3,000 tons of feldspar (microcline) and 100 tons of scrap mica (muscovite) were produced from zoned pegmatites in biotite gneiss marginal to the Boulder Creek Granite at the Bigger mine between 1937 and 1950 (Hanley et al., 1950). Baillie (1962) reports the Bigger mine core is 40 percent high-grade microcline and estimated 13,000 tons of reserves.

Clusters of pegmatites in the Clear Creek and South Platte Pegmatite districts are designated H/D for pegmatite occurrence potential. Buffer zones of felsic gneiss marginal to the districts are assigned H/C. Elsewhere in the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B except the Pikes Peak batholith which is designated M/C.

4.19.23 Industrial Abrasives

Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Numerous pegmatites in the South Platte Pegmatite district intrude the crystalline rocks of the Pikes Peak batholith in southern Jefferson and southwestern Douglas Counties (Martin, 1993). A buffer around these pegmatite clusters is designated H/C for industrial abrasive potential.

Countless pegmatites are known from the Clear Creek Pegmatite Province in northeastern Clear Creek and northwestern to central Jefferson Counties, many of which host garnet (Boos, 1954; Eckel, 1961). Several past producers or prospects developed in pegmatites concordant with Precambrian gneissic layers note garnet as a primary or tertiary commodity (USGS MRDS, 2013). Precambrian biotite schist in this region hosts abundant garnet, including spessartite, almandine, grossularite, and pyrope (Eckel, 1961). The Clear Creek Pegmatite Province is designated H/D for industrial abrasive (garnet) occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.19.24 Limestone and Dolomite

In Jefferson County, there are two limestone quarries developed in the Permian Minnekahta and Forelle Limestones of the Lykins Formation; the Lykins Formation is designated L/C for limestone potential. The Cretaceous Greenhorn Limestone hosts one prospect in this county and others elsewhere in the State. The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale (Colorado Group) is designated M/C for limestone and dolomite occurrence potential.

4.19.25 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Production from past DRMS-permitted industrial sand quarries is reported from these units in Jefferson County (Schwochow, 1981). The Lykins Formation and Dakota Sandstone are designated H/D for industrial sand occurrence potential.

Sporadic occurrences and production of industrial sand are reported from the Tertiary Dawson Arkose throughout the RGFO region (Arbogast et al., 2011). The Dawson Arkose is designated L/C for industrial sand potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are reported in alluvium throughout the RGFO region (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential.

4.19.26 Gypsum

There is minimal gypsum production reported in Jefferson County; however, there are many reports of massive white and gray gypsum at the base of the Jurassic Morrison Formation in a unit almost always identified or correlated with the Ralston Creek Formation throughout the RGFO region (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). George (1920) reports gypsum beds up to 60 feet thick below the Morrison Formation at the Garden of the Gods and Glen Eyrie in El Paso County. A massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8-mile section just above the Permian-Triassic Lykins Formation and below the Morrison Formation is reported at Perry Park in neighboring Douglas County (George, 1920). The Perry Park gypsum was mined from 1898 to 1901, and it is estimated that massive anhydrite exists at depths below 30 feet (Schwochow, 1981; Withington, 1968). In Jefferson County, the Lykins Formation hosts massive gypsum up to 20 feet thick along Bear and Deer creeks: some production was reported prior to 1875 (George, 1920; Scott, 1963; Withington, 1968). The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/C for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation and Colorado Group are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). The Niobrara Formation and Colorado Group members are designated L/B for gypsum occurrence potential in Jefferson County.

4.19.27 Sand and Gravel

Del Rio (1960) reports production of almost 6 million tons of sand and gravel, primarily from alluvium, in Jefferson County between 1954 and 1958. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, and Tertiary gravels (Tgv) are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Jefferson County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation and Paleozoic Dakota, Fountain, and Lykins Formations, all of which host sporadic sand and gravel operations in this and other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968). Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.19.28 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Jefferson County, developed in limestone members of the Colorado Group, although limestone in the overlying Fort Hays Member of the Cretaceous Niobrara Formation may crop out in the area as well (Tweto, 1979a). The Niobrara Formation and Colorado Group may host suitable source rocks where the limestone is dense, well-consolidated, and free from abundant joints and fractures (Knepper et al., 1999; Langer and Knepper, 1995). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Colorado Group is designated H/D for crushed stone aggregate occurrence potential in Jefferson County.

Dense, fine-grained Tertiary igneous rocks like basalt (traprock) satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Significant production of high-quality crushed stone, derived from basaltic flows capping North and South Table Mountains east of Golden and Ralston Butte north of Golden, is reported (Arbogast, 2011). These Tertiary basalts are assigned H/D for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Indian Creek pluton in Jefferson and Clear Creek Counties, are deemed excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed, Precambrian Boulder Creek plutons and satellites were classified as only ‘fair’ source rocks by Knepper et al., (1999). Arbogast et al. (2011) categorized the younger Pikes Peak Granite as a good-quality source for crushed stone aggregate, but Knepper et al. (1999) classified it as unsuitable due to the degree of weathering. Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Indian Creek batholith is designated H/C, the Boulder Creek Granite is assigned M/C, and the Pikes Peak Granite is assigned MB, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Fountain and Permian-Triassic Lyons Sandstone and Lykins Formations, the Jurassic Morrison Formation, the Cretaceous Dakota and Fox Hills Sandstones, and the Tertiary Dawson Arkose may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone at its contact with the Colorado Group, as well as in the undivided Lyons Sandstone and Lykins Formation, in this and nearby counties. The Dakota Sandstone is designated H/D, the undivided Lyons Sandstone and Lykins Formation are assigned M/C, the Fox Hills Sandstone is designated L/C, and remaining sedimentary rocks are assigned L/B, for crushed stone potential.

4.19.29 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The undivided Fox Hills Sandstone and Laramie Formation are designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Tertiary Arapahoe and Denver Formations and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C, and the Denver Formation and Dawson Arkose (mapped as TKdl or Tdu) are designated M/B, for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in the Precambrian granitic igneous and metamorphic rocks of the mountains in Colorado (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in igneous and metamorphic rocks of Jefferson County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The relatively unweathered Pikes Peak and Indian Creek granitic plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Sporadic outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.19.30 Clay

Del Rio (1960) reports production of 1.5 million tons of clay in Jefferson County between 1951 and 1958. Several dozen current DRMS-permitted quarries and USGS MRDS (2013) clay occurrences are noted in Jefferson County. The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone); many prospects occur in this unit in this and other counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation

(Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation and Dakota Sandstone are designated H/D for clay occurrence potential. Numerous clay producers are developed in the Permian-Triassic Lykins Formation in Jefferson County, and this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated H/C for clay occurrence potential.

Most prospects developed in the Cretaceous Graneros Shale (Colorado Group) throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). Several Jefferson County clay quarries produce from the Colorado Group; this unit is assigned M/D in areas of reported mines and M/C elsewhere for clay potential. The overlying Cretaceous Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are developed in it in this and other counties (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is assigned H/C for clay potential.

Shale interbeds of the Fox Hills Sandstone, which overly the Pierre Shale, host clay suitable for brick making as well (Vanderwilt, 1947). Abundant kaolinite with significant montmorillonite occur in clay beds near the base of the overlying Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Del Rio, 1960; Spence, 1980). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). The Fox Hills Sandstone, Laramie Formation, and Dawson Arkose are designated M/D for clay potential in areas of concentrated occurrences and M/C elsewhere.

Several USGS MRDS (2013) and DRMS-permitted clay producers occur in Quaternary alluvium that directly overlies Cretaceous shales of the Pierre Shale, Laramie Formation, and Fox Hills Sandstone in northern Jefferson County. This unit is designated M/D for clay occurrence potential. A few clay occurrences are noted in Precambrian igneous or metamorphic rocks, likely in areas of local alteration due to weathering in fault zones; buffers around these occurrences are assigned L/C for clay potential.

4.19.31 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Jefferson County hosts granites, sandstones, and conglomerates that have been quarried for dimension stone, including the Precambrian Pikes Peak, Silver Plume-aged granites, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Precambrian Pikes Peak and Indian Creek granitic plutons have been quarried for dimension stone, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak and Indian Creek plutons are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. A small outcrop of Tertiary intrusives is assigned L/B for dimension stone potential.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). These units are designated H/D for dimension and building stone occurrence potential; the Fountain Formation and Codell Sandstone capping the Colorado Group are assigned M/C for dimension stone potential. Other sandstone-bearing units in the county, but without documented production of dimension stone, include the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation and Dawson Arkose. As sandstone-bearing units, these rocks are designated M/B for dimension and building stone occurrence potential.

4.20 Kiowa County

4.20.1 Geothermal

Traditional / EGS Geothermal

The majority of Kiowa County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The whole county does have moderate favorability for EGS (Augustine, 2011), so the western portion that was analyzed by the USGS (2008) is considered M/B.

Direct-Use / Low Temperature Geothermal

Kiowa County contains no known springs or wells. The majority of Kiowa County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. The entirety of the county is above the 100°F temperature threshold for low temperature and co-produced resources.

4.20.2 Uranium

There is no recorded production of uranium in Kiowa County; however, several occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.20.3 Limestone and Dolomite

There are no limestone prospects in Kiowa County, but the Fort Hays Member of the Niobrara Formation, found throughout the county, is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). The Niobrara Formation is assigned M/D for limestone and dolomite occurrence potential.

4.20.4 Industrial Sand

Widespread Quaternary eolian sands in Kiowa County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, and one quarry occurs in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential. Limited production from sporadic DRMS-permitted industrial sand quarries is reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no permitted operations noted in Kiowa County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.20.5 Gypsum

Very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO management area, the Niobrara Formation is barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-formation limestone beds of the Niobrara (Scott, 1969). The Niobrara Formation is designated L/B for gypsum occurrence potential throughout Kiowa County.

4.20.6 Helium

Sonnenberg and von Drehle (1990) note three oil and/or gas fields in Kiowa County that have positive helium gas analyses: Left Hand, Brandon, and Jace. These fields returned results of 0.78 percent, 1.02 percent, and 1.69 percent helium, respectively. These fields are east to west from the center to the east flank of the Las Animas Arch, with helium concentration rising away from the center. Kiowa County is designated as a mix of H/D and M/D potential, as the core of the anticline is known to have lower to no helium content on the crest, whereas the Brandon sub-axis (containing the Brandon field) and the west flank show relatively elevated helium contents.

4.20.7 Sand and Gravel

High-quality sand and gravel deposits in Kiowa County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). This unit is designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in some areas (W. D. Carter, 1968); this unit is considered M/D for sand and gravel potential. The Cretaceous Niobrara Formation, typically composed of shales and limestone, hosts sporadic sand and gravel pits; buffers around these occurrences are assigned L/C for sand and gravel potential (Scott and Corban, 1964; USGS MRDS, 2013).

4.20.8 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Kiowa County; however, the Fort Hays Member of the Cretaceous Niobrara Formation has been quarried for crushed limestone in other counties (Schwochow, 1981). Dense limestones and dolomites are excellent sources of crushed stone aggregate, composing about 70 percent of production nationwide (Langer and Knepper, 1995). Also, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Niobrara Formation is designated M/C, and the Ogallala Formation is assigned L/B, for crushed stone aggregate occurrence potential.

4.20.9 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in the RGFO region from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (mixed layer illite-montmorillonite) and may be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, the Ogallala Formation is designated M/C, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.20.10 Clay

There are no USGS MRDS (2013) or DRMS clay occurrences in Kiowa County; however, the Cretaceous Pierre Shale and Niobrara Formation together cover about a third of the land surface (Tweto, 1979a). The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The underlying Smoky Hill Shale Member of the Niobrara Formation has produced some low-grade clay in other counties (Arbogast, 2011; Patterson, 1968). The Pierre Shale is designated H/C, and the Niobrara Formation is designated M/C, for clay occurrence potential.

4.20.11 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Kiowa County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). Also, the Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Ogallala Formation is designated L/B, and the Niobrara Formation is designated L/C, for dimension and building stone occurrence potential.

4.21 Kit Carson County

4.21.1 Geothermal

Traditional / EGS Geothermal

The majority of Kit Carson County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The whole county does have moderate favorability for EGS (Augustine, 2011), so the western portion that was analyzed by the USGS (2008) is considered M/B.

Direct-Use / Low Temperature Geothermal

Kit Carson County contains no known springs or wells. The majority of Kit Carson County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. The northeastern corner is below the temperature threshold and is designated M/B.

4.21.2 Industrial Sand

Quaternary eolian sands in Kit Carson County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no production is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations occur in alluvium in this and other counties; Quaternary alluvium is assigned M/C for industrial sand potential. Limited production from sporadic DRMS-permitted industrial sand pits is reported from the Pliocene Ogallala Formation throughout the RGFO region, and there is one permitted operation reported in Kit Carson County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.21.3 Helium

The northern end of the helium-containing Las Animas Arch structure projects into Kit Carson County. Sonnenberg and von Drehle (1990) reported that fields off the crest of the Las Animas arch had higher helium and nitrogen contents, with the Smoky Hill field in Kit Carson County analyzed at 4.31 percent helium. The southern portion of Kit Carson County is designated H/D because of its location on the Las Animas Arch. The L/C designation of the Denver basin for helium also enters the very northern part of the county.

4.21.4 Sand and Gravel

High-quality sand and gravel deposits in Kit Carson County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011). The widespread and highly weathered Pliocene Ogallala Formation resulted in widespread loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.21.5 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Kit Carson County; however, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Ogallala Formation is assigned L/B for crushed stone aggregate occurrence potential.

4.21.6 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in the RGFO region from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Ogallala Formation is designated M/C, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.21.7 Clay

There are no USGS MRDS (2013) or DRMS clay occurrences in Kit Carson County; however, the Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential.

4.21.8 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Kit Carson County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B for dimension and building stone occurrence potential.

4.22 Lake County

4.22.1 Geothermal

Traditional / EGS Geothermal

The majority of Lake County is designated as H/C for high temperature/EGS geothermal resources due to the combination of high EGS favorability (Augustine, 2011) and high traditional geothermal favorability (Williams et al., 2008). Areas in the southwest and north are considered H/B because of moderate EGS favorability, and the western border is M/B due to moderate-low favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Lake County contains no known springs or wells. The northern half of Lake County, which lies outside named COGCC fields but is above the 100°F threshold, is considered H/B for low temperature and/or co-produced geothermal resources. The southern half is below the temperature threshold and is designated as M/B.

4.22.2 Gold

Lake County has historically been one of Colorado's prime mineral-producing counties. Although the principal producer in recent years has been the Climax mine (molybdenum), the county has produced an estimated 3 million ounces of gold, primarily from the greater Leadville district, between 1859 and 1990 (Davis and Streufert, 1990). Parker (1974) reports production of 358,569 ounces of placer gold between 1859 and 1957. Thompson and Arehart (1990) report 344,000 ounces of placer gold recovered just from the California and Iowa Gulches.

The Leadville district at one time was perhaps the most important mining district in the country. The Carbonate Hill, Iron Hill, Breece Hill, Evans, California Gulch, and Iowa Gulch subdistricts are all considered part of the greater Leadville district. The Empire Gulch Placers were also considered part of the Leadville district by Vanderwilt (1947). The Leadville district lies west of the Mosquito Range and is characterized by Paleozoic sedimentary rocks overlying the Precambrian St. Kevin quartz monzonite which is intruded by Tertiary silicic magmas; all are heavily faulted (Cappa and Bartos, 2007; Tweto, 1979a). Several types of gold deposits characterize the greater Leadville district, including pyritic gold veins and stockworks, polymetallic veins and replacements, contact metamorphic deposits, and placers (Davis and Streufert, 1990). Cappa and Bartos (2007) report production of 3.3 million ounces of gold from the greater Leadville district area, which is designated H/D for gold occurrence potential.

The Granite district, shared with Chaffee County, was a known producer of gold. Hedlund et al. (1983) estimates about 24,000 ounces of gold were produced prior to 1912 from gold-bearing pyritic quartz veins in Precambrian migmatite at the Belle of Granite mine in the Lake County portion of the district. Another 17,000 ounces of gold were produced from the Granite Tunnel group of mines near Yankee Blade Hill (Hedlund et al., 1983). Average tenor of the veins is reported at 0.005 to 2 ounces of gold per ton (Hedlund et al., 1983). The Granite district is designated H/D for occurrence potential.

The nearby Twin Lakes district also straddles both Lake and Chaffee Counties. Highlighted by the Gordon mine, this district produced from 1884 until the 1940s (Howell, 1919; Vanderwilt, 1947). Gold-bearing veins in shear zones of the Twin Lakes granite batholith and biotite gneisses are spatially associated with Tertiary quartz monzonite porphyry dikes (Cappa and Bartos, 2007). The only production record, an estimated 120,000 ounces of gold, is reported by Davis and Streufert (1990). Vanderwilt (1947) reports recovery of 1,731 ounces of placer gold from 1932 to 1935. This district is designated H/C for gold occurrence potential along the contact zones between the batholith, metamorphic rocks, and intrusives.

In the Champion district, the Mount Champion mine opened in 1907 and produced over 26,000 ounces of gold, averaging 0.374 to 3.23 ounces per ton, from a single pyritic quartz vein filling a fault in Precambrian biotite schist and a quartz monzonite sill (Cappa and Bartos, 2007). Howell (1919) reported other veins in the nearby Lackawanna Gulch. The Lackawanna Gulch Placers in the district were quite productive from 1860 until 1918 (Cappa and Bartos, 2007). The Champion district is assigned H/C for the occurrence of gold.

Surrounding Turquoise Lake west of Leadville are the Sugarloaf and St. Kevin districts, described by Singewald (1955). First discovered in the 1880s, the districts produced mainly silver and some gold into the 1920s and are together credited with 2,989 ounces of gold production. Davis and Streufert (1990) estimate production of 10,000 ounces of gold between 1860 and 1990 in the St. Kevin district. Precambrian gneisses, schists, and granites are cut by Tertiary quartz latite porphyry dikes. Mineralized veins fill fissures up to 10 feet thick mostly in granite in proximity to contacts with gneiss or schist, and tenor up to 100 ounces of silver per ton are reported (Cappa and Bartos, 2007; Singewald, 1955). These districts, along with the surrounding geologic features are considered H/C for gold occurrence potential.

The Tennessee Pass district, shared with Eagle County, is credited with an estimated production of 16,000 ounces of gold between 1860 and 1990 (Davis and Streufert, 1990). Here, Paleozoic sedimentary rocks overlie Precambrian gneisses and schists (Cappa and Bartos, 2007). Gold occurs within jasperoid or dolomite breccia in association with quartz monzonite porphyries in the Mississippian Leadville dolostone and averages 0.3 to 0.4 ounces per ton (Beaty et al., 1987; Cappa and Bartos, 2007). Cappa and Bartos (2007) indicate that exploration continued in the district as late as the 1980s. The Tennessee Pass district is assigned H/C.

The Birdseye and Alicante district area lies in the upper Arkansas Valley north of Leadville. Minor production is reported from mineralized veins of gold-silver-lead-zinc in Precambrian granite (Vanderwilt, 1947). High-grade gold was recovered from the Little Corinne mine, and several tons of gold-silver-lead ore were shipped as late as 1935 (Vanderwilt, 1947). The Little Corinne mine occurs near the intersection of the Mosquito and highly mineralized London faults in Paleozoic sedimentary rocks (Behre, 1953). The Alicante and Birdseye district area is designated M/C for gold occurrence potential.

The Pando granite porphyry intrudes the Paleozoic sedimentary section on the border of Lake and Park Counties in the Weston Pass district creating a silicified breccia zone in the Leadville Formation (Behre, 1932). The ore contains mostly lead and zinc with some silver and a small amount of gold. This district is considered M/C for occurrence potential because of its small amount of gold production.

Lake County is also characterized by major placer districts, several which are in proximity to the lode districts and so are included in that designation (e.g., California and Iowa gulches). Others include the Buckeye Gulch Placer**,** located north of Leadville, which was discovered in 1880 (Parker, 1974). Parker (1974) reports that most of the placers here occur at the head of an alluvial fan where the hanging valley exits the canyon, but production is not known. Also, gold-bearing veins occur in Pennsylvanian sedimentary rocks near the head of Buckeye Gulch, but no production is reported (Vanderwilt, 1947). The Derry Ranch placers include workings on Box, Harrington, and Corske Creeks in the greater Twin Lakes district, and gold was recovered from alluvium and glacial drift (Cappa and Bartos, 2007). A large dredging operation was worked here from 1915 to 1932 and reportedly produced $1.3 million in gold. Placers were mostly in stream gravels with a majority of the gold found within 6 inches of the bedrock. Tributaries of the Arkansas River which drain the greater Leadville district are designated H/C for gold potential where there are documented occurrences and M/C otherwise. Elsewhere along the Arkansas River, historically and/or currently producing placers are considered H/C; areas devoid of occurrences are assigned M/B. Areas with similar alluviums and glacial drift near to producing areas are designated as M/C. Alluviums outside these areas are designated L/B.

In the remainder of Lake County, the areas surrounding historic mining districts and including rocks of Precambrian metamorphic basement and Tertiary intrusives are considered M/C where there are recorded gold occurrences in the USGS MRDS (2013). The same rocks outside documented gold occurrences are considered M/B or L/B.

4.22.3 Silver

Lake County has been a major silver producer in Colorado, and is attributed with over 64 million ounces from 1859 until the late 1970s. The geology of the mineral deposits of Lake County is covered in some detail above in the gold section (4.22.2) and below in the base-metal section (4.22.4) of this county's MPR.

The greater Leadville district area is credited with 265 million ounces of silver (Cappa and Bartos, 2007). Vanderbilt (1947) reports almost 2.5 million ounces of silver produced from 1932 to 1945. Average tenor of silver-bearing quartz veins is 2 to 40 ounces of silver per ton; supergene deposits of polymetallic mantos ranged up to 2,000 ounces of silver per ton (Cappa and Bartos, 2007). Polymetallic carbonate replacement ore is the chief deposit type, and the Mississippian Leadville dolostone is the most productive host (Cappa and Bartos, 2007). The greater Leadville district area is assigned H/D for silver occurrence potential.

The Mt. Sherman district encompasses the Iowa Amphitheatre and the Iowa Gulch headwaters region east of the Leadville district along the Mosquito Range. Host to Sherman-type carbonate replacement deposits, the Sherman mine is credited with production of 9.1 million ounces of silver with proven reserves of about 150,000 ounces of silver in 2000 (Tschauder et al., 1990; USGS MRDS, 2013). The nearby Continental Chief mine was reported to have proven reserves of 85,000 ounces of silver in 1980 (USGS MRDS, 2013). The Leadville Dolostone in this area is designated H/D for silver occurrence potential; elsewhere along the Mosquito Range it is assigned H/B. Outside of the Mosquito Range, the Leadville Dolostone is assigned L/B for silver potential.

An estimated 1.5 million ounces of silver were produced from the Dinero and adjacent mines in the Sugarloaf district between 1891 and 1923 (Singewald, 1955; Cappa and Bartos, 2007). Vanderbilt (1947) reports production of 7,805 ounces of silver between 1933 and 1945 in the combined Sugarloaf and St. Kevin districts. Mineralized fissures and fractures up to 10 feet thick fill shear zones, mostly in the Precambrian St. Kevin quartz monzonite near contacts with isolated islands of gneiss, and tenor ranges up to 100 ounces of silver per ton (Cappa and Bartos, 2007; Singewald, 1955). Native silver, tetrahedrite, and argentite are all reported (Cappa and Bartos, 2007). In the St. Kevin district, production of 306,587 ounces of silver is reported between 1914 and 1946 at the St. Kevin, Griffin, and Amity mines; tenor ranged from 6 to 107 ounces per ton (Singewald, 1955). A buffer around these districts is considered H/D for gold occurrence potential.

In the Twin Lakes district, production of 852 ounces of silver between 1932 and 1935 from veins spatially associated with quartz monzonite porphyry dikes related to the Twin Lakes batholith is reported by Vanderwilt, 1947. The Gordon mine was the most productive, and tenor averaged 4.8 ounces of silver per ton, although tenor in outlying areas ranges up to 14 ounces per ton (Cappa and Bartos, 2007). The Twin Lakes granite is designated H/C for silver potential.

In the years 1932-1945, the Granite district produced 116 ounces of silver from pyritic quartz veins in Precambrian metamorphic rocks (Cappa and Bartos, 2007; Vanderwilt, 1947). The Granite district is assigned M/C for silver potential. Just to the northeast of the Granite district, mineralized cavities in the Leadville Dolostone host ore with a silver grade up to 4.8 ounces per ton in the Weston Pass district (Cappa and Bartos, 2007). A couple of past producers are noted by the USGS MRDS (2013) and this area is assigned M/C for silver potential.

In the Champion district, mineralized pods in quartz veins that fill a reverse fault between Precambrian schist and the Mt. Champion quartz monzonite occur at the Mt. Champion mine, where an estimated 23,000 ounces of silver were produced prior to 1941 (Cappa and Bartos, 2007). Buffers around past producers in this area are assigned M/C for silver potential. In the Tennessee Pass and district, silver-bearing veins occur in a shear zone in Precambrian metamorphic rock near the headwaters of Tennessee Creek (Vanderbilt, 1947). In the Homestake district, some silver production is reported from the Homestake mine (Vanderbilt, 1947). Tenor ranged from 5.1 to 87.3 ounces of silver per ton (Cappa and Bartos, 2007). Buffers around these two districts are assigned L/C for silver potential.

There are numerous silver occurrences and minor past producers found in Precambrian felsic or granitic rocks in proximity to faults (USGS MRDS, 2013). Buffers around these occurrences are designated M/C for silver occurrence potential. Placer silver recovery amounted to 13,503 ounces between 1909 and 1945, primarily from Box Creek, although silver is also reported from the Arkansas River (Vanderbilt, 1947). Buffers around these areas are designated L/C for silver potential since most of the placer has been depleted. Anomalous “redbed-type” concentrations of silver are noted from the Pennsylvanian Minturn Formation, and this unit is designated L/B for silver occurrence potential.

4.22.4 Copper-Lead-Zinc

Lake County has historically been one of the most prolific producers of base metals in the RGFO region, as well as in Colorado. Production of lead ore exceeded 2.1 billion pounds from 1876 through 1959 (in terms of recovered metal) (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). Zinc production amounted to almost 1.5 billion pounds and copper topped 106 million pounds during the same period (Del Rio, 1960; Henderson, 1926; Vanderwilt, 1947). The Leadville district, as the chief source of historic production of base metals in Lake County, occurs in the center of the CMB and is noted for carbonate replacement deposits.

The Leadville district comprises four subdivisions: Carbonate Hill, Iron Hill, Breece Hill, and California Gulch. The primary ore hosts are a dolomite (“Blue” Member) of the Mississippian

Leadville Limestone, followed by the Devonian-Mississippian Dyer Dolomite and Ordovician Manitou Limestone, along with associated Tertiary intrusives (Cappa and Bartos, 2007; Scarbrough, Jr., 2001). Polymetallic replacement of carbonates by metalliferous fluids associated with igneous intrusives formed stratiform ore bodies (zinc-lead-silver-gold mantos). Primary base-metal sulfide ores include galena, sphalerite, and chalcopyrite. Base-metal ore grades of the mantos range from 3 to 8 percent lead, 6 to 30 percent zinc, and 0.1 to 0.3 percent copper (Cappa and Bartos, 2007). Supergene enrichment processes transformed the base-metal sulfides into their oxidized counterparts forming significant ores with grades of 20-50 percent lead, 15-40 percent zinc, and minimal copper (Cappa and Bartos, 2007). Quartz veins also carried base metals, averaging 5-15 percent lead and 4-10 percent zinc. The greater Leadville district is credited with production of 110 million pounds of copper, 2.4 billion pounds of lead, and 2 billion pounds of zinc through the early 2000s (Cappa and Bartos, 2007). In addition to very high historic production, Cappa and Bartos (2007) note that “exploration potential is perceived as excellent.” The greater Leadville district, including most of Iowa and Evans districts, is assigned H/D for copper-lead-zinc occurrence potential.

Just to the east of the Leadville district, several mines (e.g., Continental Chief and Sherman-Hilltop) were past producers on Mt. Sherman, where lead-zinc replacement and vein deposits are hosted in the Leadville Dolomite at the head of Iowa Gulch (Vanderwilt, 1947). This area is assigned H/D for base-metal occurrence potential. South of Mt. Sherman along the county line in the Weston Pass district (shared with Park County), the Leadville Dolomite contains lead-zinc replacement deposits in cavities up to 10 feet thick along a discontinuous horizon that can be traced for over a mile (Cappa and Bartos, 2007; U.S. Bureau of Mines, 1989). The Weston Pass district is assigned H/D and the surrounding Leadville Limestone is M/B for occurrence potential.

Further south, in the Granite district (shared with Chaffee County), Tertiary pyritic quartz veins in Precambrian gneiss and granite host minor amounts of chalcopyrite, galena, and sphalerite (Cappa and Bartos, 2007; U.S. Bureau of Mines, 1989). The Granite district is designated M/C.

Vanderwilt (1947) attributes minor lead production (3,700 pounds) to the Sugarloaf-St. Kevin districts in the Turquoise Lake area. Mineralization occurs in fissures up to 10 feet thick within shear zones and is associated with Tertiary igneous intrusions that cut Precambrian gneiss and Silver Plume-aged quartz monzonite (St. Kevin batholith) (Cappa and Bartos, 2007; Del Rio, 1960). Massive sulfides occur in zones of concentrated fissures containing up to 4-5 percent zinc (sphalerite), 1-2 percent lead (galena), and 0.1 percent copper (chalcopyrite) ores (Cappa and Bartos, 2007; Del Rio, 1960; U.S. Bureau of Mines, 1989). The St. Kevin-Sugarloaf districts are designated H/C.

In the Twin Lakes district of southwestern Lake County, sulfide mineralization occurs in quartz veins within shear zones of reverse faults that cut the Tertiary granodiorite-to-quartz monzonite Twin Lakes batholith (Cappa and Bartos, 2007). Veins up to 8 feet thick contain disseminated galena, sphalerite, and chalcopyrite, and zones of concentrated mineralization occur where these reverse faults are intersected by northeast-trending faults (Cappa and Bartos, 2007). One such zone over 60 feet wide occurs at the Gordon mine where Cappa and Bartos (2007) report average ore grades of 9.7 percent lead, 2.1 percent zinc and 0.7 percent copper. Vanderwilt (1947) reports 4,400 pounds of lead production between 1932 and 1945. The region of reported mineralization and production within the Twin Lakes district is assigned H/C, and the surrounding Tertiary intrusion is M/C.

Precambrian rocks with Tertiary intrusives and a concentration of base-metal prospects (USGS MRDS, 2013) in northeastern Lake County, including parts of Alicante, Climax, English Gulch, and Mosquito Range districts, are assigned H/C. In the rest of the county, areas surrounding historic mining districts and including rocks of Precambrian basement and Tertiary intrusives (e.g., Champion mine in Lackawanna district) are considered M/C where there are recorded copper-lead-zinc occurrences in the USGS MRDS (2013). The same rocks outside documented copper-lead-zinc occurrences are considered M/B.

Paleozoic sedimentary units, including the Leadville Limestone and Minturn Formation, around Buckeye Gulch, Mt. Zion, and Tennessee Pass are assigned H/C due to their proximity to Tertiary intrusives and recorded base-metal occurrences. Paleozoic sedimentary units near intrusives are considered M/B (e.g., parts of Empire and Union Gulch districts). The Leadville Limestone in the northeastern portion of the county is L/B as they could host replacement deposits similar to Weston Pass (Cappa and Bartos, 2007). The Minturn Formation is M/B for favorable geologic environment due to base-metal mineralization in that rock in other counties (e.g., Chaffee and Huerfano).

4.22.5 Iron

Hedges (1940) reports production of 2.5 million tons of black manganese-iron ore from the Leadville district through 1939. Limonite, hematite, magnetite, siderite, and manganosiderite, all as replacement deposits, occur near the top of the Mississippian Leadville Dolostone (Cappa and Bartos, 2007; Harrer and Tesch, 1959). High-grade magnetite and hematite ore assayed up to 68.3 percent iron at Breece Hill district mines (Harrer and Tesch, 1959). The greater Leadville district is assigned H/D for iron occurrence potential. The Leadville Dolostone elsewhere in the county is designated M/C.

Numerous magnetite masses occur in a quartz monzonite porphyry along Lake Creek in the Twin Lakes district (Harrer and Tesch, 1959). This area is designated M/C for iron occurrence potential.

Iron-bearing minerals (especially pyrite and magnetite) are reported in polymetallic veins, pegmatites, and stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential. Precambrian Silver Plume-related granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B.

4.22.6 Manganese

The most viable manganese occurrence in the RGFO region is found in the greater Leadville district in Lake County. Del Rio (1960) reports that over 7 billion pounds of manganese ore had been produced through 1939; Cappa and Bartos (2007) estimate 12 million pounds of manganese have been recovered in the greater Leadville district. These ores were derived from manganiferous siderite in the Leadville Limestone, of which one-third assayed between 15 to 45 percent, and the rest between 4 to 40 percent, manganese (Del Rio, 1960). The U.S. Bureau of Mines (1989) reports that a zone of manganese ore (oxidized manganosiderite), which has not been recovered, surrounds lead and zinc sulfide ores of the Leadville district, and significant manganese ore in abandoned mine dumps remains. Reserves are estimated at 4 million tons of 5 to 35 percent manganese ore in the greater Leadville district (Del Rio, 1960; U.S. Bureau of Mines, 1989). The greater Leadville district, including Carbonate Hill, Iron Hill, California Gulch, Iowa Gulch, Breece Hill, and Evans districts, as well as the Leadville Limestone elsewhere in the county, is designated H/D for manganese potential.

Almost 2 million pounds of 12 percent manganese was mined from veins in Precambrian granite (Berthoud Plutonic Suite–St. Kevin batholith) at the Dinero vein of the Sugarloaf district between 1914 and 1948 (USGS MRDS, 2013; Singewald, 1955). About thirty manganese prospects or mines are located in the St. Kevin quartz monzonite within the St. Kevin-Sugarloaf districts and scattered along the eastern portion of the county (USGS MRDS, 2013; Tweto, 1987). Another half dozen occur in early Precambrian rocks. Precambrian granite of the St. Kevin batholith is designated H/C for manganese potential; other Precambrian rocks in the county are assigned L/C.

Precambrian Silver Plume-related granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B.

4.22.7 Molybdenum

In northeastern Lake County, the large Tertiary Climax rhyolite porphyry molybdenum deposit, comprising four distinct intrusive bodies, defines a district of its own (Cappa and Bartos, 2007). Considered the world's largest molybdenum deposit, Climax has produced 500 million tons of ore and 1 million tons of molybdenum since 1917 (Wallace and Bookstrom, 1993). The mine closed in 1995, only to reopen in 2012 after molybdenum prices reached record highs.

Mineralization occurs in quartz veinlets, fractures, tabular structures, pegmatites, and dikes; also, molybdenum inclusions are found in younger intrusives (USGS MRDS, 2013). The Climax district is assigned H/D for molybdenum occurrence potential. Areas around the district within the same host rocks are H/C.

Molybdenum is found in concentric zones of veinlets associated with a postulated Tertiary stockwork in Precambrian granite near Turquoise Lake (U.S. Bureau of Mines, 1989). A Tertiary underground intrusive complex composed of a small quartz-latite porphyry stock with associated breccias and rhyolite dikes along the north edge of Turquoise Lake likely hosts molybdenum (Gese and Scott, 1993). A deep molybdenum stockwork is also postulated at the northwestern end of the Twin Lakes area near Bull Hill, possibly in association with the Twin Lakes pluton of the Grizzly Peak Caldera Complex, which spans southwestern Lake and northwestern Chaffee Counties in the RGFO region, as well as southeastern Pitkin and northeastern Gunnison Counties (Fridrich et al., 1998; Gese and Scott, 1993; U.S. Bureau of Mines, 1989). Buffers around these areas are designated M/B. Tertiary intrusive rocks are M/B. Precambrian metamorphic rocks in the rest of the county are assigned L/B.

4.22.8 Nickel

Gersdorffite (NiAsS) is reported from a galena-chalcopyrite ore in Precambrian gneiss at the Homestake mine near Tennessee Pass (Eckel, 1961). Precambrian metamorphic and igneous rocks throughout the county are designated L/B due to this occurrence and others in similar rocks in other counties.

4.22.9 Tungsten

The Climax mine first began producing tungsten as a byproduct of molybdenite processing in 1948. Hübnerite is erratically disseminated in the molybdenum ore body, which is hosted by the Idaho Springs Formation and Silver Plume Granite (Lemmon and Tweto, 1962; USGS MRDS, 2013). Occasionally, the tungsten ore fills veins as much as 0.5 inches wide, and assays average 0.03 percent WO_3 (Del Rio, 1960; Eckel, 1961). From 1955 through 1958, the value of tungsten concentrate produced at the Climax mine exceeded $11 million (Del Rio, 1960). Cobb (1960) reports production of over 300,000 units of tungsten concentrate (an estimated 4.8 million pounds of tungsten metal) between 1948 and 1960. MRDS (2013) reports an average annual production rate of 1.9 million pounds of tungsten in 1979. Reported production in 1996 was 136 million tonnes of 0.03 percent tungsten ore (USGS MRDS, 2013). The Climax district is assigned H/D for tungsten occurrence potential. Areas around the district within the same host rocks are assigned H/C.

In the Leadville district (Breece Hill), wolframite and scheelite are scattered in pyritic gold ore (Lemmon and Tweto, 1962). Tungsten is also reported at the Mt. Zion mine in association with Laramide intrusive rocks (USGS MRDS, 2013). The area around these occurrences, within the favorable host rocks, are designated M/D for tungsten potential. The remainder of Lake County is assigned M/B in areas with favorable host rocks but lacking reported prospects.

4.22.10 Beryllium

Through 1963, production of beryl from pegmatites in Lake County amounted to 311 pounds (Meeves et al., 1966). Granitic rocks throughout the county are assigned a beryllium potential of L/B.

4.22.11 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Lake County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Production of 2 billion pounds of zinc is recorded through the 2000s in Lake County, primarily in the greater Leadville district; sphalerite ores are commonly reported from the many zinc mines (Cappa and Bartos, 2007; Del Rio, 1960; Henderson, 1926; USGS MRDS, 2013; Vanderwilt, 1947). Within the Climax district, late mineral dikes within the Climax district host sphalerite mineralization (Cappa and Bartos, 2007). Supergene enrichment processes transformed base-metal sulfides into their oxidized counterparts forming significant ores with grades reaching 15-40 percent zinc; mineralized quartz veins average 4-10 percent zinc (Cappa and Bartos, 2007). Buffers around clusters of known zinc mines or individual mines are assigned H/B for gallium, germanium, and indium occurrence potential in the greater Leadville district and M/B elsewhere.

4.22.12 Rare Earth Elements

Meeves et al. (1966) report production of 26 pounds of REEs from pegmatites through 1963 in Lake County. REE-bearing monazite is recovered as a byproduct of molybdenum mining at Climax; although monazite accounts for just 0.005 percent of the deposit, the volume of ore processed allows for economic recovery (Adams, 1968b). The area around the Climax deposit is designated H/D for REE occurrence potential.

4.22.13 Niobium-Tantalum

In northeastern Lake County, the Tertiary Climax rhyolite porphyry molybdenum deposit, comprising four distinct intrusive bodies, is enriched in niobium and tantalum, although no production is reported (Ludington and Plumlee, 2009; USGS MRDS, 2013). The area around the Climax deposit is assigned L/C for niobium-tantalum occurrence potential.

4.22.14 Tellurium

Telluride minerals have been identified in the greater Leadville and Buckeye Gulch districts (Cappa and Bartos, 2007; Eckel, 1961). The greater Leadville and Buckeye Gulch districts are assigned an occurrence potential of H/D due to numerous occurrences of gold and copper mineralization and the presence of tellurides. Precambrian rocks in the rest of the county are considered L/B for tellurium occurrence.

4.22.15 Titanium

Hydrothermal ilmenite, titaniferous magnetite and rutile are all present in the Climax deposit, and titanium is listed as a tertiary commodity (Cappa and Bartos, 2007; USGS MRDS, 2013). The Climax district is considered M/C for titanium occurrence potential.

4.22.16 Uranium

Several uranium occurrences exist in Lake County, but no production is reported. All but one of the 15 occurrences described by Nelson-Moore et al. (1978) are in or near the St. Kevin district in the northwestern part of the county. These uranium occurrences are in veins, fractures, and faults in the Precambrian St. Kevin quartz monzonite. The uranium minerals occur as microscopic disseminations or coatings in precious- and base-metal deposits and are rarely concentrated. Precambrian granite of the St. Kevin batholith is designated L/C for uranium occurrence potential.

Tertiary siliceous tuffs are source rocks for uranium leached and reprecipitated in nearby fractures and faults (Olson, 1988). Production of nearly 500 pounds of uranium is reported from a seam underlying Tertiary tuffs in Saguache County (Nelson-Moore et al., 1978). Tertiary tuffs, including Laramide intrusives, in Lake County are designated L/B for uranium occurrence potential.

4.22.17 Thorium

There are no reported thorium mines in Lake County; however, monazite and brannerite ($(U,Ca,Fe,Th,Y)_3Ti_5O_{16}$) are sporadically disseminated and produced as a byproduct at the highly mineralized Climax molybdenum ore body (Olson and Adams, 1962; Schwochow and Hornbaker, 1985). Heinicke (1960) reports production of $3,000 worth of monazite in 1953. Also, thorium is reported from veins and pegmatites along mainly northwest-trending faults in Precambrian crystalline rocks in surrounding counties. A buffer around the Climax deposit is designated L/C for thorium occurrence potential; northwest-trending faults in Precambrian crystalline rocks are designated L/B.

4.22.18 Vanadium

No vanadium was produced from Lake County; however, vanadium is reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in Park and Fremont Counties; samples assayed up to 4.34 percent V_2O_5 (Nelson-Moore et al., 1978; Schwochow and

Hornbaker, 1985; USGS MRDS, 2013). The Minturn Formation is assigned L/C for vanadium occurrence potential.

4.22.19 Fluorspar

In Lake County, two fluorite prospects are developed in fissure veins hosted by the Precambrian Silver Plume Granite (Aurand, 1920; Brady, 1975). Fluorite also occurs in “topaz rhyolite” (fluorine-enriched volcanic rock) near the summit of the Tertiary Chalk Mountain intrusive, on the border with Summit and Eagle Counties (Christiansen et al., 1983; Eckel, 1961; Wegert et al., 2013). Fluorine-enrichment is documented from the Tertiary alkalic rocks at the Climax molybdenum deposit (Wallace, 2010). Fluorite occurs as green, purple, or colorless crystals, and Climax ore samples averaged 4,002 ppm fluorine with one outlier testing at 43,000 ppm fluorine (Brady, 1975; Wallace, 2010). The CMB in Lake County is locally cut by northeast-trending porphyry dikes and northwest-trending faults and boasts numerous pegmatites, all in rocks known to host fluorite elsewhere (Goddard,1947). Average content of fluorine (ppm) in Central Colorado measured highest in Precambrian igneous rocks, followed by Precambrian metamorphic and Tertiary intrusive rocks (Wallace, 2010). Precambrian igneous rocks, including the Climax mine area, are designated H/C, Precambrian biotite gneiss and Tertiary intrusives are assigned M/C, and hornblende gneiss is assigned M/B for fluorspar occurrence potential throughout the county.

4.22.20 Diamond and Gemstones

Production of turquoise is reported from a few mines developed in a fault zone near the perimeter of the Precambrian St. Kevin batholith near a contact with the Tertiary Turquoise Lake stock (Craig, 1980; Scott, 1968b). Production of about 2,000 pounds of gem turquoise was recorded from the Turquoise Chief mine in the 1930s (Eckel, 1961). Topaz is reported from within the Turquoise Lake stock, as well (Craig, 1980). In Colorado, economically productive pegmatites are far more common around the perimeter of batholiths where they contact metamorphic or intrusive rocks (Lovering and Goddard, 1950). Hence, the perimeter of the St. Kevin quartz monzonite in this area is designated H/C for gemstone occurrence potential. Zoned pegmatites are known to occur in Silver Plume-aged plutons, and the correlative St. Kevin batholith elsewhere in the county is assigned L/B for gemstone potential (Boos, 1954; Cappa and Bartos, 2007).

Rhodochrosite occurs near the perimeter of the St. Kevin quartz monzonite in the Sugarloaf district (Eckel, 1961; Singewald, 1955); this area is designated M/C for gemstone occurrence potential. Smoky quartz and topaz crystals occur in “topaz rhyolite” (fluorine-enriched volcanic rock) near the summit of the Tertiary Chalk Mountain intrusive, on the border with Summit and Eagle Counties (Christiansen et al., 1983; Eckel, 1961; Wegert et al., 2013). Rhodochrosite occurs near the contact of a St. Kevin quartz monzonite pluton and Precambrian biotite gneiss at the John Reed mine, just south of the Climax complex (Eckel, 1961; Singewald, 1955). Buffers around these mines are designated H/C for gemstone occurrence potential. Small, often microscopic, topaz crystals are widely disseminated throughout the Climax molybdenum deposit (Eckel, 1961). A buffer around this deposit is assigned M/C for gemstone potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks are designated L/C, and biotite gneisses and schists are assigned L/B, for gemstone occurrence potential in Lake County (Lovering and Goddard, 1950). The lower potential of Precambrian metamorphic rocks in Lake County compared to other counties (e.g., Boulder or Clear Creek) is due to the relative lack of gemstone, beryllium, and fluorite occurrences and commercially developed pegmatites. The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

4.22.21 Pegmatite Minerals

There is no reported production of feldspar or mica in Lake County; however, Cappa and Bartos (2007) note that microcline-bearing pegmatites, measuring up to 35 feet thick, are common in the St. Kevin quartz monzonite, which is exposed throughout the western and eastern portions of the county. Pegmatites are reportedly abundant in the Precambrian gneiss and schist surrounding the St. Kevin batholith (Singewald, 1955). Precambrian biotite gneisses and schists are designated M/B for pegmatite mineral occurrence. Precambrian plutonic rocks are considered L/B.

4.22.22 Industrial Abrasives

Garnet is an accessory mineral of “topaz rhyolite” (fluorine-enriched volcanic rock) near the summit of the Tertiary Chalk Mountain intrusive, on the border with Summit and Eagle Counties; one mine lists garnet as a primary commodity (Christiansen et al., 1983; Eckel, 1961; Wegert et al., 2013). A buffer around Chalk Mountain is designated H/C for industrial abrasive occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.22.23 Limestone and Dolomite

In Lake County, there is one USGS MRDS (2013) limestone occurrence developed in the Pennsylvanian Minturn Formation; this unit hosts prospects in other counties as well and is designated L/C for limestone and dolomite occurrence potential. The undifferentiated Leadville, Williams Canyon, and Manitou Limestones have historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). The Leadville limestone group is designated H/C for limestone and dolomite occurrence potential throughout the county.

4.22.24 Industrial Sand

There is one DRMS-permitted industrial sand operation developed in the Cambrian Sawatch Quartzite in Lake County; a buffer around this occurrence is designated L/C for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

4.22.25 Gypsum

No gypsum is reported in Lake County; however, productive gypsum quarries in western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation, equivalent to the Chubb evaporite member in South Park (Brill, 1952). Minturn Formation gypsum is known from the Swissvale, Badger Creek, Howard, and Coaldale areas of the Arkansas River corridor in Fremont County, and this unit extends into eastern Lake County (Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential.

4.22.26 Sand and Gravel

There are several USGS MRDS (2013) sand and gravel occurrences or DRMS-permitted quarries developed in Quaternary deposits, principally along the Arkansas River corridor, in Lake County. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, and glacial drift (Qd) are assigned H/C for potential (Arbogast et al., 2011).

4.22.27 Crushed Stone Aggregate

Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). Dense limestones and dolomites comprise about 70 percent of production nationwide (Langer and Knepper, 1995; Knepper et al., 1999). Cambrian to Mississippian limestones and quartzites, mapped as MC in Lake County, are assigned H/C for crushed stone potential.

Tertiary intrusive rocks occur sporadically throughout the county; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz, which is detrimental to cement-making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Laramide intrusive rocks meet the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999) and are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the St. Kevin pluton and satellites in Lake County, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered, foliated, and jointed Precambrian Boulder Creek Granite is classified as a “fair” source rock by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The St. Kevin pluton and satellites are designated H/C, and the Boulder Creek Granite is assigned M/C, for crushed stone aggregate potential. Precambrian biotite schist (Idaho Springs Formation) is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian Minturn Formation and the Tertiary Dry Union Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). These sedimentary rocks are assigned L/B for crushed stone aggregate occurrence potential.

4.22.28 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in the Precambrian granitic igneous and metamorphic rocks of Colorado (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the igneous and metamorphic rocks of Lake County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The relatively unweathered St. Kevin and Silver Plume Granites are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

The Pennsylvanian Minturn and Tertiary Dry Union Formations bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

4.22.29 Clay

There are no reported clay prospects in Lake County; however, abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). The undifferentiated Minturn and Belden Formations are designated L/B for clay occurrence potential.

4.22.30 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). There is no reported production of dimension stone in Lake County; however, igneous and sedimentary rocks that have potential to be quarried for dimension or building stone include the Precambrian Silver Plume and St. Kevin granites, the Cambrian Sawatch Quartzite, the Ordovician Manitou Limestone, the Mississippian Leadville Limestone, and the Pennsylvanian Minturn Formation (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Silver Plume Granite has been quarried for dimension stone in other counties, although where weathered, fractured, or highly jointed, granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Silver Plume Granite and St. Kevin quartz monzonite are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. Tertiary intrusive bodies are assigned L/B for dimension stone potential.

The Minturn Formation hosts numerous sandstone and limestone beds throughout its extent, but there are no reports of dimension stone production (Arbogast et al., 2011; Cappa and Bartos, 2007); the Minturn Formation is assigned M/B for dimension stone potential. Partially metamorphosed and marbleized Mississippian Leadville Limestone is quarried in Pueblo, Fremont, and Chaffee Counties; stone from the ‘Beulah marble’ in Pueblo County adorns the Colorado State Capital building (Arbogast et al., 2011; Schwochow, 1981). Undifferentiated

Cambrian through Mississippian limestone, dolomites, and quartzites (mapped as MC) are designated H/D for dimension and building stone occurrence potential.

4.23 Larimer County

4.23.1 Coal

There is a small portion of the Cheyenne Basin of the Denver Coal Region (see section 3.1.1 of this MPR) that lies in extreme northeastern Larimer County. Carroll and Bauer (2002) report production of 54,611 tons of coal from the Cretaceous Laramie Formation at 9 past-producing mines, all within the southeastern quadrant of township 11N and Range 68W, through 2001. Of an estimated 78.2 million tons of original coal resources under less than 3,000 feet of overburden in the county, roughly 109,000 tons are reportedly depleted, implying reserves of 78 million tons of coal (Carroll and Butler, 2002; Landis, 1959). The Denver Coal Region in Larimer County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.23.2 Geothermal

Traditional / EGS Geothermal

The majority of Larimer County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the southeastern corner is considered M/C because of high EGS favorability (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Larimer County contains no known wells or springs. Almost all of the western ¾ of Larimer County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The rest of Boulder County is designated as a mix of H/C and H/B for low temperature and/or co-produced geothermal resources. Those areas within named COGCC fields are considered to have a higher level of confidence.

4.23.3 Gold

Vanderwilt (1947) reports production of 357 ounces of lode gold from 1909 to 1941 in Larimer County. In the Manhattan district, gold-bearing veins are associated with Silver Plume-aged granite (Log Cabin batholith) and quartz monzonite porphyry, both intruded into Precambrian hornblende gneiss and quartz-biotite schist (Lovering and Goddard, 1950; Sims et al., 1958; Tweto, 1979a). Surficial, oxidized ore was reported to contain 1.5 to 15 ounces per ton of gold with unoxidized sulfide ores assaying at 0.25 to 0.35 ounces per ton (Lovering and Goddard, 1950). Similar veins, averaging 0.35 to 0.90 ounces of gold per ton, characterize the nearby Maysville district (Lovering and Goddard, 1950). The area around the Manhattan and Maysville districts is designated H/C for gold occurrence potential. A buffer around the Maysville district in Precambrian felsic gneiss is assigned M/B for potential.

Northwest of the Masonville district, some gold has been produced from veins associated with a tonalite stock that intrudes Precambrian metamorphic and Paleozoic sedimentary rocks in an area bounded by faults (USGS MRDS, 2013). Production of 0.02 to 0.04 ounces of gold per ton on average, but up to 2.0 ounces per ton in parts, was sporadic from about 1900 to the 1950s at the Mason and Carter mines (USGS MRDS, 2013). A buffer around the noted gold prospects has been assigned an occurrence potential of H/C.

Minor production of 0.1 ounce per ton gold is reported from prospects in the Howes Gulch district (USGS MRDS, 2013). The mineralization occurs in poorly defined veins associated with Boulder Creek Granite in Precambrian metamorphic rocks (USGS MRDS, 2013; Vanderwilt, 1947). In the Stove Prairie area northwest of the Howes Gulch region, several gold prospects occur in a similar contact zone between Precambrian felsic metamorphic rocks and Boulder Creek Granite (USGS MRDS, 2013). Buffer zones around the felsic rocks in proximity to Boulder Creek Granite in these areas are assigned M/C for gold occurrence potential. Areas surrounding Precambrian felsic metamorphic rocks and the heavily faulted central part of the county are designated L/B due to the abundance of base-metal mineralization.

4.23.4 Silver

Larimer County has been attributed with 1,492 ounces of silver production from 1909 through 1941 (Vanderwilt, 1947). In the greater Masonville district area, silver has been produced from veins in joints and fractures of a tonalite stock that intrudes Precambrian metamorphic and Paleozoic sedimentary rocks in an area bounded by faults (USGS MRDS, 2013). A buffer around the noted prospects is designated H/C for silver occurrence potential.

Numerous USGS MRDS (2013) silver prospects and mines are found in porphyry or pegmatite dikes in Precambrian felsic metamorphic rocks in the greater Manhattan and Maysville district area. Samples yielded from 0.1 to 1.5 ounces per ton of silver (USGS MRDS, 2013). The greater Manhattan and Maysville district area is designated H/C for silver occurrence potential.

Several silver occurrences occur in pegmatite in the Stove Prairie area in central Larimer County (USGS MRDS, 2013). The area is assigned M/C for silver potential. Two silver occurrences (Crist and Ackney mines) occur in association with the Sherman batholith of northern Larimer County (USGS MRDS, 2013). The Sherman batholith is designated L/C for silver occurrence potential. The Empire claim in the Howes Gulch district produced 0.5 ounces per ton silver from veins in Precambrian felsic metamorphic rocks in proximity to Boulder Creek granodiorite (USGS MRDS, 2013). The Howes Gulch district is assigned M/C for silver potential. The remainder of Precambrian felsic metamorphic rocks in the county is assigned M/B for silver occurrence potential.

4.23.5 Copper-Lead-Zinc

Larimer County is underlain primarily by Precambrian igneous and metamorphic rocks cut in places by Tertiary intrusives, with some Phanerozoic sediments along the margin of the Front Range. Copper production for Larimer and Jackson Counties was reported together and amounted to 235,328 pounds from 1898 to 1917, although how much is attributed to Larimer County is unknown. The county produced minimal zinc, with 30,722 pounds reported in 1909 from the Prairie (St. Cloud) district located in T. 10 N., R. 72 W. (Henderson, 1926). The Copper King and Iron King mines are located in the northwest quadrant of this township and range; both mines are past producers of copper and zinc (USGS MRDS, 2013). Sims et al. (1958) report that 55 tons of 18.2 percent zinc sulfide ore were shipped in 1951 from the Copper King mine. Sheridan et al. (1990) classify the ore of the Copper King mine as a Type 1 stratabound exhalative deposit. Sims et al. (1958) characterize the ore host at Copper King mine as an amphibole skarn in proximity to Silver Plume-aged granite (Log Cabin batholith). The area surrounding the Copper King mine (Prairie district) is designated H/D for base-metal potential based on past production and favorable rock types.

In the rest of the county, a cluster of base-metal past producers is reported in the USGS MRDS (2013) in the overlapping Maysville and Manhattan districts. The gneiss around the Manhattan and Maysville districts is assigned H/D for base-metal potential. Copper production is reported from the Masonville district in 1917 by Henderson (1926), and this district is designated M/C. Other base-metal occurrences are scattered but most occur in Precambrian gneiss or schist, e.g., in the Howe’s Gulch and Crystal Mountain districts (USGS MRDS, 2013). Precambrian gneisses and schists elsewhere in the county are M/B due to reported occurrences and metamorphic sulfide potential (e.g., Sheridan et al., 1990). Other Precambrian igneous rocks in Larimer County are assigned L/B for base-metal occurrence potential.

4.23.6 Iron

Iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout Larimer County are designated L/B for iron occurrence potential where no occurrences are reported and L/C where minor or non-producing occurrences are noted.

Iron-rich minerals are reported in the Silver Plume-aged Sherman and Log Cabin plutons (Eggler, 1968). Abundant magnetite is reported from the Copper King and Iron King mines in pegmatite of the Log Cabin granite (USGS MRDS, 2013); a buffer around these mines is designated M/C. Elsewhere, these Precambrian igneous bodies are designated L/B for iron occurrence potential throughout the county. Precambrian northwest-trending, iron-rich diabase dikes throughout the southern half of Larimer County host titaniferous magnetite and limonite, and one occurrence is noted at the Iron Dike mine (Eggler, 1968; USGS MRDS, 2013). Mafic dikes are designated M/C for iron potential.

Limonite and siderite concretions occur in the Rusty Zone of the Cretaceous Pierre Shale north of Overton in Pueblo County (Gilbert, 1897; Harrer and Tesch, 1959; Scott; 1969). The lower unit (Sharon Springs shale) of the Pierre Formation in Larimer County is designated L/B for iron occurrence potential. Thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Boulder and Weld Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Larimer County.

4.23.7 Manganese

Nodular purpurite ($(Mn^{+3}Fe^{+3})PO_4$) occurs in quartz diorite pegmatites in Precambrian metamorphic rocks at the Primrose Beryl lode, Double Opening prospect, and Hyatt Ranch beryl mine in the Crystal Mountain Pegmatite district (Eckel, 1961; Hanley et al., 1950; USGS MRDS, 2013). Precambrian metamorphic rocks throughout the county are designated L/C for manganese potential.

4.23.8 Molybdenum

The USGS MRDS (2013) lists seven occurrences of molybdenite in the RGFO region of Larimer County. Molybdenum occurs with tungsten as part of the scheelite-powellite solid solution series ($CaMoO_4$-$CaWO_4$) in contact-metasomatic deposits at the Lookout, Challenger, Green Rock, and Spaulding mines and Bidwell claims, all listed as past producers although no data for molybdenum are available (Belser, 1955; Belser, 1956; USGS MRDS, 2013). Molybdenum occurs as a secondary commodity in veins of the Sherman Batholith at the Iron King and Copper King mines (USGS MRDS, 2013). Areas around known occurrences are designated M/C for molybdenum potential. Other Precambrian metamorphic and igneous rocks are L/B.

4.23.9 Nickel

Trace nickel is found in Precambrian pyrrhotite-bearing gneiss (Idaho Springs Formation) and in Tertiary pitchblende-bearing veins in the Copper King mine area of the State Line district (Cappa, 1998). Two prospects in the Maysville district area report nickel laterites (USGS MRDS, 2013). The Davis Nickel prospect and Treasure Hill mine in the Livermore area are past producers of nickel (USGS MRDS, 2013; Vanderwilt, 1947). These deposits occur near the boundary of the Precambrian Sherman batholith and Idaho Springs Formation gneiss (USGS MRDS, 2013). Eckel (1961) reports either pentlandite or violarite at a small gold mine just north of Masonville. Buffers around these occurrences are M/C for nickel potential. Elsewhere, Precambrian metamorphic and igneous rocks are designated L/B due to these occurrences and others in similar rocks in other counties.

4.23.10 Tungsten

Tungsten mines and prospects are found in Precambrian granite and calc-silicate gneisses throughout central Larimer County (Belser, 1956; Lemmon and Tweto, 1962). Tungsten occurs with molybdenum as part of the scheelite-powellite solid solution series ($CaMoO_4$-$CaWO_4$) in contact-metasomatic (skarn or tactite) deposits, and—similarly to the Boulder Tungsten Belt—all known deposits are found within Tertiary northeast-trending veins (Belser, 1955; Belser, 1956).

The Stove Prairie area contains several tungsten deposits including the Lookout mine, where over 100 tons of 2 percent WO_3 were produced from 1952 to 1953 (Belser, 1956). The nearby Challenger (Heline) mine was also a producer: several tons of 0.57 percent WO_3 were reported in 1942 (Belser, 1956). Production of 10 tons of tungsten ore are reported at the proximate Bidwell claims (USGS MRDS, 2013). The Stove Prairie area scheelite-powellite series deposits are found in a contact zone in association with biotite gneiss (Idaho Springs) and Boulder Creek-aged granodiorite as mapped by Abbott (1976).

About 7 miles to the northeast of the Lookout-Challenger cluster of mines, the Spaulding and Green Rock mines host scheelite-powellite series deposits in a contact metamorphic zone in proximity to biotite gneiss and Sherman granodiorite (Belser, 1956; Tweto, 1979a; Tweto, 1987; USGS MRDS, 2013). The Green Rock mine, where scheelite occurs in an east-trending, 6-foot-wide vein, has recorded production in 1942 of 50 tons of 1 percent WO_3 (Belser, 1956). The Spaulding mine is a past producer but no data are available (USGS MRDS, 2013). The Stove Prairie area, including the Spaulding and Green Rock mines, is designated H/D for tungsten occurrence potential due to production and favorable geology (calc-silicate gneiss and Boulder Creek granodiorite) and structure (northeast-trending Tertiary veins). Surrounding areas where these geologic and structural features occur without tungsten prospects are H/C.

Several scheelite deposits north- to southwest of the Masonville mining district are recorded but production was minor (Belser, 1956; USGS MRDS, 2013). The Ball and Thompson Canyon Scheelite mines are developed in biotite gneiss and Boulder Creek Granite (USGS MRDS, 2013). The cluster of small mines just west of Masonville is developed in veins in sedimentary rocks (USGS MRDS, 2013). These areas are designated H/C for tungsten potential. The early Precambrian biotite gneisses (Idaho Springs Formation) and Boulder Creek Granite, where no tungsten occurrences are reported, are designated M/C. Other Precambrian igneous and metamorphic rocks of Larimer County are assigned L/B for tungsten occurrence potential. Sedimentary units in proximity to the Precambrian igneous and metamorphic rocks are also designated L/B.

4.23.11 Beryllium

Beryllium is a significant mineral in the pegmatites of central Larimer County, where at least 100 USGS MRDS (2013) prospects occur. Through 1963, production of beryl from pegmatites in Larimer County amounted to 358,790 pounds (Meeves et al., 1966). Beryl and chrysoberyl are found where several plutons of the Silver Plume-aged facies (Longs Peak–St. Vrain batholith and satellite intrusions of Mt. Olympus granite) intrude Precambrian metamorphic rocks in the region around the Farnsworth, Crystal Mountain, and Drake districts (Boos and Boos, 1934; Del Rio, 1960; Heinrich, 1957; Tweto, 1979a and 1987). In the Crystal Mountain district, a beryl crystal 6 feet long and 2 feet wide was found at the Big Boulder prospect, where beryl makes up about 0.5 percent of the ore and about 600 pounds were mined in 1941 (Eckel, 1961; Thurston, 1955). Clusters of beryl crystals up to 3 feet long and 1 foot in diameter occur in tonalite pegmatites, composed of up to 3 percent BeO, at the Hyatt Ranch mine (Eckel, 1961). The Hyatt zoned pegmatite, 365 feet long and up to 70 feet wide, has reported production of 50 tons of beryl from 1936 to 1955 (Thurston, 1955). Chrysoberyl crystals up to 3 inches long have been mined at the Wisdom Ranch prospects in the same district (Vanderwilt, 1947). An estimated 3 to 4 tons of beryl have been mined at the Buckhorn Mica mine between 1884 and 1955 (Thurston, 1955). Over 1300 pegmatites have been mapped in the region surrounding the Farnsworth, Crystal Mountain, and Drake districts, which are designated H/D for beryllium potential (Thurston, 1955). Numerous pegmatite and beryllium deposits peripheral to these districts are considered H/C for beryllium potential. The occurrence potential for beryllium is considered L/B in the granitic rocks of the rest of Larimer County.

4.23.12 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Larimer County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.23.1 of this MPR) is designated L/B for germanium occurrence potential.

The county produced 30,722 pounds of zinc in 1909 from the Prairie (St. Cloud) district located in Township 10N, Range 72W. (Henderson, 1926). About 55 tons of 18.2 percent zinc sulfide ore were shipped in 1951 from the Copper King mine in this district; sphalerite is a reported mineral (Sims et al., 1958; USGS MRDS, 2013). Buffers around this and several other sphalerite-bearing mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.23.13 Rare Earth Elements

No REE production is noted for Larimer County; however, swarms of beryl-bearing pegmatites occur in the greater Crystal Mountain Pegmatite district, some of which host trace REEs (Adams, 1968; Meeves et al., 1966). Allanite is known from zoned quartz-diorite pegmatites at the Crystal Snow mine (Meeves et al., 1966; USGS MRDS, 2013). To the northeast of the district, the Vona Mae pegmatites host monazite at the contact of Boulder Creek Granite and Precambrian schist; samples yielded 0.5 percent Ce_2O_3 and 0.5 percent La_2O_3, plus trace yttrium (Meeves et al., 1966; USGS MRDS, 2013). Along a fault in Sherman Granite, beryl- and thorium-bearing pegmatites host monazite at the Red Head claims in the Prairie Divide (St. Cloud) district (Adams, 1968; Meeves et al., 1966; Olson and Adams, 1962). A northeast-trending pegmatite in Precambrian gneiss hosts trace yttrium at the Soda Springs claims in the Maysville district (USGS MRDS, 2013). All of these areas are designated L/C for REE occurrence potential.

4.23.14 Niobium-Tantalum

Meeves et al. (1966) report production of 102 pounds of niobium-tantalum minerals from Larimer County. A swarm of Precambrian northwest-trending quartz diorite pegmatite dikes in Idaho Springs Formation schist host columbite and tantalite in the greater Crystal Mountain Pegmatite district (Heinrich, 1957; Thurston, 1955). Based on specific gravity measurements, samples from this district are estimated to contain 39 to 76 percent Ta_2O_5 and 10 to 48 percent Nb_2O_5 (Thurston, 1955). Columbite-tantalite masses 2 to 3 inches long are reported from the Buckhorn pegmatite, but commercial viability is low due to the sporadic nature (Hanley et al., 1957; Thurston, 1955). Euhedral tantalite crystals, up to 1 inch wide, are abundant at the Tantalum prospect; samples contain an estimated 76 percent Ta_2O_5 and 10 percent Nb_2O_5 (Hanley et al., 1950; Thurston, 1955). The Red Head claims, developed in pegmatite in Sherman Granite in northern Larimer County, host columbite and tantalite (Nelson-Moore et al., 1978). Buffers along Precambrian northwest-trending pegmatite swarms in the greater Crystal Mountain district and elsewhere in the county are designated M/C for niobium-tantalum occurrence potential.

4.23.15 Tellurium

There are no reported occurrences of tellurium in Larimer County; however, Precambrian rocks in the RGFO region of the county are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks.

4.23.16 Titanium

Northwest-trending, Precambrian mafic dikes throughout the southern half of Larimer County host titaniferous magnetite, and one occurrence is noted at the Iron Dike mine (Eggler, 1968; USGS MRDS, 2013). The Iron Dike is designated M/C for titanium occurrence potential; mafic dikes elsewhere in the county are designated M/B. Also, titanium is reported from a uranium- and beryl-bearing pegmatite in Precambrian gneiss at the New Hope claims, although no production is reported (USGS MRDS, 2013). A buffer around this occurrence is designated L/C for titanium potential.

4.23.17 Uranium

Minor uranium production is reported for Larimer County. About 4,100 pounds of U_3O_8 have been recovered from the county, with nearly all of it (~3,800 pounds) from the Copper King mine, which worked a vein hosting 0.3 percent uranium ore in Precambrian Sherman Granite northeast of Red Feather Lakes (Nelson-Moore et al., 1978; Tweto, 1979a). Several other mines recovered small amounts of uranium from veins and pegmatites along a fault in the same unit northeast of the Manhattan district area; the Uranium Queen mine produced 340 pounds of U_3O_8 from 0.48 percent ore (Nelson-Moore et al., 1978). This Precambrian unit surrounding these mines is designated H/C for uranium occurrence potential.

Several pounds of uranium (carnotite and autunite) were produced from the Cretaceous Dakota Sandstone at the Wahketa mine, northeast of Howes Gulch (Nelson-Moore et al., 1978). Several uranium prospects occur in Mesozoic sedimentary rocks of other counties in the Jurassic undivided Morrison, Entrada, and Ralston Creek group and the Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from these units is also reported in Pueblo and Park Counties (Nelson-Moore et al., 1978). All these units in Larimer County are designated L/B for uranium potential.

Several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential. Also, near the northeastern county border, Larimer County is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units are assigned H/D for uranium potential.

Numerous uranium occurrences, some with very minor production, are hosted by zoned, often beryl-bearing, pegmatites in Precambrian metamorphic rocks (USGS MRDS, 2013). Secondary mineralization resulted in scattered uranium minerals coating grains and fracture surfaces, such as at the Soda Springs Group of mines in the Maysville district (Nelson-Moore et al., 1978). The majority of these occurrences are in the greater Crystal Mountain pegmatite district. Buffers around these occurrences are designated L/C for uranium potential.

4.23.18 Thorium

In Larimer County, two monazite deposits (one outside the RGFO region) occur in beryllium-bearing pegmatites along faults within the Precambrian Sherman Granite intrusion (Nelson-Moore et al., 1978; USGS MRDS, 2013). A sample at the Red Head claim (RGFO region) assayed 3.66 percent ThO_2 but no production is reported (Nelson-Moore et al., 1978). A third prospect is found in pegmatite along a fault in the Precambrian Boulder Creek Granite: a sample assayed 0.2 percent ThO_2 (USGS MRDS, 2013). Buffers along faults in Precambrian metamorphic rocks are assigned L/C for thorium occurrence potential.

4.23.19 Vanadium

In Larimer County, about 13 pounds of vanadium were recovered from 633 tons of sulfide-magnetite ore in the Precambrian Sherman granite pegmatite at the Copper King mine (Nelson-Moore et al., 1978). Also in Sherman granite pegmatite, production of 22 pounds of vanadium from 140 tons of 0.01 percent V_2O_5 ore is reported from the Uranium Queen mine (Nelson-Moore et al., 1978). Buffers around these mines are designated M/C for vanadium occurrence potential.

The Jefferson County Pallaora mine, developed in the Cretaceous Dakota Sandstone, produced 256 pounds of vanadium (Nelson-Moore et al., 1978). In Larimer County, production of 6 pounds of vanadium (carnotite and tyuyamunite) from 6 tons of 0.05 percent V_2O_5 ore recovered from the Dakota Sandstone is reported from the Wahketa mine (Nelson-Moore et al., 1978). Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone (Del Rio, 1960; Schwochow and Hornbaker, 1985). The undifferentiated Morrison Formation, Entrada Sandstone, and Dakota Sandstone mapped unit is designated H/C for vanadium occurrence potential in Larimer County.

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation and underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are associated with uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The small portion of the Laramie Formation and Fox Hills Sandstone that are mapped in the northwestern corner of the county are designated L/B for vanadium occurrence potential.

4.23.20 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, as well as Paleozoic alkalic diatremes and Tertiary intrusives, all of which are found in Larimer County (Wallace, 2010). Fluorite at 2 prospects occurs in pegmatites of the Sherman Granite; Sherman Granite showed elevated fluorine concentrations ranging up to 2,000 ppm (Brady, 1975; USGS MRDS, 2013). Two other fluorspar prospects are located in the Precambrian Idaho Springs biotite gneiss (USGS MRDS, 2013). The State Line district hosts numerous fluorite-bearing alkalic diatremes (Hausel, 1998). Also, topaz rhyolite (fluorine-enriched volcanic rock) hosts fluorite at Specimen Mountain along the Continental Divide in Larimer County (Christiansen et al., 1983; Brady, 1975). Precambrian igneous rocks and the area around the State Line district diatremes are designated H/C for fluorspar occurrence potential. Precambrian biotite gneiss and Tertiary intrusives are assigned M/C, and hornblende gneiss is assigned M/B, for fluorspar potential throughout the county.

4.23.21 Diamond and Gemstones

In the State Line district of Larimer County, kimberlite diatremes were first reported in 1964, and diamonds were first identified in 1975 by Professor Malcolm McCallum at Colorado State University, leading to a vigorous exploration campaign in the district (McCallum and Mabarak, 1976). The Kelsey Lake mine was North America's first commercial diamond producer, beginning operations in 1996. In 1998, the mine, about 4 miles west of U.S. Highway 287 near the Wyoming border, was put into limited production status eventually closing due to legal issues, and the site was reclaimed by 2006 (Cappa, 2007; CGS, 1999). At the time of preparing this MPR, the Kelsey Lake Project still holds an active DRMS permit (No. M1992-034) with Great Western Diamond Company (Brighton, MI) listed as the operator. The Kelsey Lake pipes produced many diamonds over 1 carat in weight, including two weighing over 28 carats, one of which was the largest faceted U.S. diamond at 16.8 carats with an estimated value of over $250,000 (Hausel, 1998). Reserves are estimated at 18.7 million tons of diamond ore with a grade of 3.4 to 4.6 carats per 100 tonnes (Cappa et al., 2003).

Elsewhere in the State Line district, production at the Chicken Park kimberlite complex averaged 6.7 carats per 100 tonnes; for comparison, worldwide commercial kimberlite ore grades average 5 to 680 carats per 100 tonnes (Hausel, 1998). The largest diamond found at the Chicken Park kimberlites weighed 2.6 carats (Hausel, 1998). Hausel (1998) reports production of 40,305 diamonds from the Sloan group of kimberlites with an average grade of 7.6 carats per 100 tonnes; the largest diamond recovered weighed 5.51 carats. Chromium diopside and pyrope garnet megacrysts worthy of faceting into “Cape emeralds” and “Cape rubies”, respectively, are also reported from the Sloan kimberlites (Hausel, 1998). Just outside the RGFO management region in western Larimer County, production of 89,000 diamonds is reported from the George Creek kimberlite dikes; test pits yielded grades ranging from 18 to 135 carats per tonne (Hausel, 1998). Numerous other Larimer County kimberlites have tested positive for diamonds, and most also host gem-quality garnet or chromium diopside (Hausel, 1998). The greater State Line district is designated H/D for diamond and gemstone occurrence potential; the surrounding Precambrian rocks are assigned M/C for diamond and gemstone potential.

Through 1963, production of beryl from pegmatites in Larimer County amounted to 358,790 pounds (Meeves et al., 1966). Over 1,300 beryl-bearing pegmatites have been mapped in the region surrounding the Farnsworth, Crystal Mountain, and Drake districts (Heinrich, 1957; Thurston, 1955). Beryl, chrysoberyl, and accessory gem minerals are found where several plutons of the Silver Plume-aged facies (Longs Peak–St. Vrain batholith and satellite intrusions of Mt. Olympus granite) intrude Precambrian metamorphic rocks in this region (Boos and Boos, 1934; Del Rio, 1960; Heinrich, 1957; Tweto, 1979a and 1987). In the Crystal Mountain district, a beryl crystal 6 feet long and 2 feet wide was found at the Big Boulder prospect (Eckel, 1961;

Thurston, 1955). Clusters of euhedral, bluish-green beryl crystals up to 3 feet long and 1 foot in diameter occur in tonalite pegmatites at the Hyatt Ranch mine; tourmaline is also reported (Eckel, 1961). The Hyatt zoned pegmatite, 365 feet long and up to 70 feet wide, has reported production of 50 tons of beryl from 1936 to 1955 (Thurston, 1955). Chrysoberyl crystals up to 3 inches long have been mined at the Wisdom Ranch prospects in the same district; beryl and garnet are also reported (Eckel, 1961; Vanderwilt, 1947). Well-formed black tourmaline crystals up to 4 inches long are commonly found in the greater Crystal Mountain pegmatite district; rare rose quartz is also reported (Eckel, 1961; Hanley et al., 1950; Heinrich, 1957). The greater Crystal Mountain, Farnsworth, and Drake district area is designated H/D for gemstone occurrence potential.

Tertiary topaz rhyolite is reported from Specimen Mountain along the Continental Divide in Larimer County (Christiansen et al., 1983). Specimen Mountain is well known for opal, agate, and onyx gemstones, as well as chalcedony, jasper, rock crystal, and well-formed clear to light-pink topaz; geodes are also commonly found (Eckel, 1961; Pearl, 1972). The Tertiary rocks around this mountain are designated H/C for gemstone occurrence potential.

Colorado Alabaster Supply has quarried alabaster (ornamental gypsum) from the Permian-Triassic Lykins Formation near Livermore since 1969; in 2003, 200 tons were produced (Cappa et al., 2003; Pearl, 1972). Beds of white, pinkish-white, and gray alabaster beds, some intricately banded, average 3 to 4 feet thick (Pearl, 1972). The Lykins Formation in this area is designated H/D for gemstone occurrence potential; further north and south, it is designated H/C.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the south, Precambrian felsic metamorphic rocks are designated M/C, and biotite gneisses and schists are assigned M/B, for gemstone occurrence potential elsewhere in the county (Lovering and Goddard, 1950). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954). Pegmatites are known to occur in the Longs Peak-St. Vrain batholith, and this unit is designated L/B for gemstone occurrence potential (Boos, 1954).

4.23.22 Pegmatite Minerals

Meeves et al. (1966) report production of 88,660 pounds of sheet mica and 2,022 tons of scrap mica from pegmatites of Larimer County. Pegmatites are abundant where several plutons of the Silver Plume-aged facies (Longs Peak–St. Vrain batholith and satellite intrusions of Mt. Olympus granite) intrude Precambrian metamorphic rocks in the region around the greater Farnsworth and Crystal Mountain districts, including an area to the north and northeast (Boos and Boos, 1934; Del Rio, 1960; Heinrich, 1957; Tweto, 1979a and 1987). Perthite ($KAlSi_3O_8$) and scrap mica occur in economic quantities in this region of central Larimer County (Thurston, 1955). Pegmatites in this region contain 20 to 70 percent perthite, and zoned pegmatites contain crystals as great as 10 feet in diameter (Thurston, 1955). The Hyatt Pegmatite is composed of 96 percent perthite in its core, and production of 400 tons of potash spar and 30 tons of scrap mica are reported in 1948 (Gilkey, 1960; Thurston, 1955). Production of 180 tons of scrap mica and a few hundred pounds of sheet mica is reported at the Buckhorn Mica mine through 1942 (Thurston, 1955). Several hundred tons of feldspar were produced from a pegmatite containing 80 percent microcline in its core at the Double Opening prospect (Baillie, 1962). Baillie (1962) estimates reserves at 10,000 tons of feldspar at the Big Boulder prospect. The hundreds of pegmatites and reported production earn this region a pegmatite mineral occurrence potential of H/D.

The Maysville district area is designated H/B due to one feldspar and several mica occurrences in Precambrian felsic gneiss (USGS MRDS, 2013). Elsewhere in the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B.

4.23.23 Industrial Abrasives

In the State Line district of Larimer County, kimberlite diatremes were first reported in 1964, and diamonds were first identified in 1975 (McCallum and Mabarak, 1976). Diamond reserves are estimated at 18.7 million tons of ore with a grade of 3.4 to 4.6 carats per 100 tonnes (Cappa et al., 2003). Worldwide, about 20 percent of mined diamonds are gem-quality, and 80 percent of those mined are better suited for industrial purposes (Arbogast et al., 2011). Hausel (1998) reports production of 40,305 diamonds from the Sloan group of kimberlites with an average grade of 7.6 carats per 100 tonnes; pyrope garnet megacrysts are also reported (Hausel, 1998). Numerous other Larimer County kimberlites have tested positive for diamonds, and most also host garnet (Hausel, 1998). The greater State Line district area is designated H/D for industrial abrasive occurrence potential.

Over 1,300 pegmatites have been mapped in the region surrounding the Farnsworth, Crystal Mountain, and Drake districts, where several plutons of the Silver Plume-aged facies (Longs Peak–St. Vrain batholith and satellite intrusions of Mt. Olympus granite) intrude Precambrian metamorphic rocks (Boos and Boos, 1934; Del Rio, 1960; Heinrich, 1957; Thurston, 1955; Tweto, 1979a). Garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Massive brown garnet accompanies chrysoberyl in pegmatites at the Wisdom Ranch prospect (Hanley et al., 1950). The greater Farnsworth, Crystal Mountain, and Drake pegmatite area is designated H/C for industrial abrasive potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB south of the county, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950).

Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.23.24 Limestone and Dolomite

In Larimer County, there are 3 limestone occurrences located in the Pennsylvanian-Permian Ingleside and Fountain Formations, correlative with the Maroon and Minturn Formations which host limestone occurrences in other counties. This unit is designated M/C for limestone and dolomite potential. There is one limestone quarry developed in the Permian Minnekahta and Forelle Limestones of the Lykins Formation; the Lykins Formation is designated L/C for limestone potential. The Cretaceous Greenhorn Limestone hosts one prospect in this county and others elsewhere in the State. The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale (Colorado Group) is designated M/C for limestone and dolomite occurrence potential.

4.23.25 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Significant production of industrial sands is reported from numerous DRMS-permitted operations in these units in Larimer and other counties (Schwochow, 1981). The Lykins Formation and Dakota Sandstone are designated H/D for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

Quaternary eolian sands in eastern Larimer County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential.

4.23.26 Gypsum

Most USGS MRDS (2013) gypsum occurrences in Larimer County are located in the hogbacks and foothills on the east side of the mountain front, extending from Wyoming to the Boulder

County border. Gypsum has been mined in Larimer County for many years, and it continues to be produced to this day. The DRMS has issued four permits for gypsum mines in the county, two of which are still active (the Munroe Gypsum Quarry and the Suzanne Marie mine) and one that is in temporary cessation (Boettcher Gypsum Quarry).

Gypsum is commonly reported from the Permian-Triassic Lykins Formation in Larimer and other counties: a gypsum deposit averaging 24 feet thick is exposed at the base of the Lykins Formation in a unit correlated with or identified as the Blaine Gypsum elsewhere in the RGFO region (George, 1920; Irwin, 1977; Maher, 1946). Withington (1968) reports gypsum lenses up to 50 feet thick in the Lykins Formation along the Front Range across Larimer County. Colorado Alabaster Supply has quarried alabaster (ornamental gypsum) from the Lykins Formation near Fort Collins since 1969; in 2003, 200 tons were produced (Cappa et al., 2003; Pearl, 1972). Beds of white, pinkish-white, and gray alabaster beds, some intricately banded, average 3 to 4 feet thick (Pearl, 1972). Other Larimer County quarries have produced gypsum from the Lykins Formation for industrial purposes (Withington, 1968). The Lykins Formation is designated H/D for gypsum occurrence potential.

Although no bedded gypsum is reported from within the Jurassic Morrison Formation in Larimer County, there are many reports of massive white and gray gypsum at its base in a unit almost always identified as or correlated with the Ralston Creek Formation throughout the RGFO region (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). George (1920) reports gypsum beds up to 60 feet thick below the Morrison Formation at the Garden of the Gods and Glen Eyrie in El Paso County. A massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick and traceable for 8 miles, occurs above the Permian-Triassic Lykins Formation and just below the Morrison Formation at Perry Park in Douglas County (George, 1920). Vanderbilt (1947) reports production of gypsum from the (undivided) Morrison and Ralston Creek Formations in Larimer County. The undivided Morrison and Ralston Creek Formations are designated H/D for gypsum occurrence potential.

Throughout the RGFO region, the Cretaceous Niobrara Formation and underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Also, granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Niobrara Formation and the Colorado Group (George, 1920). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential in Larimer County.

4.23.27 Helium

The southeastern corner of Larimer County is designated L/C for helium due to its location near the Denver Basin.

4.23.28 Sand and Gravel

Del Rio (1960) reports production of over 2.2 million tons of sand and gravel, primarily from alluvium, in Larimer County between 1954 and 1958. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, as well as glacial drift (Qd) and Tertiary gravels (Tgv), are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary units of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Larimer and other counties, the Paleozoic Fountain and Lykins Formations and Cretaceous Dakota and Fox Hills Sandstones and Laramie Formation host sand and gravel operations (W. D. Carter, 1968; Schwochow, 1981); these units are assigned L/C for sand and gravel potential. Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in some areas (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered M/D for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in highly weathered and disintegrated Precambrian rocks (grüs) throughout the county (Schwochow, 1981); buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.23.29 Crushed Stone Aggregate

There are several DRMS-permitted crushed stone aggregate operations in Larimer County, developed in limestone members of the Colorado Group, although limestone in the overlying Fort Hays Member of the Cretaceous Niobrara Formation may crop out in the area as well (Tweto, 1979a). The Niobrara Formation and Colorado Group may host suitable source rocks where the limestone is dense, well-consolidated, and free from abundant joints and fractures (Knepper et al., 1999; Langer and Knepper, 1995). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Colorado Group is designated H/D for crushed stone aggregate occurrence potential.

Tertiary intrusive rocks occur sporadically throughout the county; dense, fine-grained igneous rocks satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz, which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Laramide intrusive rocks meet the stringent physical and chemical standards of a good-quality crushed stone aggregate (Knepper et al., 1999) and are assigned H/C for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Longs Peak-St. Vrain and Sherman plutons and satellites in Larimer County, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed Precambrian Boulder Creek Granite is classified as only a 'fair' source rock by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Silver Plume-aged granites are designated H/C, and the Boulder Creek Granite is assigned M/C, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Fountain Formation and Permian-Triassic Lyons Sandstone and Lykins Formations, the Jurassic Morrison Formation, and the Cretaceous Dakota and Fox Hills Sandstones may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone at its contact with the Colorado Group, as well as in the undivided Lykins Formation and Lyons Sandstone, in this and Boulder Counties. The Dakota Sandstone is designated H/D, the undivided Lykins Formation and Lyons Sandstone are assigned M/C, the Fox Hills Sandstone is designated L/C, and remaining sedimentary rocks are assigned L/B, for crushed stone potential.

4.23.30 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

The Tertiary Ogallala Formation is highly weathered in part, resulting in loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds; production of volcanic ash is reported from this unit in Yuma County (Knepper et al., 1999; Schwochow, 1981). The Tertiary White River Formation is composed of ashy claystone and sandstone (Knepper et al., 1999). The Ogallala Formation is designated M/C, and the White River Formation is designated L/B, for lightweight aggregate occurrence potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the mountains of Colorado, including in Precambrian igneous and metamorphic rocks of Larimer County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). The relatively unweathered Longs Peak-St. Vrain and Sherman granitic plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

A small outcrop of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite (Arbogast et al., 2011; Knepper et al., 1999; USGS MRDS, 2013; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential

4.23.31 Clay

Over a dozen clay occurrences are noted in the USGS MRDS (2013) in Larimer County. The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone); many prospects occur in this unit in this and other counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation and Dakota Sandstone are designated H/D for clay occurrence potential. There are several clay prospects developed in the Permian-Triassic Lykins Formation along the Front Range; this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated M/C for clay occurrence potential.

Most prospects developed in the Cretaceous Graneros Shale (Colorado Group) throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). Several Larimer County clay quarries produce from the Colorado Group; this unit is assigned M/C for clay potential. The Cretaceous Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay is produced from this unit in Larimer and other counties (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential.

Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making (Vanderwilt, 1947); the Fox Hills Sandstone is designated L/C for clay potential. The Tertiary White River Formation is known to host occasional claystones suitable for use in making bricks (Vanderwilt, 1947); this unit is assigned L/B for clay potential.

4.23.32 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Larimer County hosts granites, sandstones, and conglomerates that have been quarried for dimension stone, including the Precambrian Silver Plume-aged granites, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

Silver Plume-aged granites and granodiorites have been quarried for dimension stone in the RGFO region, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Sherman and

Longs Peak-St. Vrain plutons are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B. A limited areal extent of Tertiary intrusives at the westernmost border of the RGFO portion of Larimer County is assigned L/B for dimension stone potential.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Sharps (1963) described over 30 sandstone quarries, primarily in the Lyons Sandstone, in Larimer and Boulder Counties; many buildings on the University of Colorado-Boulder campus used this material. These units are designated H/D for dimension and building stone occurrence potential; the Fountain Formation and Codell Sandstone capping the Colorado Group are assigned M/C for dimension stone potential.

Other sandstone-bearing units in the county, but without documented production of dimension stone, include the Cretaceous Fox Hills Sandstone and Tertiary White River and Ogallala Formations. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension or building stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the White River Formation and Fox Hills Sandstone are designated M/B, for dimension and building stone occurrence potential.

4.24 Las Animas County

4.24.1 Coal

The RGFO portion of the Raton Mesa Coal Region (see section 3.1.2 of this MPR), which falls entirely within Huerfano and Las Animas Counties, is host to over 380 historic coal mines (Boreck and Murray, 1979; Carroll and Bauer, 2002). Production of 187 million tons of coal between 1864 and 2002 from 261 mines developed in the Upper Cretaceous Vermejo and Raton Formations is reported in Las Animas County (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). There are 32 non-active CDRMS coal exploration and coal permits. There is one active, but idle, CDRMS coal permit between Weston and Stonewall at the New Elk mine. Of an estimated 12.4 billion tons of original coal resources under less than 3,000 feet of overburden and a realistic recoverability of 35 percent, about 4.3 billion tons of coal remain in the RGFO portion of the Raton Mesa Coal Region, which includes both Huerfano and Las Animas Counties (Brandt, 2015; Landis, 1959). The RGFO portion of the Raton Mesa Coal Region is designated H/D for coal occurrence potential. RGFO management area coal occurrence potential is shown on Map 7-1 in section 7.

4.24.2 Geothermal

Traditional / EGS Geothermal

The eastern portion of Las Animas County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The rest of Las Animas County varies from low to high EGS favorability (Augustine, 2011 and low traditional geothermal favorability with pockets of moderate favorability in the southwestern corner (Williams et al., 2008). These combinations lead to designations of L/B in the central portion, M/C in the west, H/B in a small area of the southwest, and M/B in the rest of the county.

Direct-Use / Low Temperature Geothermal

Although Barrett and Pearl (1978) did not report any thermal springs or wells in Las Animas County, Cappa and Hemborg (1995) described seven in their report: five springs and two wells with temperatures of 68 to 84^{o}F. These warm geothermal waters provide subtle hints of the system that is thought to exist in the Raton Basin, a deep Laramide-age sedimentary basin. The geothermal system was discovered by the numerous recently drilled coalbed methane wells and associated injection wells in the basin (Morgan, 2009).

Morgan (2009) and Bohlen (2012) provide information on the geothermal resource in the central part of the Raton Basin, building on the work by Dixon (2004). Pioneer Natural Resources Company is the principal private enterprise involved in methane drilling and production. It also has actively evaluated the geothermal resource, but as yet, it has released only limited data to the public (Macartney, 2011). Morgan (2009) used bottom-hole temperatures from over 1,900 drill holes to characterize the resource. These bottom-hole temperature data, including their incumbent corrections and assumptions, indicate that temperatures of 150^{o}C may exist at depths less than 5,200 feet in the east-central part of the basin where the calculated geothermal gradients are highest. Similar temperatures were thought to exist over a larger area at depths less than 8,200 feet (Morgan, 2009).

Morgan (2009) described the mean geothermal gradient from uncorrected bottom-hole temperatures as 45.3 ±12.5^{o}C/km, and a mean gradient from corrected bottom-hole temperatures as 49.2 ±11.9^{o}C/km. He reported gradients in the northeastern part of the central Raton Basin in the 40 to 70^{o}C/km range, and noted that gradients decreased to below 40^{o}C/km in the northwestern part of the central Raton Basin. He calculated the mean heat flow in the basin at 115 to 65 mW/m^2, which is about twice as high as the typical heat flow in the High Plains.

The deep geothermal resource in the central part of the Raton Basin is thought to exist in Paleozoic and Middle and Lower Mesozoic sedimentary rocks that are unlikely to have high permeability, meaning this is an enhanced geothermal system prospect (Morgan, 2009). The

Triassic Chinle Formation, Permian-Pennsylvanian Sangre de Cristo Formation, and/or Pennsylvanian Madera Formation are potential hosts of the deep geothermal reservoir.

Las Animas County contains two known wells and 5 known springs (NREL, 2016). These locations are designated as H/D for direct use. A portion of the central Raton Basin in southwestern Las Animas County coincides with COGCC fields, and is therefore designated as H/C. An area extending northeast of the Raton Basin and an area in the northwestern portion of the county are considered H/B. The rest of the county is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources.

4.24.3 Gold

Although historic gold production was not significant Las Animas County, there is a high occurrence potential around the Spanish Peaks near the La Veta mining district (shared with Huerfano County). Production of lode gold in the vicinity of West Spanish Peak, as well as placer gold along streams that drain this area, amounted to 168 ounces prior to 1908 (Budding and Kluender, 1983; Vanderwilt, 1947). Samples from an adit of the Bullseye mine contained 0.026 ounces per ton of gold (Budding and Kluender, 1983). The area around the Spanish Peaks intrusive is designated H/C. Trujillo Creek, which drains this area into Las Animas County, is assigned L/B along its upper reach.

4.24.4 Silver

Vanderwilt (1947) reports shipments of 4 tons of lead-silver ore from the Las Animas County portion of the West Spanish Peak area during 1934 to 1935. Several silver-bearing prospects (Spanish Gold mine, Uncle Sam and Little Mattie lodes) are noted in the area by the USGS MRDS (2013). The La Veta district and the surrounding area of the Spanish Peaks are assigned M/C for silver occurrence potential. Anomalous “redbed-type” concentrations of silver are noted from the Pennsylvanian Minturn Formation, and this unit is designated L/B for silver occurrence potential.

4.24.5 Copper-Lead-Zinc

According to Widmann et al. (2003), no significant copper resources have been reported in Las Animas County; however, some of the rock types may be similar to those hosting copper deposits just over the county line in the Carrizo Creek district of southwestern Baca County (described above). A buffer of the Morrison Formation / Entrada Sandstone (designated L/B) and the Dakota Sandstone / Purgatoire Formation (designated M/B) extends from the Carrizo Creek district into the southeasternmost part of Las Animas County. A buffer of the Morrison Formation / Entrada Sandstone and Dockum Group / Sheep Pen Sandstone surrounding the Allen Jones copper prospect in southern Bent County (Nelson-Moore, et al., 1978) extends into the northern portion of the county, and is designated L/B. Four tons of lead-silver ore were extracted in 1934 and 1935 from the West Spanish Peak area (La Veta district; shared with Huerfano County) in western Las Animas County (Vanderwilt, 1947), giving this area an occurrence potential of H/D. The Minturn and Sangre de Cristo Formations are designated H/B for Paleozoic redbed copper potential (Lindsey and Clark, 1995).

4.24.6 Iron

Limonite and siderite concretions are reported from a shale unit of the Cretaceous Laramie Formation near Trinidad in Las Animas County by Harrer and Tesch, 1959; this unit is called the Vermejo Formation by Harbour and Dixon (1959). A sample from the 40-foot-thick layer contained 35.03 percent iron (Harrer and Tesch, 1959). Iron concretions in the same unit are found above a coal seam at the El Moro mine; samples averaged 53.07 percent iron (Harrer and Tesch, 1959). The Vermejo Formation is designated L/C for iron occurrence potential. The Dockum Group is noted for iron occurrences in nearby Baca County, and in Las Animas County this unit is assigned L/B.

4.24.7 Manganese

Due to a single occurrence of manganese in the Dockum Group in southwestern Baca County, the Dockum group in Las Animas County is assigned L/B for manganese potential. Tertiary igneous rocks are also assigned L/B due to occurrences in similar rocks in other counties (e.g., Custer).

4.24.8 Molybdenum

There are no known occurrences of molybdenum in Las Animas County; however, a few small pockets of Tertiary intrusives are designated M/B due to occurrences in similar rocks in other counties (e.g., Custer).

4.24.9 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Las Animas County; however, 262.6 million tons of coal was produced in the Raton Mesa Coal Region (see sections 3.1.2 and 4.24.1 of this MPR), shared with Huerfano County. The Raton Mesa Coal Region is designated L/B for germanium occurrence potential.

4.24.10 Uranium

In Las Animas County, 1 pound of uranium was produced from carnotite and the rare tyuyamunite ($Ca(UO_2)_2V_2O$) hosted by the Sangre de Cristo Formation at the Virginia No. 14 mine (Nelson-Moore et al., 1978; USGS MRDS, 2013). Samples yielded a grade of 0.05 percent U_3O_8 (USGS MRDS, 2013). Carnotite is also reported from the same unit at the Fan Dyke No. 1

prospect (USGS MRDS, 2013). About 40 tons of 0.07 percent U_3O_8 ore were produced from the Sangre de Cristo Formation in Huerfano County (Nelson-Moore et al., 1978). Carnotite, autunite, and tyuyamunite are reported from numerous mines and prospects in the Sangre de Cristo Formation, and samples from Huerfano County assayed up to 0.36 percent U_3O_8 (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for uranium occurrence potential.

Several uranium prospects occur in Mesozoic sedimentary rocks in this and neighboring Bent County in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from these units is reported in Pueblo County (Nelson-Moore et al., 1978). These units in Las Animas County are designated L/B for uranium occurrence potential.

A sample from the lower Pierre Shale (Sharon Springs Member?) near the contact with the Niobrara Formation at the Airborne Anomaly occurrence measured 0.4 percent U_3O_8 (USGS MRDS, 2013). A buffer along the contact between these units in Las Animas County is designated L/B.

4.24.11 Vanadium

There are no vanadium occurrences in Las Animas County; however, historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Vanadium is reported from the Dockum Group in southwestern Baca County; the Dockum Group is designated L/B for vanadium potential. Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

Vanadium is reported from several sediment-hosted copper deposits in the Pennsylvanian Minturn Formation in Park, Fremont, and Custer Counties; samples assayed up to 0.59 percent V_2O_5 (Nelson-Moore et al., 1978; Schwochow and Hornbaker, 1985; USGS MRDS, 2013). The Minturn Formation is assigned L/C for vanadium occurrence potential.

Nelson-Moore et al. (1978) report production of 6 pounds of 0.55 percent V_2O_5 at the Anal No. 1 mine in the Oligocene Farisita conglomerate of the Huerfano Formation. Vanadium occurs with uranium in limonite-stained lenses at this and at a couple of other nearby prospects (USGS MRDS, 2013). The Huerfano Formation is designated L/B for vanadium occurrence potential.

Samples from mines in the Permian Sangre de Cristo Formation of Huerfano County host carnotite and assayed up to 4.0 percent V_2O_5 (Nelson-Moore et al., 1978). Several other Sangre de Cristo Formation prospects report high V_2O_5 grades as well, including the Parks Lode (2.6 percent) and Halls property (2.3 percent), although no production is recorded (Nelson-Moore et al., 1978). The Sangre de Cristo Formation is designated M/C for vanadium occurrence potential.

4.24.12 Limestone and Dolomite

There is only one limestone prospect in Las Animas County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; both are found throughout the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential. The Pennsylvanian Minturn and Belden Formations host limestone prospects in other counties and are designated L/C for limestone potential.

4.24.13 Industrial Sand

Quaternary eolian sands in Las Animas County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted along the Purgatoire River; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, and two DRMS-permitted quarries are reported in the Dakota Sandstone in Las Animas County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica (Vanderwilt, 1947). The Dakota Sandstone is designated H/C for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no permitted operations noted from this unit in Las Animas County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.24.14 Gypsum

Three gypsum quarries are noted in Las Animas County, all developed in the Jurassic Ralston Creek Formation (sometimes undivided from the overlying Morrison Formation) in the eastern part of the county (Schwochow, 1981; USGS MRDS, 2013). Along the Purgatoire River in Red

Canyon, a massive gypsum bed 5 feet thick caps extensively exposed Triassic “redbeds” (Darton, 1906). The Ralston Creek Formation in this region includes pink alabaster and white gypsum units (Scott, 1968a; Weist, 1965). A few tons of ornamental gypsum (alabaster) was mined from the same rock unit further east in the county (Withington, 1968). Additionally, Dockum Group rocks crop out in portions of eastern Las Animas County. The Triassic Dockum Group directly overlies the gypsiferous beds of the Upper Permian Taloga Formation, Day Creek Dolomite (anhydrite), and Blaine Gypsum (descending order), all of which correlate with the Lykins Formation, known to host gypsum in other Colorado counties (Irwin, 1977; Maher, 1946; Maher and Collins, 1952; McLaughlin, 1954). The undivided Morrison and Ralston Creek Formations, as well as the Dockum Group and undivided Upper Permian units, are designated H/C for gypsum occurrence potential.

Productive gypsum quarries in western Fremont County occur in the Swissvale Gypsum Member of the Pennsylvanian Minturn Formation, and this unit extends into western Las Animas County (Brill, 1952; Johnson et al., 1984; Tweto, 1979a; Wallace et al., 1997; Withington, 1962). In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation or the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO region, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential throughout Las Animas County.

4.24.15 Helium

Helium was discovered in the Model Anticline northeast of Trinidad in Las Animas County sometime in the 1920s and by 1931, 5,160,000 cubic feet of helium had been produced (Stilwell et al, 2011). In the 1950s, the U.S. Government controlled the Model Dome gas field as a helium reserve. Model Dome gas was produced by the Lyons Formation, with pay formations thought to be in the Triassic or Jurassic (Clair and Bradish, 1956). Helium concentration in Model Dome was 8 percent, on average. The closed structural extent of the Model Anticline, as mapped by the USGS (1947), is designated H/D based on known past production and a reserve of 261, 559,000 cubic feet of helium calculated by Clair and Bradish (1956).

4.24.16 Sand and Gravel

Numerous USGS MRDS (2013) and DRMS-permitted sand and gravel operations occur in Quaternary deposits in Las Animas County. High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terrace alluvium or gravels (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in some areas (W. D. Carter, 1968; Del Rio, 1960); this unit is considered M/D for sand and gravel potential. Sand and gravel operations are also developed in the Cretaceous Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation in this and other counties (W. D. Carter, 1968; USGS MRDS, 2013); these units are assigned L/C for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in various rock units throughout the county along rivers and tributaries; buffers around these occurrences are designated L/C for sand and gravel occurrence potential.

4.24.17 Crushed Stone Aggregate

There are numerous past DRMS-permitted crushed stone aggregate operations in Las Animas County, likely developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated H/C along its contact between the Fort Hays Member and underlying Colorado Group in the area of production, and M/C elsewhere, for crushed stone potential. The Colorado Group is designated M/B for crushed stone aggregate occurrence potential.

Tertiary basalt crops out in southern Las Animas County; dark, dense, fine-grained volcanic rocks (traprock) like basalt satisfy the physical and chemical standards for high-quality crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Tertiary basalt is assigned H/C for crushed stone potential. Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Small outcrops of Precambrian Boulder Creek Granite in the westernmost part of the county are assigned M/C for crushed stone potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Paleozoic Minturn and Sangre de Cristo Formations, the Mesozoic Dockum Group, Morrison Formation, Dakota Sandstone, Trinidad Sandstone, and Vermejo Formation, and the Tertiary Raton, Poison Canyon, Cuchara, and Ogallala Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several past DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in Las Animas County. The Dakota Sandstone is designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.24.18 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Purgatoire Formation and Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential.

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (mixed layer illite-montmorillonite) and may also be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, and the Ogallala Formation is designated M/C, for lightweight aggregate occurrence potential.

The Pennsylvanian Minturn Formation and other Cretaceous to Tertiary sedimentary units, including the Trinidad, Vermejo, Raton, Poison Canyon, Cuchara, and Huerfano Formations, bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which commonly occurs in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). A small outcrop of Boulder Creek Granite is assigned M/B for lightweight aggregate potential. Significant outcrops of mostly mafic tuffs and breccias from Tertiary basaltic flows in southern Las Animas County may host perlite, scoria, or pumice (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.24.19 Clay

The best quality refractory clays in the RGFO region are found in the Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; there are several clay prospects in these units in eastern Las Animas County and numerous others throughout the RGFO region (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; USGS MRDS, 2013; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the underlying Jurassic Morrison Formation; several USGS MRDS (2013) prospects in this unit occur in this and other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Purgatoire Formation and Dakota Sandstone are designated H/D for clay occurrence potential; the Morrison Formation is assigned M/C for clay potential.

Several prospects developed in the Cretaceous Graneros Shale (Colorado Group), the Smoky Hills Member (Niobrara Formation), and the overlying Pierre Shale throughout the RGFO region have produced a high-quality fire clay, but most prospects produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds (Arbogast, 2011; Landis, 1959b; Schultz, 1978; USGS MRDS, 2013). The Pierre Shale is assigned H/C, and the Colorado Group and Niobrara Formation are assigned M/C, for clay potential.

The Cretaceous to Tertiary Trinidad, Vermejo, and Raton Formations of southern Colorado are correlative with the Fox Hills Sandstone, Laramie Formation, and Dawson Arkose, respectively, of northern Colorado. Abundant kaolinite with significant montmorillonite occur in shale of the Cretaceous Laramie Formation and shale interbeds of the underlying Fox Hills Sandstone host clay suitable for brick making (Spence, 1980; Vanderwilt, 1947). The Tertiary Dawson Arkose commonly hosts mica clay in sandstone pockets or lenses; kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). Several USGS MRDS (2013) clay occurrences are reported from the southern Colorado equivalent rocks. The Trinidad, Vermejo, and Raton Formations are designated L/B for clay occurrence potential.

Abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). Common shale layers occur in the Tertiary Cuchara and Huerfano Formations. The Belden, Cuchara, and Huerfano Formations are designated L/B for clay occurrence potential.

4.24.20 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Las Animas County hosts rock units that have been quarried for dimension stone, including Paleozoic and Mesozoic sandstones and limestones and Tertiary sedimentary and igneous rocks (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The correlative Pennsylvanian Minturn, Fountain (northern Colorado), and Sangre de Cristo (southern Colorado) Formations host numerous sandstone and limestone beds throughout their extent; building stone production is reported from the Fountain Formation in northern counties (Arbogast et al., 2011; Cappa and Bartos, 2007; Lindvall, 1968; Schwochow, 1981). The Fountain Formation is the only conglomerate quarried for dimension stone in the RGFO region (Lindvall, 1968; Schwochow, 1981). The Minturn and Sangre de Cristo Formations are assigned M/B. Significant production of high-quality dimension stone is reported from the Dakota Sandstone throughout the Front Range, although no production is reported in southeastern Colorado from this unit (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). The Dakota Sandstone is assigned H/C for dimension stone potential; the overlying Jurassic Morrison Formation is assigned M/B for dimension stone potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in the RGFO region (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential. Production of good-quality dimension stone is reported from the overlying, undivided Cretaceous Vermejo and Trinidad Formations (Lindvall, 1968); this unit is assigned M/C for dimension stone potential.

The basal, massive, locally conglomeratic sandstone unit of the Tertiary Raton Formation is well-cemented and unweathered in part, and it holds potential for use as dimension or building stone (Johnson, 1958; 1961). The overlying Poison Canyon Formation is composed in part of massive, unweathered, buff to red arkosic sandstone that also holds potential for use as building stone (Johnson, 1958; 1961). The Cuchara Formation caps the Tertiary sedimentary units in part of the county; the Cuchara Formation hosts thin-bedded to massive, red, pink, and white, well-cemented sandstone beds which hold potential for use as dimension or building stone (Johnson, 1958; 1961). The Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). Though no dimension stone production is documented for the Raton, Poison Canyon, or Cuchara Formations, as sandstone-hosting units they are designated M/B for dimension and building stone potential; the Ogallala Formation is assigned L/B for potential. Minor Tertiary intrusive outcrops are assigned L/B for building stone potential.

4.25 Lincoln County

4.25.1 Geothermal

Traditional / EGS Geothermal

The entirety of Lincoln County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Lincoln County contains no known springs or wells. The majority of Lincoln County is considered H/B for low temperature and/or co-produced geothermal resources because it is above the 100°F temperature threshold for low temperature and co-produced resources, but outside named COGCC fields. Scattered areas within named fields are designated as H/C.

4.25.2 Uranium

There is no recorded production of uranium in Lincoln County; however, several occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.25.3 Industrial Sand

Widespread Quaternary eolian sands in Lincoln County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and one occurrence is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are reportedly developed in alluvium in Lincoln County along Big Sandy Creek; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, and there are several DRMS-permitted operations in this unit in Lincoln County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.25.4 Helium

The southeastern part of Lincoln County covers the western flank of the Las Animas Arch anticline (e.g., Sonnenberg and con Drehle, 1990). Lincoln County has an H/D designation for helium in the southeastern corner due to favorable geologic setting.

4.25.5 Sand and Gravel

High-quality sand and gravel deposits in Lincoln County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011). In northern Lincoln County, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.25.6 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Lincoln County; however, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Ogallala Formation is assigned L/B for crushed stone aggregate occurrence potential.

4.25.7 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Ogallala Formation is designated M/C, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.25.8 Clay

There are no reported USGS MRDS (2013) or DRMS clay occurrences in Lincoln County; however, the Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential.

4.25.9 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Lincoln County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B for dimension and building stone occurrence potential.

4.26 Logan County

4.26.1 Geothermal

Traditional / EGS Geothermal

The eastern portion of Logan County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). About half of the county has moderate favorability for EGS (Augustine, 2011) and low traditional favorability (USGS 2008) and is considered M/B. The northwestern portion has a low EGS favorability and therefore is designated as L/B.

Direct-Use / Low Temperature Geothermal

Logan County contains no known springs or wells. The majority of Logan County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. A few areas in the northwest are below the temperature threshold and are designated M/B.

4.26.2 Industrial Sand

Widespread Quaternary eolian sands in Logan County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential in Logan County. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium in Logan County along the South Platte River; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, and there is one permitted operation noted in Logan County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.26.3 Helium

Most of Logan County is designated L/C for helium due to its location in the Denver Basin.

4.26.4 Sand and Gravel

Del Rio (1960) reports production of over a million tons of sand and gravel, primarily from alluvium, in Logan County between 1956 and 1958. Abundant high-quality sand and gravel deposits in Logan County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Sand and gravel operations are developed in the lower sandstone and conglomerate unit of the Oligocene White River Formation in this and other counties (Cullen, 1960); this unit is designated L/C for sand and gravel occurrence potential. Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.26.5 Crushed Stone Aggregate

There is one reported past DRMS-permitted crushed stone aggregate operation developed in the Tertiary White River Formation in northeastern Logan County. Well-cemented and unweathered sandstone units in the White River and overlying Ogallala Formations may meet the requisite qualifications for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The White River and Ogallala Formations are assigned L/B for crushed stone aggregate occurrence potential.

4.26.6 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in the RGFO region from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). Suitable expandable clays may be found in the underlying Arikaree Formation, which hosts abundant volcanically derived clasts, and the White River Formation, which is composed of ashy claystones and sandstones (Knepper et al., 1999). The Ogallala Formation is designated M/C, and the White River and Arikaree Formations are assigned L/B, for lightweight aggregate occurrence potential.

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential.

4.26.7 Clay

There are two USGS MRDS (2013) fire clay occurrences in Logan County, both developed in the Cretaceous Pierre Shale; the Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential. The Tertiary White

River Formation is known to host occasional claystones suitable for use in making bricks; this unit is assigned L/B for clay potential (Vanderwilt, 1947). Fuller's earth is reported near Sterling by Patterson (1968). A few sand and/or gravel pits also produce alluvial clay from along the South Platte River in this and other counties; the alluvium mapped unit is designated L/C for clay potential.

4.26.8 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Logan County, the Tertiary White River Formation, Arikaree Group, and Ogallala Formation host sandstones in part, but have no documented production of dimension stone. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the White River Formation and Arikaree Group are designated M/B, for dimension and building stone occurrence potential.

4.27 Morgan County

4.27.1 Coal

A small portion of the Cheyenne Basin is located in northwestern Morgan County, and a small portion of the Denver Basin extends into the southwestern corner of Morgan County. Both basins are part of the Denver Coal Region (see section 3.1.1 of this MPR). No historic coal mines or production are noted in Morgan County. The Cheyenne Basin is designated H/B and the Denver Basin is assigned H/C for coal occurrence potential. RGFO management area coal occurrence potential is shown on Map 7-1 in section 7.

4.27.2 Geothermal

Traditional / EGS Geothermal

The entirety of Morgan County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Morgan County contains no known springs or wells. The majority of Morgan County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C.

4.27.3 Iron

No iron production is reported in Morgan County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from Weld and Boulder Counties, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential where it occurs in extreme northeastern and southeastern Morgan County.

4.27.4 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Morgan County; however, the Denver Coal Region in the county (see sections 3.1.1 and 4.27.1 of this MPR) is designated L/B for germanium occurrence potential.

4.27.5 Titanium

Though no titanium production is reported for Morgan County, economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone is designated L/B for titanium occurrence potential in Morgan County.

4.27.6 Uranium

Although no uranium occurrences are known in Morgan County, a large part of the county is underlain by the Laramie Formation and Fox Hills Sandstone, which host significant uranium resources in Weld County. These units in Morgan County are designated L/B for potential.

4.27.7 Vanadium

There are no reported vanadium occurrences in Morgan County; however, carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation and underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Also, minor amounts of vanadium are associated with uranium reserves in the western Cheyenne Basin in these units by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.27.8 Industrial Sand

Widespread Quaternary eolian sands in Morgan County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and a few quarries are developed in eolian sands in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, a couple past and current DRMS-permitted industrial sand operations are noted in Morgan County along Bijou Creek and the South Platte River; Quaternary alluvium is assigned M/C for industrial sand potential.

4.27.9 Helium

All of Morgan County is designated L/C for helium due to its location in the Denver Basin.

4.27.10 Sand and Gravel

Del Rio (1960) reports production of over 700,000 tons of sand and gravel, primarily from alluvium, in Morgan County between 1956 and 1958. High-quality sand and gravel deposits in Morgan County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011). The Cretaceous Fox Hills Sandstone and overlying Laramie Formation, which have been sporadically quarried on a small scale in several counties, is designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968).

4.27.11 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Morgan County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Fox Hills Sandstone is designated L/C for crushed stone aggregate occurrence potential.

4.27.12 Lightweight Aggregate

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone is composed of 20 to 40 percent moderately to highly expandable clay (mixed layer illite-montmorillonite with some deleterious kaolinite) and silt, and it may be a suitable resource for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.27.13 Clay

There are several USGS MRDS (2013) refractory clay occurrences developed in the Cretaceous Pierre Shale of Morgan County; the Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Pierre Shale and Laramie Formation are designated H/C for clay potential.

Shale interbeds of the Cretaceous Fox Hills Sandstone and the Tertiary White River Formation are known to host sporadic claystones suitable for use in making bricks (Vanderwilt, 1947); these units are designated L/C for clay potential. A couple of sand pits produce clay from the alluvium along the South Platte River in this and other counties; the alluvium mapped unit is designated L/C for clay potential.

4.27.14 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Morgan County, the Cretaceous Fox Hills Sandstone and Tertiary White River Formation, although hosting sandstones in part, have no documented production of dimension stone. As sandstones, these units are designated M/B for dimension and building stone occurrence potential.

4.28 Otero County

4.28.1 Geothermal

Traditional / EGS Geothermal

The majority of Otero County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). The southwestern corner is designated L/B due to low EGS favorability.

Direct-Use / Low Temperature Geothermal

Otero County contains no known wells or springs. Approximately the southwestern quarter of Otero County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The rest of Otero County is designated as H/B for low temperature and/or co-produced geothermal resources.

4.28.2 Uranium

There are no occurrences or reports of production of uranium in Otero County; however, several uranium prospects occur in Mesozoic sedimentary rocks in neighboring Bent and Las Animas Counties in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production from these units is reported in Pueblo County (Nelson-Moore et al., 1978). These units in Otero County are designated L/B for uranium occurrence potential.

Also, several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.28.3 Vanadium

There are no vanadium occurrences in Otero County; however, historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the

Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

4.28.4 Limestone and Dolomite

There are no operating limestone mines within Otero County, but the Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; both are found throughout the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential.

4.28.5 Industrial Sand

Quaternary eolian sands in Otero County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in other counties, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, although no production is reported for Otero County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries elsewhere assayed as high as 98.7 percent silica (Vanderwilt, 1947). Industrial sand has also been reportedly recovered from the Lytle Sandstone Member of the Purgatoire Formation (Arbogast et al., 2011). The undifferentiated Dakota Sandstone and Purgatoire Formation are designated H/C for industrial sand occurrence potential.

4.28.6 Gypsum

Three gypsum quarries are noted in nearby Las Animas County, all developed in the Jurassic Ralston Creek Formation (sometimes identified as the basal unit of the Morrison Formation), which extends into Otero County (Schwochow, 1981; USGS MRDS, 2013). Darton (1906) reports a 30-foot-thick bed of gypsum below the Morrison Formation at the Garden of the Gods (El Paso County), now recognized as the underlying Ralston Creek Formation. In Las Animas County, a massive gypsum bed, 5 feet thick, caps extensively exposed Triassic “redbeds” along Red Canyon near the Purgatoire River and likely corresponds to the Ralston Creek Formation (Darton, 1906). The Ralston Creek Formation in this region includes pink alabaster and white gypsum units (Scott, 1968a; Weist, 1965). The undivided Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential in southeastern Otero County.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO region, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). Ornamental alabaster has been produced from the Niobrara Formation and Colorado Group near La Junta in Otero County (Vanderwilt, 1947; Eckel, 1961). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential throughout Otero County.

4.28.7 Helium

The northeastern part of Otero County covers the western flank of the Las Animas Arch anticline. Although the demarcation between high and medium potential is ambiguous due to lack of drilling, northeastern Otero County has H/D and M/D designations for helium potential due to favorable geologic setting.

4.28.8 Sand and Gravel

High-quality sand and gravel deposits in Otero County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) by Tweto (1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011). The Cretaceous Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation host sand and gravel operations in other counties (W. D. Carter, 1968; USGS MRDS, 2013); these units are assigned L/C for sand and gravel potential.

4.28.9 Crushed Stone Aggregate

There are several past DRMS-permitted crushed stone aggregate operations in Otero County, likely developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has been quarried for crushed limestone in the RGFO region (Schwochow, 1981). The underlying

Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as ‘fair’ source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Cretaceous Dakota Sandstone and underlying Jurassic Morrison Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are sporadic crushed stone operations developed in the Dakota Sandstone in other counties. The Dakota Sandstone is designated L/C, and the Morrison Formation is assigned L/B, for crushed stone potential.

4.28.10 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Purgatoire Formation and Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential. The Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay and contains slightly to highly expansive illite and montmorillonite; this shale member may be a suitable resource for Leca (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B for lightweight aggregate occurrence potential.

4.28.11 Clay

The clay-bearing Jurassic Morrison Formation and Cretaceous Purgatoire Formation, Dakota Sandstone, Colorado Group (including the Graneros Shale), and Niobrara Formation (including the Smoky Hills Member) together cover about half of Otero County. Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Morrison Formation, and clay producers from this unit are reported from other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). Several prospects developed in the Graneros Shale and Smoky Hills Member throughout the RGFO region, including Otero County, have produced a lower-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The best quality refractory clays in the RGFO region are found in the Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; several past producers occur in southeastern Otero County (Arbogast et al., 2011; Patterson, 1968; USGS MRDS, 2013). The undifferentiated Purgatoire Formation and Dakota Sandstone are designated H/D for clay occurrence potential. The Morrison Formation, Colorado Group, and Niobrara Formation are assigned M/C for clay potential. A small area covered in Pierre Shale is assigned H/C for clay potential.

4.28.12 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Though no dimension stone production is reported from Otero County, the Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential.

Significant production of high-quality dimension stone is reported from the Cretaceous Dakota Sandstone throughout the Front Range, although no production of dimension stone is noted from the plains region (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). The Dakota Sandstone is designated H/C, and the underlying, sandstone-bearing Jurassic Morrison Formation is assigned M/B, for dimension and building stone occurrence potential.

4.29 Park County

4.29.1 Coal

The South Park Coal Region (see section 3.1.3 of this MPR) in north-central Park County has been a notable past producer of coal from coalbeds of the Upper Cretaceous Laramie Formation (Scarbrough, 2001). Beds are thinner (12 inches) and less exploitable in the southern extent of the region in the Hartsel district and thicken (up to 40 feet where beds are folded at the King Cole mine) towards the north in the Como district (Scarbrough, 2001). Carroll and Bauer (2002) report production of nearly 725,000 tons of coal from the King Cole and American group of mines through 2001. Production of almost 59,000 tons of coal from the No. 1 mine is reported from 1885 (Scarbrough, 2001).

Of an estimated 92.3 million tons of original coal resources under less than 3,000 feet of overburden in the county, roughly 1.5 million tons are reportedly depleted, implying reserves of 90.8 million tons of bituminous-grade coal (Carroll and Butler, 2002; Landis, 1959). Bituminous-grade coal reserves are estimated at 135 million tons by Scarbrough (2001). Coal reserves in the central and southern parts of the South Park Coal Region are likely limited (Washburne, 1910). A buffer around the northern half of the South Park Coal Field is designated H/D for coal occurrence potential; the southern half is assigned M/C. RGFO management area coal occurrence potential is shown on Map 7-1 in section 7.

4.29.2 Geothermal

Traditional / EGS Geothermal

The majority of Park County is designated as M/B for high temperature/EGS geothermal resources due to the combination of high-moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). Moderate traditional favorability in the central portion of the county (extending northwest from Elevenmile Reservoir) and high traditional favorability on the western border lead to designations of M/C, with the very western margin being considered H/C.

Direct-Use / Low Temperature Geothermal

Geothermal waters issue to the ground surface in two areas in Park County. One of the areas is Hartsel Hot Springs, where two springs discharge 118 to 126°F water (NREL, 2016). At the second area, the Rhodes Warm Spring is 79°F (NREL, 2016). McCarthy et al. (1982) conducted a geothermal resource assessment of Hartsel Hot Springs and described the springs as emerging from the lower part of the Morrison Formation, near its contact with the underlying Garo Sandstone. They discuss the various interpretations of the structural geology of the area, and conclude that it is not possible to accurately characterize the geologic structure using the available data. They map the trace of the Santa Maria Fault ~600 feet northeast of the springs and conclude that the fault may be a conduit for warm waters. They suggest that future exploration should focus on the Santa Maria Fault and the Dakota Sandstone aquifer.

McCarthy et al. (1982) also conducted electrical resistivity survey, shallow temperature measurements (~5 feet deep), and soil mercury sampling at the Hartsel area. The highest shallow temperatures, 96°F, were found immediately northeast of the springs, between the hot springs and the fault. Temperatures decreased slowly southeastward to 55ºF. The resistivity survey found a low resistivity trend that paralleled the fault. The soil mercury sampling yielded mixed results, although the mercury concentrations peaked near the fault in the sampling area north of the Town of Hartsel. They concluded that the heat source likely is either radioactive decay in the Precambrian granitic rocks or simply a higher than normal geothermal gradient, and that the heated water rises up the Santa Maria Fault. The springs may mark a zone of higher permeability along the fault zone.

Park County contains three springs in the NREL (2016) database. These locations are designated as H/D for direct use. The Hartsel A Spring, with a temperature of >122°F, has a 5 mile buffer zone that is H/D potential, as the U.S. EERE (2004) and NREL (2016) deem this the distance sufficiently hot waters can be transported for direct use. The southern half of Park County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The northern portion, except for the very northwestern corner, is H/B for low temperature and/or co-produced geothermal resources.

4.29.3 Gold

Scarbrough (2001) reports production of 1,328,369 ounces of gold from 1859 to 1982 in Park County. Through 1957, placer gold production of 342,183 ounces is reported for the county by Parker (1974). The greater Alma district, which includes the Buckskin, Horseshoe, Mosquito, Consolidated Montgomery, Pennsylvania, Sacramento, and Alma Placers subdistricts, is the most productive gold-producing region in the county. The earliest discoveries occurred along the east slope of the Mosquito Range (Henderson, 1926). The London polymetallic quartz vein deposits of the Mosquito district were discovered in 1873, and the London mine became the largest in the district, producing from 1875 to 1942 (Scarbrough, 2001). Ore bodies occur primarily in a shattered zone on the footwall of the London Fault near the base of the Minturn or Belden Formations (Scarbrough, 2001). The producing area in this district is bound by Laramide intrusives to the southwest, Silver Plume-aged granite to the north, and Precambrian biotite gneisses to the northwest. The London group of mines produced 263,273 ounces of gold, averaging 2.9 ounces per ton, through 1931 (Scarbrough, 2001). The Mosquito district, including the London group of mines, is attributed with production of over 570,000 ounces of gold from 1859 to 1956 (Scarbrough, 2001).

Among the smaller constituent subdistricts, Buckskin was first prospected in 1861. The Sawatch Quartzite is intruded by Tertiary quartz monzonite in this district. Parallel steeply dipping faults contain mineralized fault gouge (Patton et al., 1912). Where these fissure veins cut the contact between quartz monzonite sills and the Sawatch Quartzite, gold-bearing lead-zinc-silver mantos are formed. Some placer gold was also recovered within the Buckskin subdistrict in glacial and fluvial gravels. The Buckskin district produced nearly 20,000 ounces of gold from 1932 to 1957 (Scarbrough, 2001).

Other subdistricts include the Consolidated Montgomery, which is characterized by veins of gold-silver-lead-zinc in Precambrian granite and schist (the most productive), silver-gold-zinc mantos in the Devonian Parting Quartzite (base of Chaffee Group), silver-lead-copper-gold mantos in the Mississippian Leadville Limestone, and placer deposits (Scarbrough, 2001). The district produced nearly 6,000 ounces of gold between 1932 and 1956 (Scarbrough, 2001). The Sacramento subdistrict is host to at least a dozen, gold-bearing uranium mines along the southern extension of the London fault which separates the Pennsylvanian Minturn Formation and various pre-Pennsylvanian sedimentary units including the Leadville, Williams Canyon, and Manitou limestones, Harding Sandstone, Fremont Dolomite, and Chaffee Group (Tweto, 1979a; USGS MRDS, 2013). Only 1 percent of production along the London fault comes from the Sacramento district, and that occurred early on (Singewald, 1947). Though only worked until 1882, ore at the Sacramento mine assayed at 0.75 ounce per ton of gold (Singewald and Butler, 1941).

The Alma Placers district is credited with production of 20,271 ounces of gold between 1932 and 1953 (Scarbrough, 2001). The gold occurs in medium-to-coarse outwash gravels on bedrock within two terminal moraines (Vanderwilt, 1947). The Greater Alma district is mostly assigned H/D for gold occurrence potential; the Sacramento, Horseshoe, western portion of the Consolidated Montgomery, and northern portion of the Alma subdistricts are designated H/C for potential due to limited number of producers.

Northeast of the Alma Placers district lies Tarryall Creek, which drains Mount Silverheels and flows southeast across Park County to the South Platte River. The Tarryall Creek district produced 16,670 ounces of placer gold between 1932 and 1957 (Scarbrough, 2001). Additionally, numerous pyritic quartz veins host some gold within a contact metamorphic zone related to the Montgomery Gulch Stock, but the district is only credited with 72 ounces of lode gold through 1957 (Scarbrough, 2001). The Tarryall Creek district and the upper third of Tarryall Creek are designated H/D for gold occurrence potential.

Southeast of the Alma district, the contiguous Beaver Creek and Fairplay districts are credited with production of 113,324 ounces of placer gold between 1932 and 1957 (Scarbrough, 2001). Placers are found in the morainal outwash gravels, mined largely in the 1940s. The Beaver Creek district also contains some vein deposits in the Leadville Limestone. These two districts are considered H/D for gold occurrence potential.

Areas of less significant production include the Halls Gulch (Halls Valley) district where a mere 20 ounces of gold were reportedly produced between 1933 and1941 from veins in Precambrian gneiss or placers (Scarbrough, 2001). The Guffey-Micanite district hosts minor amounts of gold in a variety of environments including tungsten-copper-zinc skarns, veins and stratabound deposits in Precambrian metamorphic rocks, and Precambrian pegmatites (Scarbrough, 2001). The greater Tarryall Springs district area, including the Mountaindale and Lake George districts, produced almost incidental gold in Precambrian rock. Since gold is known to exist in these regions, they are considered to have a moderate potential of accumulation and are designated M/C. Sporadic gold occurrences are noted in the Pikes Peak batholith in this and other counties (e.g., Teller) and the batholith is designated M/B.

4.29.4 Platinum-Group Metals

Eckel et al. (1997) report a minor amount of placer platinum in Park County in the Iron Hill Placer mine and lode platinum in Mosquito Gulch. The occurrence potential for PGMs in the vicinity of the Iron Hill Placer mine in northwestern Park County is assigned L/C. The anecdotal report of lode platinum by Eckel et al. (1997) has never been substantiated, and the location is unspecified, therefore the occurrence potential for PGMs is assigned L/B for the Mosquito Gulch area in Park County.

4.29.5 Silver

Approximately 9.4 million ounces of silver was reportedly produced in Park County between 1859 and 1989, primarily from the greater Alma district (Scarbrough, 2001). The Mosquito subdistrict is credited with production of 446,698 ounces of silver from 1932 through 1956 (Scarbrough, 2001). Primary production came from polymetallic veins associated with Tertiary porphyries in the Minturn Formation, followed by mantos in the Leadville Dolostone (Scarbrough, 2001). About 237,000 ounces of silver was reportedly produced from the London mine group from 1875 to 1931 (Scarbrough, 2001). Where past producing mines are noted, these geologic units are designated H/D for silver occurrence potential in this subdistrict; elsewhere they are designated H/B.

On the east side of the Mosquito Range in the Horseshoe subdistrict, the Hilltop-Last Chance mine near the headwaters of Fourmile Creek (tributary of Sacramento Creek) produced an estimated 410,000 ounces of silver between 1901 and 1923 (Behre, 1953; Scarbrough, 2001). Tenor ranging from 6.5 to 25 ounces of silver per ton characterized ore recovered from replacement deposits chiefly in the Leadville Dolostone and secondarily from the Devonian Dyer Dolomite, both of which are separated from the Minturn Formation by the Hilltop Fault (Scarbrough, 2001). These units here are designated H/D for silver potential.

Over 131,000 ounces of silver was recovered from the Buckskin subdistrict between 1932 and 1957 (Scarbrough, 2001). The Orphan Boy mine was likely the chief producer of silver in this district, with typical tenor ranging from 10 to 25 ounces of silver per ton from mantos and replacement vein deposits in the Leadville Dolostone (Scarbrough, 2001; Tweto, 1979a; USGS

MRDS, 2013). Paleozoic units in Buckskin district area are designated H/D for silver potential. Quaternary glacial alluviums are assigned L/B for placer silver potential.

Scarbrough (2001) reports production of 79,131 ounces of silver from the Consolidated Montgomery subdistrict between 1932 and 1957. The Russia mine, one of the largest pas silver producers in the greater Alma district, produced silver from mantos in the Leadville Dolostone as well as the Ordovician Manitou Limestone (Scarbrough, 2001). Tenor averaged 14 to 18 ounces of silver per ton, but ranged up to 700 ounces per ton in areas of supergene concentration (Scarbrough, 2001). The greater Consolidated Montgomery district area is designated H/D for silver potential.

Placer silver production amounted to 20,132 ounces from 1924 to 1945, principally from glacial moraines and outwash gravels in the Fairplay, Alma Placers, Hall Valley, Beaver Creek, and Tarryall Creek districts (Scarbrough, 2001). The Fairplay district is designated H/D and the remaining districts are designated H/C for silver occurrence potential.

In the Guffey-Micanite district (shared with Fremont County), limited silver production is reported from exhalative deposits along the Currant Creek fault zone near the contact of Precambrian biotite gneiss and Boulder Creek-aged and Silver Plume-aged granites (Sheridan et al., 1990; USGS MRDS, 2013). The cluster of silver prospects along the Currant Creek fault zone is designated M/C.

No silver production is reported from the greater Tarryall Springs, Mountaindale, and Lake George district areas; however, there are several silver prospects occurring near contacts of Precambrian igneous and metamorphic rocks and/or along faults (Tweto, 1979a; USGS MRDS, 2013). Buffers around these prospects are designated L/C for silver occurrence potential except the Apex mine, which is assigned M/C, due to reported of production by Scarbrough, 2001.

There are numerous silver occurrences and minor past producers found in Precambrian felsic gneiss along faults in other counties; these rocks in Park County are devoid of USGS MRDS (2013) silver occurrences and are assigned M/B. Anomalous concentrations of silver are noted from the Pennsylvanian Minturn Formation in southwestern Park County, and this unit is designated L/B for silver occurrence potential (Scarbrough, 2001). The Pikes Peak batholith is designated M/B for silver occurrence potential due to sporadic silver occurrences in this and nearby El Paso and Teller Counties.

4.29.6 Copper-Lead-Zinc

Scarbrough (2001) compiled historic production records from USBM Minerals Yearbooks for Park County, including district details, for the years 1859-1998 (although there are no base-metal data after 1982). Park County boasts significant historic base-metals production: 3.2 million pounds of copper, 62.4 million pounds of lead, and 12.7 million pounds of zinc (Scarbrough, 2001).

Scarbrough (2001) consolidates the most productive districts in northwestern Park County into the greater Alma district umbrella, including, from north to south, the Consolidated Montgomery, Buckskin, Horseshoe, Mosquito, Pennsylvania, and Sacramento districts. Four types of base-metal deposits occur throughout the Greater Alma district (Vanderwilt, 1947). The first type of deposit occurs in pyritic quartz veins with base-metal mineralization (sphalerite, galena, and chalcopyrite) found in the London mine group (Mosquito district) along the London Fault near the base of the Pennsylvanian Minturn and/or Belden Formations (Scarbrough, 2001; Vanderwilt, 1947). The primary host rock is the 175- to 275-foot-thick quartz monzonite and rhyolite London ore porphyry zone, and mineralization is concentrated along the London Fault footwall, although some ore occurs in veins below and above the zone (Vanderwilt, 1947; Scarbrough, 2001). The leader of historic base-metal (primarily the London mine type deposits) production in Park County is the Mosquito district, southeast of Mosquito Peak, and through 1956 (last reported data) the district produced 663,150 pounds of copper, 14.5 million pounds of lead, and 598,000 pounds of zinc (Scarbrough, 2001).

The second type of base-metal deposit occurs principally in the Consolidated Montgomery and Buckskin districts in polymetallic veins of the Cambrian Sawatch Quartzite (Scarbrough, 2001). Galena, sphalerite, and minor chalcopyrite ores occupy up to 30 percent of the veins (Scarbrough, 2001). The Buckskin district produced 828,670 pounds of copper, 20.4 million pounds of lead, and 9.0 million pounds of zinc between 1875 and 1957 (Scarbrough, 2001).

The third type, previously described in the Lake County, Leadville district portion of this MPR, occurs in mantos and veins primarily in the “Blue” Member (dolomite) of the Mississippian Leadville Limestone, but also in the Devonian-Mississippian Dyer Dolomite and Ordovician Manitou Limestone (Cappa and Bartos, 2007; Scarbrough, Jr., 2001). Polymetallic replacement of Paleozoic carbonates, as well as supergene enrichment processes, in the Consolidated Montgomery, Buckskin, Horseshoe, Mosquito, and Sacramento districts produced 6-10 percent lead (galena, cerussite), 5 percent zinc (sphalerite, smithsonite, hemimorphite), and minor copper (chalcopyrite, covellite, chalcocite) ores (Scarbrough, 2001).

Lastly, polymetallic veins containing copper, lead, and zinc occur in Precambrian igneous and metamorphic rocks of the Greater Alma district (Vanderwilt, 1947). For example, galena, sphalerite, and minor chalcopyrite ores fill fissure veins and irregular pods in the Silver Plume Quartz Monzonite at the Champaign mine of the Mosquito district (Scarbrough, 2001; USGS MRDS, 2013). Due to high historic production and ubiquitous mineralization, the bulk of the Greater Alma mining district of northwestern Park County, including (in part or whole) the Consolidated Montgomery, Buckskin, Horseshoe, Mosquito, Pennsylvania, and Sacramento districts, are assigned H/D for base-metal occurrence. The northwesternmost portion of the Greater Alma district, including the northern part of the Consolidated Montgomery district, is

H/C where Precambrian rocks are found; Tertiary igneous rocks of the westernmost Greater Alma district are L/B.

South of the Greater Alma district, the Weston Pass district straddles the Park-Lake county line and is discussed in the Lake County section (4.22) of this MPR. Lead-zinc replacement deposits fill cavities along a bedding plane of a dolomitized unit ("Blue" Member) of the Leadville Limestone (Cappa and Bartos, 2007; Scarbrough, 2001; U.S. Bureau of Mines, 1989). In the Ruby mine, the base-metal sulfides (galena plus some sphalerite) are coated in their oxidized equivalents (cerussite, calamine, and smithsonite) and disseminated along a stratigraphic horizon (Del Rio, 1960). The Ruby mine produced approximately 800 tons of 22-40 percent zinc and 5-18 percent lead ore (Scarbrough, 2001). The Weston Pass district is assigned H/D and the surrounding Leadville Limestone is M/B for occurrence potential. Other Paleozoic sedimentary units bordering Tertiary intrusives in western Park County are M/B.

Occurrences of base metals in the southeastern quadrant of Park County are concentrated in two regions: the eastern Tarryall Springs-Mountaindale-Lake George districts and the southern Guffey-Micanite district (shared with Fremont County). Both regions are underlain by Precambrian igneous and metamorphic rocks which host several types of base-metal deposits. Sheridan et al. (1990) recognize two types of stratabound exhalites in these regions: Type 1 deposits, which are metamorphosed to the upper amphibolite facies and commonly contain sphalerite, gahnite, chalcopyrite, and galena, and Type 3 deposits, which are usually found in calc-silicate gneisses and commonly contain tungsten and copper. Heinrich (1981) identifies Type 1 as a copper-zinc skarn and Type 3 as an uncommon tungsten-copper skarn in this county, both of which are also described in the Chaffee and Fremont County sections (4.7; 4.16) of this MPR. Additionally, base-metal mineralization occurs in polymetallic veins within greisenized rocks in both regions (Scarbrough, 2001). Finally, disseminated chalcopyrite and bornite occur in pegmatite at the Copper King mine of the Guffey district (Scarbrough, 2001). Production data are scarce from either region, but Scarbrough (2001) reports 12,000 pounds of copper and 4,000 pounds of lead from the Guffey district in 1946-47 and 1955-56. The variety of favorable geological environments, the reported occurrences from USGS MRDS (2013), and the reported production validate an assignment of H/D for the Tarryall Springs-Mountaindale-Lake George and Guffey-Micanite regions. The Precambrian rocks surrounding these regions are M/B for gneisses and L/B for others.

Volcanic-hosted lead-zinc deposits and tungsten-copper skarns occur in Central Park County, including the Bath, Garo, and Hartsel districts, although no production is reported (Scarbrough, 2001). Base metals are found in ash and lahar deposits of the Oligocene Antero Formation (Scarbrough, 2001). Tungsten-copper (scheelite-djurleite) lenses occur in calc-silicate veins in Precambrian gneiss (Scarbrough, 2001). Lead-zinc-bearing veins are also reported in the Minturn Formation southwest of Hartsel (USGS MRDS, 2013). The Minturn and Belden Formations around Garo are M/C; south of Garo, they have the same H/B base-metal occurrence potential for redbeds discussed elsewhere. The ash-flow tuff of the Antero Formation (equivalent to the lower member of the Thirtynine Mile Andesite) is L/B.

In the north, the Tarryall Creek district has a Tertiary intrusion into Paleozoic sedimentary units that hosts mostly gold with minor base metals (Vanderwilt, 1947). Also, minor base-metal mineralization occurs in pyritic quartz veins within a zone of contact metamorphism encircling the Tertiary Montgomery Gulch Stock (Scarbrough, 2001). This area is designated M/C and the Paleozoic units and Tertiary intrusives outside the district are L/B. In northern Park County, there are several occurrences of base-metal mineralization in polymetallic veins in Precambrian gneisses in the Halls Gulch and Princeton regions (Scarbrough, 2001; USGS MRDS, 2013); these regions and the same rocks in the northeastern quadrant of the county are assigned M/B, whereas other Precambrian rocks in the quadrant are L/B.

4.29.7 Iron

Masses of magnetite, limonite, and hematite occur as replacement and contact-metamorphic deposits, likely associated with Tertiary intrusions, in the greater Tarryall Creek district (Harrer and Tesch, 1959). Magnetite as big as cobbles also occur along Tarryall Creek and its tributaries, and samples contained 51.4 percent iron. Magnetite ore, assayed at 46.7 percent iron, was mined at the headwaters of Beaver Creek (Harrer and Tesch, 1959; USGS MRDS, 2013). The greater Tarryall Creek district area is designated H/C for iron occurrence potential.

Bog-type iron deposits occur along Hall Valley where hydrous iron-oxides, chiefly limonite, have been (and continue to be) deposited (Harrer and Tesch, 1959; USGS MRDS, 2013). Several private and one USGS MRDS (2013) producers are noted along the exposure which is several miles long, 100 feet wide, and up to 6 feet thick (Harrer and Tesch, 1959). Samples assayed up to 48.4 percent iron (Harrer and Tesch, 1959). The area along Handcart Gulch and extending along the North Fork of the South Platte River is designated H/C for iron occurrence potential.

Limonite, hematite, magnetite, siderite, and manganosiderite all occur as replacement deposits near the top of the Mississippian Leadville Dolostone, and significant production is reported in Lake County (Cappa and Bartos, 2007; Harrer and Tesch, 1959). The Leadville Dolostone is assigned M/C throughout the major mining districts of northwestern Park County and L/B elsewhere. Also, ironstone concretions are reported from the Cretaceous Pierre Shale, although no production is reported (Scarbrough, 2001). The Pierre Shale throughout the county is designated L/B for iron occurrence potential.

Late-stage syenite, fayalite, phonolite, and other mafic intrusions into the Precambrian Pikes Peak batholith host iron-rich minerals (Smith et al., 1999). In the greater Mountaindale, Tarryall Springs, and Lake George district area, the Redskin stock host numerous iron occurrences and minor past producers that list iron as a secondary or tertiary commodity (USGS MRDS, 2013).

The Redskin stock is assigned H/C for iron occurrence potential; other mafic units devoid of occurrences are designated M/B. The Pikes Peak batholith is designated L/B for iron potential.

Magnetite and hematite, as masses, and pyrite as veins, occur as replacements of mostly carbonates in a contact metamorphic zone where the Upper Cretaceous-Tertiary Whitehorn stock (Calumet granodiorite) intruded the Mississippian Leadville Dolostone in Chaffee County (Behre et al., 1936; Wrucke, 1974). The Whitehorn stock is designated L/B in southwestern Park County.

Precambrian Silver Plume-related granites host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported from this unit in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B. Iron-bearing minerals (especially pyrite and magnetite) are reported in polymetallic veins, pegmatites, and stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential.

4.29.8 Manganese

Rhodochrosite crystals in a shear zone in Precambrian metamorphic rocks were mined from 1876 to 2004 at the Sweet Home mine, known as one of the best rhodochrosite sources in Colorado, in the Alma district (Arbogast et al., 2011; USGS MRDS, 2013). The nearby Fanny Barret mines (Fanny #1, #2, #3, #4) are listed as a past producer of manganese from Precambrian granite (USGS MRDS, 2013). The polymetallic replacement deposits of the Hock Hocking mine (Alma district) are found in fissure veins of the Paleozoic Minturn Formation and contain manganese oxides (Patton et al., 1912; USGS MRDS, 2013). The Iron mine (Tarryall Springs district) is listed as a past producer of manganese from Tertiary intrusive rocks in the Minturn and Belden Formations (Singewald, 1942; USGS MRDS, 2013). Rhodonite is also reported from the Tarryall Springs district by Scarbrough (2001). The Black Mountain deposit yielded manganese from the Oligocene Thirtynine Mile Andesite in the Black Mountain district of southern Park County (Scarbrough, 2001; USGS MRDS, 2013). Scarbrough (2001) theorizes that devitrified volcanic rocks were subsequently mineralized with manganese. Wells et al. (1952) further add that the low-grade ore of Black Mountain occurs as manganese nodules, and beneficiation readily concentrates it to 44 to 65.6 percent manganese. Precambrian metamorphic and igneous rocks around the Greater Alma and Tarryall Springs districts, as well as the Thirtynine Mile Andesite in southern Park County are considered M/C for manganese potential. Precambrian metamorphic and igneous rocks elsewhere in the county are assigned a potential of L/B due to occurrences elsewhere in Park and neighboring counties (e.g., Jefferson, Chaffee, Lake, and El Paso).

4.29.9 Molybdenum

In Park County, molybdenum occurs as an accessory mineral in greisen-hosted beryllium deposits, tungsten skarns, and polymetallic veins in Precambrian igneous (especially Silver Plume Granite) and metamorphic rocks (Scarbrough, 2001). Numerous molybdenum occurrences are reported in beryllium mines within the greisenized Precambrian Redskin granitic stock within the Pikes Peak batholith in the Mountaindale district (USGS MRDS, 2013). The Redskin mine was originally developed for molybdenum in 1919 and some ore was shipped during WW I (Scarbrough, 2001). Tungsten- or tungsten-copper skarns contain molybdenite in several mines in the nearby Tarryall Springs and Lake George districts (Heinrich, 1981; Scarbrough, 2001; USGS MRDS, 2013). The greater Tarryall Springs district area, where molybdenum occurrences are reported, is designated H/C for molybdenum potential.

In the Guffey district, molybdenite occurs in veinlets and fractures in Idaho Springs Formation gneiss at the Crescent mine (Scarbrough, 2001). Molybdenum occurs in veins of Precambrian granite at the White Swan site in the Alma district (Scarbrough, 2001). These occurrences are designated M/C for molybdenum potential. Tertiary intrusive rocks elsewhere are M/B. Precambrian metamorphic and igneous rocks in the rest of the county are assigned L/B.

4.29.10 Nickel

Several prospects (Osiris property; Osirio mines), in the Princeton-Crosson district (shared with Jefferson County) in Precambrian amphibole schist (Idaho Springs Formation) near the boundary with the Pikes Peak granite, are recorded as past-producers of nickel (USGS MRDS, 2013). Precambrian metamorphic and igneous rocks throughout the county are designated L/B due to these occurrences and others in similar rocks in nearby counties.

4.29.11 Tungsten

Three distinct clusters of tungsten-bearing mines, in several distinct environments, occur in Park County. The Alma district to the northwest, Guffey district to the southeast, and the Tarryall Springs-Lake George-Mountaindale combined district area are home to numerous tungsten mines and prospects, although only a few have reported production. Concentrations of tungsten are found in Type 3, stratabound exhalative deposits, tungsten- or tungsten-copper skarns, tungsten-bearing greisens, in contact metamorphic zones, and with gold in glacial drift (Hawley, 1969; Hawley and Wobus, 1977; Heinrich, 1981; Sheridan et al., 1990; USGS MRDS, 2013). The favorable geologic rocks, Precambrian biotite or calc-silicate gneisses (Idaho Springs Formation) and Boulder Creek Granite, are host to most of the deposits.

Like the nearby Climax mine (Lake County), the Sweet Home mine (Alma district) contains tungsten as hübnerite in a northeast-striking quartz vein in Precambrian biotite gneiss (Lemmon and Tweto, 1962). One thousand pounds of hübnerite, assayed at 2 percent WO_3, was reportedly shipped (Belser, 1956). Hübnerite in pyritic quartz veins in biotite gneiss is also reported in the nearby Wheeler and Andes (South Platte Gulch) mines, although only minor production is reported (Belser, 1956; Lemmon and Tweto, 1962). Just to the southeast, tungsten occurs with gold as placer deposits in glacial drift (USGS MRDS, 2013). Due to minor production, despite favorable host rocks, the Alma area is designated H/C for tungsten potential; the Alma placer area is L/C.

Sheridan et al. (1990) list four Type 3, tungsten-bearing stratabound exhalative deposits in the Park County portion of the Guffey district. Type 3 deposits occur in lenses or disseminated in calc-silicate gneisses and typically contain tungsten as scheelite, sometimes in association with powellite as part of the solid solution series with molybdenum (Sheridan et al., 1990). Idaho Springs Formation gneisses and Boulder Creek Granite, both cut by pegmatites, underlie the Guffey district, and scheelite-bearing lenses and pods within the gneiss are found at the B&G claim, West deposit, School Section prospect, and Lues Gulch (Skinney) prospect (Belser, 1956; Heinrich, 1981). Heinrich (1981) classifies these deposits as tungsten skarns. A School Section prospect assay found 0.84 percent WO_3 (Belser, 1956). Scheelite is rimmed in powellite at the West Deposit, and the two minerals occur together at the Crescent mine (Heinrich, 1981; USGS MRDS, 2013). Several other occurrences are noted in the area, within the same favorable rock host, and—like the Fremont County portion of the Guffey district—a tungsten occurrence potential of H/D is assigned.

Sheridan et al. (1990) list six Type 3, tungsten-bearing stratabound exhalative deposits in the greater Tarryall Springs district. These six plus another nine occurrences are identified as tungsten skarns by Heinrich (1981). The deposits occur as lenses or are disseminated in Idaho Springs Formation gneiss and sometimes amphibolite, frequently in proximity to pegmatites (Heinrich, 1981). Assays of five of these occurrences range from 0.60 to 1.82 percent WO_3, and over 28 tons of WO_3 ore were shipped from the Round Mountain Group and Jasper Queen mines during WW II (Belser, 1956; Heinrich, 1981).

In addition to scheelite-bearing exhalative deposits or skarns, wolframite is found in the Precambrian beryllium greisens, which are highly altered rocks from granitic sources, and associated northeast-trending veins (Hawley, 1969). The Tarryall Springs area greisens are associated with the Redskin, Tarryall, and Lake George plutons of the Pikes Peak batholith and typically host small amounts of tungsten and molybdenum (Hawley, 1969). A few of the MRDS (2013) occurrences are listed as past producers (most likely of beryllium), but no data are reported. The greater Tarryall Springs region where occurrences are reported is designated H/D for occurrence potential; the same rocks in surrounding areas are H/C. Other igneous and metamorphic rocks in the county, including Pikes Peak granite, are L/B.

4.29.12 Beryllium

Through 1963, production of beryl from pegmatites in Park County amounted to 61,566 pounds (Meeves et al., 1966). Beryllium is found in numerous pegmatites throughout the Mountaindale, Tarryall Springs, Lake George, and Guffey-Micanite districts, primarily at contacts of Precambrian granite (Boulder Creek batholith facies) and gneiss. The Meyers Ranch pegmatite (Guffey-Micanite district) produced an estimated 25 tons of beryl between 1930 and 1950, and the Big Horn Sheep pegmatite (Tarryall Springs district) produced about 10 tons of beryl (Hanley et al., 1950; Scarbrough, 2001). The Guffey-Micanite district area is considered H/D due to past production from pegmatites such as the Meyers Ranch, an estimated beryl reserve of 38 to 150 tons, as well as favorable geological and structural features (Hanley et al., 1950).

The Boomer mine in the Badger Flats area (Mountaindale district) was a major producer of non-pegmatitic beryllium (beryl, bertrandite, and euclase) starting in 1956 after the discovery of high grade vein-type beryllium ore (Meeves 1966). The Boomer mine produced 678 tons of up to 11.2 percent BeO ore; production lasted until about 1965 (Scarbrough, 2001). Much of the ore occurs in greisen, a granular rock composed of quartz and muscovite, in association with topaz, fluorite, molybdenum, tin, and/or tungsten; the greisens are formed from the alteration of granitic intrusives by late stage differentiates (Hawley, 1969). Mineralized tabular fissure veins range from a few inches up to 10 feet thick in shear zones along the potassic Redskin granitic stock and at the contact of Precambrian granite and gneiss (Brady, 1975; Hawley, 1969; Meeves, 1966). The occurrence potential for beryllium in Park County is H/C surrounding the Redskin stock, as well as the greater Mountaindale, Tarryall Springs, and Lake George districts. A buffer zone of Precambrian rocks immediately surrounding this area is assigned M/B due to favorable geological and structural features.

The Pikes Peak batholith is assigned M/B for beryllium potential due to beryllium occurrences associated with pegmatites in other counties. Granitic rocks in the rest of the county are designated L/B.

4.29.13 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Park County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Production of 12.7 million pounds of zinc is recorded through the 2000s in Park County, primarily in the greater Alma district; sphalerite ores are commonly reported from the many zinc mines (Del Rio, 1960; Henderson, 1926; Scarbrough, 2001; USGS MRDS, 2013; Vanderwilt, 1947). Production of 598,000 pounds of zinc is reported from mines developed in the quartz monzonite and rhyolite London ore porphyry zone along the London Fault footwall (Scarbrough, 2001). Also, galena, sphalerite, and minor chalcopyrite ores occupy up to 30 percent of polymetallic veins in the Cambrian Sawatch Quartzite around the Buckskin district; 9.0 million pounds of zinc were produced here between 1875 and 1957 (Scarbrough, 2001). Buffers around clusters of known zinc mines or individual mines are assigned H/B for gallium, germanium, and indium occurrence potential in the Alma and Buckskin districts and M/B elsewhere.

The South Park Coal Region lies in the north-central part of the county (see sections 3.1.3 and 4.29.1 of this MPR), and nearly 725,000 tons of coal were produced (Carroll and Bauer, 2002). The coal region is designated L/B for germanium occurrence potential.

4.29.14 Rare Earth Elements

The composite Pikes Peak batholith hosts the most REE-enriched pegmatites in the United States (Simmons and Heinrich, 1980). The pink Pikes Peak granite assayed up to 853 ppm total REE oxides, about 4 times the normal crustal abundance (Smith et al., 1999). In Park County, the potassic Tarryall quartz monzonite and sodic Lake George syenite intrusions assayed up to 398 and 904 ppm total REE oxides respectively (Smith et al., 1999). Beryllium-bearing, non-zoned pegmatites in the Lake George area (e.g., Teller mine and Christie Ward-Lucky Thirteen 1&2 claims) host allanite, euxenite, gadolinite, monzonite, samarskite, xenotime, and yttrofluorite in pegmatites; both are listed as producers (Adams, 1968; Haynes, 1960; Olson and Adams, 1962; Scarbrough, 2001; USGS MRDS, 2013). About 5,000 pounds of gadolinite and 10,000 pounds of yttrofluorite were recovered from the Teller mine pegmatite (Scarbrough, 2001). A buffer around the Teller mine is designated H/D for REE occurrence potential; the composite Pikes Peak batholith elsewhere, including the Lake George and Tarryall stocks, the Rosalie Lobe, and the greater Tarryall Springs pegmatite region, is designated M/C for REE potential.

In the Guffey-Micanite district area, shared with Fremont County, beryllium-bearing pegmatite pods and lenses up to 130 feet wide and 375 feet long occur in Precambrian granite and gneiss and host monazite, euxenite, and allanite (Adams, 1968; Olson and Adams, 1962; Scarbrough, 2001). Euxenite, allanite, and monazite are also reported from the Baumer and Meyers Ranch pegmatites (Heinrich and Bever, 1957). Small pegmatites in Precambrian gneiss host monazite and euxenite in the Hartsel district; no production is reported (Scarbrough, 2001). Areas around reported REE occurrences at pegmatite mines are assigned L/C for REE occurrence potential.

4.29.15 Niobium-Tantalum

Meeves et al. (1966) report production of 2,020 pounds of niobium-tantalum minerals from pegmatites in Park County through 1963. Beryl-bearing pegmatites in Precambrian crystalline rocks host columbite and tantalite in the greater Tarryall Springs and Guffey-Micanite district areas of Park County (Scarbrough, 2001). Analysis revealed that samples from the northeast-trending Meyers Ranch pegmatite in the Guffey district contained up to 48.3 percent Nb_2O_5 and 26.5 percent Ta_2O_5, and the deposit yielded one ton of columbite-tantalite ore (Hanley et al., 1950; Scarbrough, 2001). Columbite crystals range up to 4x3x2 inches in size, and reserves were estimated at 15 to 30 tons of columbite in 1950 (Hanley et al., 1950). Also, euxenite and samarskite are reported from a couple of pegmatites (e.g., Katydid mine) associated with the Lake George pluton (Nelson-Moore et al., 1978). Buffers along noted USGS MRDS (2013) pegmatite occurrences are designated L/C for niobium-tantalum occurrence potential, except the Meyers Ranch pegmatite area which is designated H/C due to production and estimated reserves.

Euhedral fergusonite crystals, as well as microlite and samarskite, are reported from several of over 50 zoned pegmatites in the Pikes Peak batholith within the South Platte Pegmatite district of Jefferson County, which extends into the northeastern corner of Park County (Haynes, 1965; Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite (Simmons and Heinrich, 1980). Buffers along pegmatite zones in Pikes Peak Granite in the greater South Platte Pegmatite district of Park County are designated L/B for niobium-tantalum occurrence potential.

4.29.16 Tellurium

Telluride minerals were identified in mine dumps at the Alma district by Geller (1993). The Greater Alma district of northwestern Park County is considered H/C because of known occurrences of telluride minerals, as well as numerous copper and gold mines. Precambrian rocks in the remainder of the county are assigned an occurrence potential of L/B.

4.29.17 Titanium

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals, and several past producers are noted from El Paso and Teller Counties (Smith et al., 1999; USGS MRDS, 2013). Mapped alkalic and mafic intrusions in the Pikes Peak batholith in Park County are designated L/B for titanium potential.

Potential economic concentrations of rutile, in association with topaz and sillimanite, occur on the border of Clear Creek and Jefferson Counties in Precambrian interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite (Sheridan and Marsh, 1976; Sheridan et al., 1968). This unit is designated L/B in Park County. Titanium is listed as a tertiary commodity at the Meyers Ranch feldspar and mica mine in the Guffey-Micanite district; a sample assayed 2.64 percent TiO_2 (USGS MRDS, 2013). A buffer around this mine is designated L/C for titanium potential.

Precambrian, northwest-trending, mafic dikes in Larimer and Boulder Counties host titaniferous magnetite, and titanium occurrences are noted in both counties (Eggler, 1968; USGS MRDS, 2013). Buffers along several Precambrian mafic dikes in the South Park basin are designated L/B for titanium potential.

4.29.18 Uranium

Through 1978, 5,532 pounds of uranium were produced from several small mines in Park County (Nelson-Moore et al., 1978). The Lucky Jim mine produced 2,267 pounds of uranium from 741 tons of ore with an average grade of 0.18 percent U_3O_8 (Nelson-Moore et al., 1978). Here, autunite was mined from stratiform carbonaceous lenses in tuffaceous siltstones along a fault in the Oligocene Antero Formation northeast of Hartsel (Nelson-Moore et al., 1978). The Antero Formation in this area is designated H/C for uranium occurrence potential.

The Garo (Shirley May) Deposit was first prospected in 1903 and produced 40 tons of 1 percent uranium ore in 1919, and another 593 pounds of U_3O_8 was recovered from 180 tons of 0.16 percent uranium ore in 1952 (Nelson-Moore et al., 1978; Wilmarth, 1959). Torbernite and carnotite were mined from carbonaceous layers of the Jurassic Morrison Formation and redbeds of the Pennsylvanian Maroon Formation (Nelson-Moore et al., 1978; Wilmarth, 1959). Also, several uranium prospects occur in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group in other counties, as well. (Nelson-Moore et al., 1978; USGS MRDS, 2013). These groups in Park County are designated H/C for uranium occurrence potential.

Over 2,300 pounds of U_3O_8 and significant vanadium were obtained from about 550 tons of ore produced from several mines near Kenosha Pass (Nelson-Moore et al., 1978). The uranium was produced from fractures and shear zones in Precambrian crystalline rocks at the Gem Dandy, Tedco, and MacGeorge mines, where ore assays averaged slightly over 0.2 percent U_3O_8 (Nelson-Moore et al., 1978). A buffer along the main fault is designated H/C for uranium potential. Numerous base- and precious-metal mines along the London Fault report uranium, and the units around the fault are designated H/C for uranium potential. Buffers along several other faults hosting uranium occurrences are designated M/C.

A number of occurrences are associated with veins filling faults and fissures, as well as shear zones, in the Precambrian Pikes Peak Granite, Idaho Springs Formation gneiss and schist, and Silver Plume-aged granites including the Kenosha, Cripple Creek, Tarryall, Redskin, and Lake George plutons (Nelson-Moore et al, 1978; Scarbrough, 2001). Although these mines produced significant quantities of precious metals and base metals, very little uranium production was reported. Buffers around these occurrences are designated M/B or L/C for uranium occurrence potential.

Significant uranium production is reported from the Tertiary Echo Park Formation and Tallahassee Creek Conglomerate in association with the overlying Wall Mountain Tuff and lower member of the Thirtynine Mile Andesite (respectively) in both Teller and Fremont Counties (Hon, 1984; Nelson-Moore et al., 1978). Samples from various past-producing mines in these counties from this unit assayed up to 0.44 percent U_3O_8 (Nelson-Moore et al., 1978). In Park County, the Hass group of mines produced 32 pounds of U_3O_8 from 0.1 percent ore in this unit (Nelson-Moore et al., 1978). The Tallahassee Creek Conglomerate, Echo Park Formation, Wall Mountain Tuff, and Thirtynine Mile Andesite are designated H/B for uranium occurrence potential; the area around the Hass group of mines is assigned H/D; other Tertiary intrusives throughout the county are assigned L/B. In the greater Tarryall Springs-Lake George area, numerous beryllium-bearing pegmatites host uranium in Precambrian igneous and metamorphic rocks. This area is designated M/C for uranium potential.

4.29.19 Thorium

There is no thorium production noted for Park County; however, thorium occurs in veins and pegmatites along northwest-trending faults in Precambrian crystalline rocks in Park and several neighboring counties. Buffers along faults in Precambrian crystalline rocks are designated L/C for thorium occurrence potential where USGS MRDS (2013) occurrences are clustered and L/B elsewhere.

4.29.20 Vanadium

In Park County, about 180 tons of 0.71 percent V_2O_5 ore were recovered from mineralized lenses near fault intersections in the Pennsylvanian Minturn Formation at the Garo (Shirley May) uranium-vanadium copper deposit (Nelson-Moore et al., 1978). Tyuyamunite, metatyuyamunite, and volborthite ($Cu_3V_2O_7(OH)_2$) are reported from the Garo Deposit, and samples assayed up to 4.34 percent V_2O_5 (Nelson-Moore et al., 1978; Wilmarth, 1959). At the Goermer Lease near Guffey, 4 pounds of vanadium were produced from 0.3 tons of 0.59 percent V_2O_5 ore from the Minturn (Nelson-Moore et al., 1978). The Minturn Formation is designated H/D for vanadium occurrence potential in the area surrounding the Garo Deposit; elsewhere it is assigned L/C.

At the Amrine and Perrigue claims (Lady Elk uranium lode), 180 pounds of vanadium were recovered from 45 tons of 0.20 percent V_2O_5 ore near the juncture of the evaporite facies of the Minturn Formation and Ordovician Harding Quartzite (Nelson-Moore et al., 1978). A buffer around this mine is assigned H/C for vanadium potential.

In northern Park County, 43 pounds of vanadium were produced from 372 tons of 0.01 percent V_2O_5 ore in mineralized fissures in a shear zone of the Precambrian Silver Plume-aged quartz monzonite (Kenosha pluton) at the Gem Dandy mine (Nelson-Moore et al., 1978; USGS MRDS, 2013). The nearby Tedco and MacGeorge mines, also worked near intersecting faults in Kenosha granite, yielded another 36 pounds of vanadium (Nelson-Moore et al., 1978). The Kenosha granite is this area is designated H/C for vanadium occurrence potential.

Significant uranium and vanadium production is reported from the Eocene Echo Park Formation and overlying Oligocene Tallahassee Creek Conglomerate in Fremont County (Nelson-Moore et al., 1978). Remnants of Echo Park Formation and Tallahassee Creek Conglomerate in Park County are assigned H/C for vanadium potential.

Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

Carnotite and tyuyamunite are reported in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone of Weld County (Nelson-Moore et al., 1978; USGS MRDS, 2013). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone throughout the county are designated L/B for vanadium occurrence potential.

4.29.21 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, as well as Tertiary intrusives, all of which are found in Park County (Wallace, 2010). The Pikes Peak composite batholith comprises the main granitic body plus numerous late-stage peraluminous to peralkaline granitic plutons and pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999; Tweto, 1987). Fluorite is a primary accessory mineral in all phases of the Pikes Peak composite batholith and related pegmatites; the composite batholith averaged 2,140 to 3,500 ppm fluorine and ranged up to 100,000 ppm (Wallace, 2010). Several fluorspar prospects are developed in the Park County portion of the batholith (USGS MRDS, 2013). Fluorite is a common accessory mineral in the many beryl-bearing greisens developed in Precambrian igneous and metamorphic rocks of the greater Tarryall Springs-Mountaindale-Lake George district area (Brady, 1975; Hawley, 1969; Wallace, 2010). In the Lake George district, blue and colorless fluorspar occurs in *en echelon* northwest-striking, northeast-dipping veins and fissures; the Kyner mine produced almost 100 tons of metallurgical-grade fluorspar (Brady, 1975). The area around the Kyner mine is designated H/D for fluorspar occurrence potential; Precambrian igneous rocks elsewhere, including all phases of the Pikes Peak batholith, are designated H/C for fluorspar potential. Precambrian biotite gneiss is assigned M/C, and hornblende gneiss is assigned M/B, for fluorspar potential.

In the Kenosha Pass area, a fissure vein, 3- to 15-feet wide and traceable for 3,000 feet, hosts green and purple fluorite in Precambrian biotite gneiss near a contact with Silver Plume Granite; the deposit was worked from 1913 to1914 and again in 1943 (Aurand, 1920; Brady, 1975; Del Rio, 1960). In the Alma district, a Tertiary Climax-type hydrothermal pulse, related to the Climax molybdenum deposit just 8 miles to the northwest, generated fluorite-bearing veins in Precambrian biotite gneiss; translucent, purple, cubic crystals up to a half inch in diameter are found in this area (Aurand, 1920; Brady, 1975; Eckel, 1961; Lüders et al., 2009; Wallace, 2010). Precambrian biotite gneiss and Tertiary intrusives are assigned M/C for fluorspar potential.

4.29.22 Diamond and Gemstones

Outstanding deep-red rhodochrosite crystals, some displayed in museums around the world, have been extracted from the Sweet Home gemstone mine in the Alma district of Park County since 1876 (Lüders, 2009; Scarbrough, 2001). A Tertiary Climax-type hydrothermal pulse, related to the Climax molybdenum deposit just 8 miles to the northwest, resulted in rhodochrosite-, topaz-, and fluorite-bearing veins and widespread alteration of Precambrian gneissic wallrock in this area (Lüders et al., 2009). The USGS MRDS (2013) estimates production of $5 million of rhodochrosite specimens since 1876 from this deposit. A buffer around the Sweet Home gemstone mine is designated H/D for gemstone occurrence potential.

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, all of which host pegmatites, some of which bear gemstones (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999). The Crystal Peak pegmatites, famous for gem-quality amazonite, topaz, smoky quartz, amethyst, and fluorite, are located on the eastern perimeter of the sodic Lake George ring complex, which spans the Park-Teller County border (Eckel, 1961; Kile and Eberl, 1999; Pearl, 1972; Smith et al., 1999). This area has been worked since 1865, having produced amazonite crystals up to 18 inches in length and smoky quartz crystals weighing 52 pounds (Eckel, 1961; Pearl, 1972). A smaller late-stage intrusion, which spans the Park-Jefferson county line north of the Lake George pluton, also hosts pegmatites, and two gemstone prospects produced topaz, fluorite, and quartz from zoned quartz monzonite porphyry (Simmons and Heinrich, 1980; Smith et al., 1999; USGS MRDS, 2013). Well-developed blue and white topaz crystals, weighing up to 50 pounds and up to 2 feet long, were recovered at the McGuire group of deposits in this area (Simmons and Heinrich, 1980). Buffers around the Lake George ring complex and the smaller intrusion to the north are designated H/D for gemstone occurrence potential.

Clusters of feldspar- and beryl-bearing pegmatites are found throughout the greater Guffey-Micanite district, shared with Fremont County (Martin, 1993; Meeves et al., 1966). Gem-quality crystals of beryl, garnet, black tourmaline, and rose quartz have been recovered (Heinrich, 1957). The Meyers Ranch pegmatite produced an estimated 25 tons of beryl between 1930 and 1950 (Hanley et al., 1950; Scarbrough, 2001). Bright-blue to yellow euhedral beryl crystals up to 10 inches in diameter were recovered from this northeast-trending pegmatite; abundant gem-quality rose quartz and tourmaline crystals are also reported (Hanley et al., 1950; Pearl, 1972; Scarbrough, 2001). The Meyers Ranch pegmatite area is designated H/D, and the greater Guffey-Micanite district elsewhere is designated H/C, for gemstone occurrence potential.

The Boomer mine in the Badger Flats area (Mountaindale district) was a major producer of non-pegmatitic beryllium (beryl, bertrandite, and euclase) starting in 1956 and produced 678 tons of up to 11.2 percent BeO ore (Meeves et al., 1966; Scarbrough, 2001). Much of the beryl occurs in greisenized portions of the Redskin stock or Cripple Creek (Silver Plume) pluton in association with topaz and fluorite; some gem-quality aquamarine crystals also occur (Hawley, 1969). Large bodies of massive garnet containing good crystals are reported from the Mountaindale district region (Eckel, 1961). Beryl, fluorite, and topaz are reported from mines developed in the Redskin stock (Eckel, 1961; Scarbrough, 2001; USGS MRDS, 2013). Black tourmaline crystals up to 6 inches long were recovered from Wilkerson Pass (Eckel, 1961; Pearl, 1972). The greater Tarryall Springs-Lake George-Mountaindale districts area, including the Lake George, Tarryall, and Redskin stocks, is designated H/D for gemstone occurrence potential.

Large crystals and clusters of blue-to-white barite crystals up to 5 inches long have been recovered from the Pennsylvanian Minturn Formation in the Hartsel district (Eckel, 1961; Pearl, 1972; Scarbrough, 2001). Several agate and chalcedony prospects are also reported from the area between Hartsel and Antero Junction (Eckel, 1961). The Minturn Formation in the Garo area, north of Hartsel, hosts abundant blue agate and fluorescent chalcedony (Pearl, 1972). The Minturn Formation in this area is designated M/C for gemstone occurrence potential.

Peridot (gem-quality olivine) crystals have been recovered from Tertiary vesicular basalt that caps mesas near Badger and Herring Creeks in southwestern Park and northwestern Fremont Counties (Arbogast et al., 2011; Cappa, 2007). This mapped unit is designated M/C for gemstone occurrence potential.

Amazonite, smoky quartz, topaz, and amethyst occur sporadically throughout the Pikes Peak region, including the Rosalie Lobe (Lone Rock pluton) in northern Park County (Arbogast et al., 2011, Pearl, 1972). The Pikes Peak granite outside areas of gemstone occurrences is assigned M/C for gemstone potential. Zoned pegmatites are known to occur in Silver Plume-aged plutons, and the correlative Indian Creek, Kenosha, Cripple Creek, and St. Kevin plutons in Park County are assigned L/B for gemstone potential (Boos, 1954, Boos and Aberdeen, 1940). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian felsic metamorphic rocks are designated L/C, and biotite gneisses and schists are assigned L/B, for gemstone occurrence potential in Park County (Lovering and Goddard, 1950). The lower occurrence potential of gemstones in Precambrian metamorphic rocks of Park County compared to other counties (e.g., Boulder or Clear Creek) is due to the relative lack of known gemstone, beryl, and fluorite prospects and commercially developed pegmatites in these rocks outside the Lake George-Tarryall Springs area.

4.29.23 Pegmatite Minerals

Meeves et al. (1966) report production of 504 tons of scrap mica from Park County pegmatites through 1963. Martin (1993) estimates production of several thousand tons of feldspar and several hundred tons of mica from the Guffey-Micanite district (shared with Fremont County). An estimated 200 tons of feldspar and 150 tons of scrap mica have been produced through 1942 from pegmatites intruded in Precambrian biotite gneiss adjacent to Tertiary intrusives at the Meyers Ranch mine of the Guffey-Micanite district (Baillie, 1962; Hanley et al., 1950). Subhedral crystals of microcline average 6 feet in length and 8 inch books of muscovite could be recoverable as sheet mica (Hanley et al., 1950). Also in this district, the Famous Lode and Little Joe mica prospects produced a small amount of 60 percent mica from pegmatites in Tertiary intrusive rocks adjacent to Precambrian biotite gneiss (Hanley et al., 1950; USGS MRDS, 2013).

Numerous small microcline- and muscovite-bearing pegmatites have been mined in the greater Tarryall Springs-Mountaindale-Lake George district area (Scarbrough, 2001). The USGS MRDS (2013) reports production of 90 tons of feldspar per week in 1942 from pegmatites in Precambrian biotite gneiss adjacent to Boulder Creek-aged granite at the Daniels mine. In September 1944, daily production of 15 tons of feldspar was reported from the mineralized hanging wall between the Pikes Peak granite and Precambrian Silver Creek-aged quartz monzonite (Cripple Creek pluton?) at the Blue Bird mine (USGS MRDS, 2013).

Clusters of pegmatites in the Guffey-Micanite and greater Tarryall Springs districts are designated H/D for pegmatite occurrence potential. The area around the Lake George pluton (shared with Teller County) and reported past producers is designated H/C for pegmatite occurrence potential. Elsewhere in the county, Precambrian felsic metamorphic rocks in proximity to Precambrian plutons are designated H/B for pegmatite mineral occurrence potential; biotite gneisses and schists are M/B. Precambrian plutonic rocks are considered L/B except the Pikes Peak batholith which is designated M/C.

4.29.24 Industrial Abrasives

There is no reported production of industrial abrasives in Park County; however, garnets are known to occur in abundance in contact-metamorphic and calc-silicate layers of Precambrian rocks, as well as pegmatites, in Colorado (Eckel, 1961; Lovering and Goddard, 1950). Clusters of pegmatites in Precambrian metamorphic rocks are found throughout the greater Guffey-Micanite district, shared with Fremont County (Martin, 1993; Meeves et al., 1966). A buffer around these pegmatite clusters is designated H/C for industrial abrasive potential.

Numerous small pegmatites have been mined in the greater Tarryall Springs-Mountaindale-Lake George district area (Scarbrough, 2001). Large bodies of massive garnet in Precambrian metamorphic rocks are reported from the Mountaindale district region (Eckel, 1961). A buffer around these clusters of pegmatites is designated H/C for industrial abrasive occurrence potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB, Precambrian metamorphic rocks elsewhere in the county are designated M/C for industrial abrasive potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.29.25 Limestone and Dolomite

There are no limestone prospects in Park County, but the undifferentiated Leadville, Williams Canyon, and Manitou Limestones have historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). The Leadville limestone group is designated H/C for limestone and dolomite occurrence potential throughout the county.

The Cretaceous Greenhorn Limestone hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado; both are found throughout the county (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale (Colorado Group) is designated M/C for limestone and dolomite occurrence potential. The Pennsylvanian Minturn and Belden Formations host limestone prospects in other counties and are designated L/C for limestone potential; the Pennsylvanian-Permian Maroon Formation is assigned L/B for limestone potential.

4.29.26 Industrial Sand

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, which crops out in Park County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). The Dakota Sandstone is designated H/C for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

4.29.27 Gypsum

Although the USGS MRDS (2013) does not note any gypsum occurrences in Park County, Widmann et al. (2011), Houck et al. (2012), and geologic mapping by De Voto (1971), Tweto, 1979a, and Kirkham et al. (2007b, 2012a) document the presence of minable gypsum beds in the evaporite facies of the Pennsylvanian Minturn Formation in the west-central part of the county. Kirkham et al. (2012a) described a small open-cut excavation and an associated disturbed area about 2 miles west of Antero Reservoir where gypsum was mined; both the evaporite facies of the Minturn and the Jurassic Morrison and Ralston Creek Formations are mapped in this area (Tweto, 1979a). Productive gypsum quarries in nearby western Fremont County occur in the

Swissvale Gypsum Member of the Minturn Formation, equivalent to the Chubb evaporite member in South Park (Brill, 1952). In some places (Fremont County) of the Minturn Formation, gypsum beds between 100 to 200 feet thick prevail, likely as a result of folding and thickening of the unit (Brill, 1952; Withington, 1968). Elsewhere, the Minturn gypsum is compressed into lenses or domes and cannot be traced continuously (Brill, 1952; Withington, 1968). The Minturn Formation is designated M/B for gypsum occurrence potential; the evaporite facies of the Minturn Formation is designated M/C.

Although no bedded gypsum is reported from within the Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). George (1920) reports gypsum beds up to 60 feet thick below the Morrison Formation at the Garden of the Gods and Glen Eyrie in El Paso County. Several gypsum quarries hosted by the Ralston Creek Formation occur in Pueblo and Fremont Counties (USGS MRDS, 2013). George (1920) identified a massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8-mile section above the Permian-Triassic Lykins Formation and just below the Morrison Formation at Perry Park in Douglas County. The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/C for gypsum occurrence potential in Park County.

Very pure gypsum (anhydrite) was produced at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (correlative with the Benton Formation) (George, 1920). Throughout the RGFO region, the Niobrara Formation and Colorado Group are reportedly barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds of these units (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation as well (Scott, 1969). The Niobrara Formation and Colorado Group (Benton Formation) are designated L/B for gypsum occurrence potential in Park County.

4.29.28 Sand and Gravel

Several sand and gravel prospects are developed in Quaternary deposits in Park County (USGS MRDS, 2013). High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, as well as glacial drift (Qd) and Tertiary gravels (Tgv), are assigned H/C for potential (Arbogast et al., 2011).

The Cretaceous Dakota Sandstone hosts sporadic sand and gravel operations throughout the RGFO region (W. D. Carter, 1968; Schwochow, 1981); these units are assigned L/C for sand and gravel potential. Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in various rock units throughout the county, principally along creek beds; buffers along these creek beds are assigned M/C, and around other individual occurrences are designated L/C, for sand and gravel occurrence potential.

4.29.29 Crushed Stone Aggregate

In Park County, Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). The limestone members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999; Langer and Knepper, 1995). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Colorado Group overall was only classified as a 'fair' source rock for this usage (Langer and Knepper, 1995; Knepper et al., 1999). Cambrian to Mississippian limestones and quartzites, mapped as MC or MDO in Park County, are assigned H/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Dense, fine-grained Tertiary volcanic rocks like basalt (traprock) satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Significant production of high-quality crushed stone from basaltic flows is reported from other counties (Arbogast, 2011). Tertiary andesitic lavas and breccias (mapped as Tpl) may be too porous with abundant deleterious constituents in part to meet the requirements of crushed stone aggregate (Knepper et al., 1999). Tertiary igneous rocks are assigned H/C for crushed stone potential, except rocks of the lower member of the Thirtynine Mile Andesite, mapped as Tpl, which are assigned M/B.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Indian Creek, Kenosha, and Cripple Creek plutons in Park County, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed, Precambrian Boulder Creek Granite is classified as only a 'fair' source rock by Knepper et al., (1999). Arbogast et al. (2011) categorized the younger Pikes Peak Granite as a good-quality source for crushed stone aggregate, but Knepper et al. (1999) classified it as unsuitable due to the degree of weathering. Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites are designated H/C, the Boulder Creek Granite is assigned M/C, and the Pikes Peak Granite is assigned M/B, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, felsic and hornblendic gneisses are assigned H/B, and undivided metamorphic rock units are assigned M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian Minturn Formation, Jurassic Morrison Formation, Cretaceous Dakota and Fox Hills Sandstones, and the Tertiary South Park and Dry Union Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in the RGFO region. The Dakota and Fox Hills Sandstones are designated L/C, and remaining sedimentary rocks are assigned L/B, for crushed stone potential.

4.29.30 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Various Pennsylvanian to Tertiary sedimentary units, including the Belden, Minturn, South Park, and Dry Union Formations in Park County, bear sporadic interbedded shale that may be suitable sources for Leca (Knepper et al., 1999); these units are assigned L/B for lightweight aggregate potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the igneous and metamorphic rocks of Park County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). There are several past DRMS-permitted vermiculite operations developed in these rocks (Del Rio, 1960). The relatively unweathered Pikes Peak, Kenosha, Indian Creek, and Cripple Creek granitic plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Significant outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite; several developed occurrences are noted in Park and other counties (Arbogast et al., 2011; Knepper et al., 1999; USGS MRDS, 2013; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.29.31 Clay

There is only one clay prospect in Park County, developed in the Cretaceous Colorado Group (USGS MRDS, 2013). Throughout the RGFO region, most prospects developed in the Graneros Shale (Colorado Group) have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The Colorado Group is assigned M/C for clay potential.

The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone) and Glencairn Shale Member (Purgatoire Formation); numerous producers occur in this unit in nearby counties of the Front Range (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation; a few producers in this unit are noted from other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Dakota Sandstone, Purgatoire Formation, and Morrison Formation are designated H/D for clay occurrence potential.

The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the

Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). Sporadic shale interbeds of the underlying Fox Hills Sandstone host clay suitable for brick making (Vanderwilt, 1947). The Laramie Formation and Pierre Shale are designated H/C for clay potential. The Fox Hills Sandstone is assigned L/C for clay potential.

Abundant dark-gray to black shale occurs in the Pennsylvanian Belden Formation (Scarbrough, 2001). The undifferentiated Minturn and Belden Formations are designated L/B for clay occurrence potential.

4.29.32 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). There is no reported production of dimension stone in Park County; however, granites, sandstones, and limestones that have potential to be quarried for dimension stone include the Precambrian Pikes Peak and Silver Plume-aged granites, the Cambrian Sawatch Quartzite, the Ordovician Manitou Formation, the Cretaceous Dakota and Codell Sandstones, and Tertiary Wall Mountain Tuff (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Pikes Peak and Silver Plume-aged granites have been quarried for dimension stone in other counties, although where weathered, fractured, or highly jointed, granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak, Indian Creek, Kenosha, and Cripple Creek granitic plutons are designated H/C, and the older and more weathered Boulder Creek Granite is designated M/C, for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Undifferentiated Cambrian through Mississippian limestone, dolomites, and sandstones (mapped as MDO or MC) are designated H/D for dimension and building stone occurrence potential since production is reported from the Cambrian Sawatch Quartzite, as well as the Ordovician Manitou Limestone and Harding Sandstone (Del Rio, 1960; Schwochow, 1981). Significant production of high-quality dimension stone is reported from the Dakota Sandstone throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). This unit is designated H/D for dimension stone potential; the Codell Sandstone capping the Colorado Group is assigned M/C for dimension stone potential. The Pennsylvanian Minturn Formation, Cretaceous Fox Hills Sandstone, and Tertiary South Park Formation (correlative with the Denver Formation and Dawson Arkose) host numerous sandstone and limestone beds throughout their extent, but there are no reports of dimension stone production from these units

(Arbogast et al., 2011; Cappa and Bartos, 2007); these units are assigned M/B for dimension stone potential.

The Wall Mountain Tuff is a welded rhyolitic ash-flow tuff that occurs as isolated remnants up to 200 feet thick in Park County (Arbogast et al., 2011; Del Rio, 1960; Scarbrough, 2001; Tweto, 1979a). The deposits have been quarried in Douglas County for high-quality dimension and building stone (Del Rio, 1960). The Wall Mountain Tuff is designated H/D for dimension stone potential; other Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.30 Phillips County

4.30.1 Geothermal

Traditional / EGS Geothermal

Although Phillips County does have moderate favorability for EGS, the entire county is designated L/A for high temperature/EGS geothermal resources due to a lack of analysis indicating traditional geothermal favorability (Augustine, 2011; Williams et al., 2008).

Direct-Use / Low Temperature Geothermal

Phillips County contains no known wells or springs. Most of Phillips County is designated as M/B because the estimated temperature is below the 100°F threshold for low temperature and co-produced resources. The western margin of Phillips County is designated as H/B for low temperature and/or co-produced geothermal resources.

4.30.2 Industrial Sand

Quaternary eolian sands in Phillips County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, although no occurrences are noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, and there is one quarry developed in the Ogallala Formation in Phillips County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.30.3 Helium

Most of the western part of Phillips County is designated L/C for helium due to its location near the Denver Basin.

4.30.4 Sand and Gravel

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, including Phillips County, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential. Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

4.30.5 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Phillips County; however, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Ogallala Formation is assigned L/B for crushed stone aggregate occurrence potential.

4.30.6 Lightweight Aggregate

There is no reported production of lightweight aggregate in Phillips County; however, the Tertiary Ogallala Formation is highly weathered in part, resulting in loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds; production of volcanic ash is reported from this unit in nearby Yuma County (Knepper et al., 1999; Schwochow, 1981). The Ogallala Formation is designated M/C for lightweight aggregate occurrence potential.

4.30.7 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Phillips County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B for dimension and building stone occurrence potential.

4.31 Prowers County

4.31.1 Geothermal

Traditional / EGS Geothermal

The entirety of Prowers County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The northwestern part of the county does have moderate favorability for EGS (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Prowers County contains no known springs or wells. The majority of Prowers County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. A few isolated patches are below the 100°F temperature threshold for low temperature and co-produced resources and are therefore designated M/B.

4.31.2 Uranium

There are no occurrences or reports of production of uranium in Prowers County; however, several uranium prospects occur in Mesozoic sedimentary rocks in neighboring Bent and Las Animas Counties in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group (Nelson-Moore et al., 1978; USGS MRDS, 2013). Production in these units is reported from Pueblo County (Nelson-Moore et al., 1978). These units in Prowers County are designated L/B for uranium occurrence potential.

4.31.3 Vanadium

A single vanadium occurrence, but no production, is reported in Prowers County. Pyroxene from a syenite dike associated with the Two Buttes laccolithic dome and intruded in Entrada Sandstone yielded about 0.04 percent V_2O_5 (Hillebrand, 1900). Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in El Paso, Fremont, and Pueblo Counties (USGS MRDS, 2013). Vanadium is also associated with copper mineralization in the Triassic Sheep Pen Sandstone of the Dockum Group in southwestern Baca County (USGS MRDS, 2013). The Dakota Sandstone and Dockum Group are designated L/B for vanadium occurrence potential.

4.31.4 Limestone and Dolomite

There are no operating limestone mines within Prowers County, but the Cretaceous Greenhorn Limestone, found throughout the county, hosts operating mines elsewhere in the State, and the Fort Hays Member of the Niobrara Formation is the leading source of cement-quality limestone in Colorado (Wolfe, 1968). The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential.

4.31.5 Industrial Sand

Quaternary eolian sands in Prowers County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and several DRMS-permitted quarries are developed in eolian sands in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted throughout the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado include the Cretaceous Dakota Sandstone, although no production from this unit is reported for Prowers County (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 98.7 percent silica (Vanderwilt, 1947). Industrial sand has also been reportedly recovered from the Lytle Sandstone Member of the Purgatoire Formation (Arbogast et al., 2011). The undifferentiated Dakota Sandstone and Purgatoire Formation are designated H/C for industrial sand occurrence potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, although there are no permitted operations noted in Prowers County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.31.6 Gypsum

There are no producing gypsum mines in Prowers County; however, gypsum and anhydrite beds of the Upper Permian Day Creek Dolomite underlie all of Prowers County, ranging in thickness from 10 to 60 feet; it is 12 feet thick at the only known outcrop, near Two Buttes in the southeasternmost part of the county (Voegeli and Hershey, 1965). The rocks around Two Buttes are mapped as the Triassic Dockum Group and Upper Permian undivided and correlate with the Lykins Formation, which is known to host gypsum in other Colorado counties (Irwin, 1977;

Maher, 1946; Maher and Collins, 1952; McLaughlin, 1954); these units are designated H/C for gypsum occurrence potential.

At the base of the Jurassic Morrison Formation, which is found in southwestern Prowers County, a massive gypsum bed, 5 feet thick, caps the Triassic “redbeds” in the Two Buttes vicinity (Darton, 1906). This basal unit of the Morrison Formation is likely equivalent to the Ralston Creek Formation, which hosts pink alabaster and white gypsum units in southeastern Colorado (Scott, 1968a; Weist, 1965). The undivided Morrison and Ralston Creek Formations are designated H/C for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced for the cement industry at a Pueblo County mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO region, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds of these units (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-unit limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential throughout Prowers County.

4.31.7 Helium

The Barrel Springs gas field on the southeast flank of the Las Animas Arch anticline in central Prowers County tested positive for 0.91 percent helium (Sonnenberg and von Drehle, 1990). Other wells in the county show ranges of up to 0.91 percent helium. The west half (approximately) of the county is designated M/D for helium potential as it lies in a similar geologic setting to Bent County on the southern end of the anticline.

4.31.8 Sand and Gravel

High-quality sand and gravel deposits in Prowers County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Prowers County, the Cretaceous Codell Sandstone (uppermost Colorado Group) hosts numerous sand and gravel prospects and permitted quarries just north of the Arkansas River (W. D. Carter, 1968; USGS MRDS, 2013); this unit is designated M/D for sand and gravel potential. Overlying this unit, the Niobrara Formation, typically composed of shales and limestone, hosts sporadic sand and gravel pits (Scott and Corban, 1964; USGS MRDS, 2013); buffers around these occurrences are assigned L/C for sand and gravel potential.

Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone, which has been extensively quarried in some areas (W. D. Carter, 1968; Del Rio, 1960; Voegeli and Hershey, 1965); this unit is considered M/D for sand and gravel potential. Sand and gravel operations are also developed in the Cretaceous Dakota Sandstone and Lytle Sandstone Member of the Purgatoire Formation in this and other counties (W. D. Carter, 1968; USGS MRDS, 2013); these units are assigned L/C for sand and gravel potential.

4.31.9 Crushed Stone Aggregate

There are a few past DRMS-permitted crushed stone aggregate operations in Prowers County, likely developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide (Langer and Knepper, 1995). The Niobrara Formation is designated M/C, and the Colorado Group is designated M/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Jurassic Morrison Formation, Cretaceous Dakota Sandstone, and Tertiary Ogallala Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There is one DRMS-permitted crushed stone quarry developed in the Dakota Sandstone in Prowers County. The Dakota Sandstone is designated L/C, and the Morrison and Ogallala Formations are assigned L/B, for crushed stone potential.

4.31.10 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Purgatoire Formation and Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999). The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential.

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). The underlying Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay (mixed layer illite-montmorillonite) and may also be a suitable resource for expandable clay (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B, and the Ogallala Formation is designated M/C, for lightweight aggregate occurrence potential.

4.31.11 Clay

The clay-bearing Jurassic Morrison Formation and Cretaceous Purgatoire Formation, Dakota Sandstone, Colorado Group (including the Graneros Shale), and Niobrara Formation (including the Smoky Hills Member) together cover most of Prowers County. Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Morrison Formation; clay production is reported from this unit in other counties (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992; USGS MRDS, 2013). Several prospects developed in the Graneros Shale and Smoky Hills Member throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). The best quality refractory clays in the RGFO region are found in the Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; there is one clay prospect in these units in southwestern Prowers County and numerous others throughout the region (Arbogast et al., 2011; Patterson, 1968; USGS MRDS, 2013). The undifferentiated Purgatoire Formation and Dakota Sandstone are designated H/D for clay occurrence potential. The Morrison Formation, Colorado Group, and Niobrara Formation are assigned M/C for clay potential.

4.31.12 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Prowers County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Ogallala Formation is designated L/B, and the Niobrara Formation is designated L/C, for dimension and building stone occurrence potential.

Significant production of high-quality dimension stone is reported from the Cretaceous Dakota Sandstone throughout the Front Range, although no production of dimension stone is noted from the plains region (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). The Dakota Sandstone is designated H/C, and the underlying, sandstone-bearing Jurassic Morrison Formation is assigned M/B, for dimension and building stone occurrence potential.

4.32 Pueblo County

4.32.1 Geothermal

Traditional / EGS Geothermal

The majority of Pueblo County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). An area in the southwest is considered M/C because of moderate traditional favorability, and the southeastern corner is L/B due to low EGS favorability.

Direct-Use / Low Temperature Geothermal

Pueblo County contains two known wells, the Don K Ranch (82°F) and the Clark Spring (77°F). These locations are considered H/D for direct use. The majority of Pueblo County is below the 100°F temperature threshold for low temperature and co-produced resources, so the southwestern portion is considered M/B. The northeastern quadrant is above the temperature threshold and is designated H/B.

4.32.2 Gold

There are no reported gold occurrences in Pueblo County; however, the Arkansas River upstream from the Pueblo reservoir is designated L/B due to occurrences in neighboring Fremont County.

4.32.3 Silver

Although there are no reported silver occurrences in Pueblo County, the Precambrian felsic metamorphic terrain in the western part of the county is designated L/B due to silver occurrences in similar rocks in nearby counties (Custer and Huerfano).

4.32.4 Copper-Lead-Zinc

According to Henderson (1926), there was reported production of base metals within Pueblo County, but the source of production is unknown and the county of attribution may be incorrect. Regardless, the Precambrian material of the Wet Mountains in the western portion of the county is considered M/B for occurrence potential due to base-metal occurrences in similar rocks in nearby counties.

4.32.5 Iron

Limonite and siderite concretions occur in the Rusty Zone of the Cretaceous Pierre Shale north of Overton in Pueblo County (Gilbert, 1897; Harrer and Tesch, 1959; Scott; 1969). The 440-foot-thick zone hosts iron-bearing concretions ranging in diameter from a few inches to 3 feet with centers of limestone or pyrite (Scott, 1969). Production is reported from the Overton-Steele Hollow Iron deposits between Baculite Mesa and the Arkansas River where ore averaged 22 to 32 percent iron (Harrer and Tesch, 1959; USGS MRDS, 2013). The Rusty Zone exceeds 600 feet in thickness south of Pueblo, and hosts concretions up to 6 inches thick and 2 feet long (Harrer and Tesch, 1959). The lower unit (Sharon Springs shale) of the Pierre Formation in Pueblo County is designated H/C for iron occurrence potential.

Iron-bearing minerals are reported in stratabound sulfide deposits in Precambrian metamorphic rocks (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks throughout the county are designated L/B for iron occurrence potential. Precambrian Silver Plume-related granites are reported to host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). Silver Plume-related granite in the county is assigned L/B. The Mississippian Leadville Dolostone hosts limonite, and several past producers are noted from other counties (Cappa and Bartos, 2007); this unit is designated L/B in Pueblo County.

4.32.6 Manganese

There are no known occurrences of manganese in Pueblo County; however, Precambrian igneous and metamorphic rocks are designated L/B for manganese potential due to occurrences in the same rocks in nearby counties (Custer and Chaffee).

4.32.7 Molybdenum

There are no known molybdenum prospects in Pueblo County, but Precambrian metamorphic and igneous rocks in the southwestern area of the county are designated L/B since molybdenum occurs in similar rocks in neighboring Fremont County.

4.32.8 Nickel

There are no known occurrences of nickel in Pueblo County, but Precambrian metamorphic and igneous rocks throughout the county are designated L/B for nickel potential due to minor occurrences in similar rocks in nearby Custer County.

4.32.9 Tungsten

There are no known tungsten prospects in Pueblo County, but Precambrian metamorphic and granitic rocks in the southwestern area are designated L/B since tungsten occurs in similar rocks in neighboring Fremont County.

4.32.10 Tellurium

There is no reported production of tellurium in Pueblo County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in other counties.

4.32.11 Titanium

There is no recorded production of titanium in Pueblo County; however, the abundance of accessory minerals, especially sphene, is diagnostic of the San Isabel Granite (Boyer, 1962). The San Isabel Granite in western Pueblo County is assigned L/B for titanium potential.

4.32.12 Uranium

Production of over 10,000 tons of uranium ore averaging 0.15 percent U_3O_8 (32,213 pounds U_3O_8) is reported from the George Avery Ranch mine through 1971 (Nelson-Moore et al., 1978). Carnotite and uraninite are both reported from tabular deposits within the Dakota Sandstone, and samples assayed up to 1.12 percent U_3O_8 (Nelson-Moore et al., 1978; USGS MRDS, 2013). Several uranium prospects occur in either the Jurassic undivided Morrison, Entrada, and Ralston Creek group or Cretaceous Dakota Sandstone and Purgatoire Formation group in other counties as well (Nelson-Moore et al., 1978; USGS MRDS, 2013). These groups in the productive area are designated H/C; elsewhere in the county they are designated L/B for uranium occurrence potential.

Also, several uranium occurrences are noted from the organic-rich black shale of the lower unit of the Cretaceous Pierre Shale (Sharon Springs Member) near the underlying contact with the Niobrara Formation throughout eastern Colorado (Landis, 1959b; Nelson-Moore et al., 1978). Samples averaged 0.001 percent uranium, and anomalous concentrations up to 0.006 percent in Cheyenne County, 0.005 percent in Crowley County, and 0.004 percent in Kiowa County are associated with thin bentonitic clay beds stratigraphically scattered throughout the Sharon

Springs Member (Landis, 1959b). The Sharon Springs Member of the Pierre Shale is designated L/B for uranium occurrence potential.

4.32.13 Vanadium

Historically, much of the vanadium produced in Colorado was recovered from the Jurassic Morrison Formation and Entrada Sandstone; these units are assigned M/B for vanadium potential (Del Rio, 1960; Schwochow and Hornbaker, 1985). Also, carnotite occurs in several prospects developed in the Cretaceous Dakota Sandstone in this (George Avery Ranch) and El Paso and Fremont Counties (Nelson-Moore et al., 1978; USGS MRDS, 2013). The Dakota Sandstone is designated L/B for vanadium occurrence potential.

4.32.14 Fluorspar

There are no documented fluorite prospects in Pueblo County; however, average fluorine content (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks (Wallace, 2010). The Precambrian San Isabel pluton is designated H/C, and hornblende gneiss is assigned M/B, for fluorspar occurrence potential in western Pueblo County.

4.32.15 Pegmatite Minerals

There are no reported occurrences of pegmatites or production of feldspar or mica in Pueblo County. Nonetheless, Precambrian felsic metamorphic rocks are designated M/B for pegmatite mineral potential due to occurrences in the same rock types in other counties. Precambrian plutonic rocks are assigned L/B.

4.32.16 Industrial Abrasives

There is no reported production of industrial abrasives in Pueblo County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks elsewhere in the RGFO management area, these rocks are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.32.17 Limestone and Dolomite

There are a few limestone prospects in Pueblo County developed in either the Cretaceous Greenhorn Limestone or Fort Hays Member of the Niobrara Formation; both units also host operating mines elsewhere in the State. The undifferentiated Greenhorn Limestone, Carlile Shale, and Graneros Shale is designated M/C for limestone and dolomite occurrence potential; the Niobrara Formation is assigned M/D for potential. A small area of undifferentiated Mississippian to Ordovician limestone units (Leadville, Williams Canyon, and Fremont Limestones) is designated H/C for limestone and dolomite potential, as the Leadville group of limestones have historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947).

4.32.18 Industrial Sand

Quaternary eolian sands in Pueblo County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and one occurrence is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in the RGFO region; Quaternary alluvium is assigned M/C for industrial sand potential.

Geologic formations that preserve ancient beaches and dunes typically host high-silica sands; the most prevalent producers of quartz-rich sand in Colorado are the Permian-Triassic Lykins Formation and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Bohannon and Ruleman, 2009; Vanderwilt, 1947). Samples from Lykins Formation and Dakota Sandstone quarries in Douglas and Jefferson Counties assayed as high as 96.7 and 98.7 percent silica, respectively (Vanderwilt, 1947). Three DRMS-permitted industrial sand operations occur in the Dakota Sandstone in southwestern Pueblo County. Industrial sand has also been reportedly recovered from the Lytle Sandstone Member of the Purgatoire Formation (Arbogast et al., 2011). The undifferentiated Dakota Sandstone and Purgatoire Formation, as well as the Lykins Formation are designated H/C for industrial sand occurrence potential.

4.32.19 Gypsum

Several gypsum deposits hosted by the Jurassic Ralston Creek Formation occur in northwestern Pueblo County and are continuous with deposits in northeastern Fremont County (USGS MRDS, 2013). Although no bedded gypsum is reported from within the Jurassic Morrison Formation, there are many reports of massive white and gray gypsum at its base in a unit almost always identified as or correlated with the Ralston Creek Formation (Scott, 1963; Van Horn, 1976; Weist, 1965; Witherington, 1968). Darton (1906) reports a 30-foot-thick bed of gypsum below the Morrison Formation at the Garden of the Gods (El Paso County); George (1920) reports massive gypsum up to 60 feet thick below the Morrison Formation at nearby Glen Eyrie. The Stevens Gypsum mine in Pueblo County is developed in the Lower Cretaceous Colorado Group, although production is likely recovered from the underlying Morrison and Ralston Creek Formations; production of 700 tons of gypsum per month at one point is reported (George, 1920; USGS MRDS, 2013). George (1920) identified a massive gypsum layer averaging 40 feet thick, but ranging up to 75 feet thick, along a traceable 8-mile section at the top of the Permian-Triassic Lykins Formation and just below the Morrison Formation at Perry Park in Douglas County. The undivided Morrison and Ralston Creek Formations and the Lykins Formation are designated H/D for gypsum occurrence potential.

Very pure gypsum (anhydrite) was produced for the cement industry at the Stone City mine developed in the Cretaceous Niobrara Formation and the underlying Colorado Group (Graneros Shale, Greenhorn Limestone, and Carlile Shale Members) (George, 1920). Throughout the RGFO region, the Niobrara Formation and Colorado Group are barren of bedded gypsum; however, gypsum lenses and nodules, as well as selenite crystals and veinlets, occur in thin shale or bentonite beds of these units (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1963 and 1969; Scott and Corban, 1964; Van Horn, 1976; Wood et al., 1957). Granular and nodular gypsum is reported from mid-formation limestone beds of the Niobrara Formation (Scott, 1969). Abundant disseminated gypsum stringers and selenite crystals occur in association with bentonite beds of the Colorado Group (Gilbert, 1897; Johnson, 1958 and 1959; Scott, 1969; Van Horn, 1976; Weist, 1965; Wood et al., 1957). The Niobrara Formation and Colorado Group are designated L/B for gypsum occurrence potential throughout the county.

4.32.20 Sand and Gravel

Del Rio (1960) reports production of almost 6 million tons of sand and gravel, primarily from alluvium, in Pueblo County between 1954 and 1958. High-quality sand and gravel deposits in Pueblo County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). The Paleozoic Fountain Formation, Lykins Formation, Dakota Sandstone, and Lytle Sandstone Member of the Purgatoire Formation host sand and gravel operations in this and other counties (W. D. Carter, 1968); these units are assigned L/C for sand and gravel potential. Additionally, the Cretaceous Codell Sandstone (uppermost Colorado Group) hosts a few sand and gravel prospects and DRMS-permitted quarries in this and other counties (W. D. Carter, 1968; USGS MRDS, 2013). Overlying this unit, the Niobrara Formation, typically composed of shales and limestone, hosts sporadic sand and gravel pits (Scott and Corban, 1964; USGS MRDS, 2013); buffers around these occurrences are assigned L/C for sand and gravel potential.

4.32.21 Crushed Stone Aggregate

There are numerous DRMS-permitted crushed stone aggregate operations in Pueblo County, developed in the Fort Hays Member of the Cretaceous Niobrara Formation, which has also been quarried for crushed limestone in other counties (Schwochow, 1981). The underlying Carlisle and Greenhorn Limestone Members of the Colorado Group may also host suitable source rocks (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide, although the Niobrara Formation and Colorado Group overall were only classified as 'fair' source rocks for this usage (Langer and Knepper, 1995; Knepper et al., 1999). Also, Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). The Niobrara Formation is designated H/D along a belt of aggregate operations and M/C elsewhere for crushed stone aggregate potential; the Colorado Group is designated M/B, for crushed stone potential. Cambrian to Mississippian limestones and quartzites, mapped as MDO, are assigned H/C for crushed stone aggregate potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the San Isabel pluton in Huerfano, Pueblo, and Custer Counties, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The San Isabel pluton and satellites are designated H/C, and Precambrian felsic and hornblendic gneisses (Idaho Springs Formation) are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Pennsylvanian-Permian Fountain and Permian-Triassic Lykins Formations, the Jurassic Morrison Formation, Cretaceous Dakota Sandstone, and the Tertiary Santa Fe Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). There are several DRMS-permitted crushed stone quarries developed in the Dakota Sandstone in the RGFO region. The Dakota Sandstone is designated L/C, and the remaining sedimentary rocks are assigned L/B, for crushed stone aggregate occurrence potential.

4.32.22 Lightweight Aggregate

Highly expansive bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (slightly expansive illite) are moderately abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hansen and Crosby, 1982; Hosterman and Patterson, 1992). Though not typically quarried as a lightweight aggregate, bentonite is useful as a clay binder in the production of Leca (Gomathi and Sivakumar, 2014). Refractory clay has been quarried from the overlying Cretaceous Glencairn Shale Member of the Purgatoire Formation and Dry Creek Canyon Member of the Dakota Sandstone; however, this high-quality clay is only slightly expansive and not well-suited for use as Leca (Arbogast et al., 2011; Patterson, 1968). Some illite- and montmorillonite-bearing clays of the Cretaceous Colorado Group shale members are highly expansive but sometimes calcareous (Hansen and Crosby, 1982; Knepper et al., 1999).

The lightweight aggregate occurrence potential is L/B for the Dakota Sandstone, Purgatoire Formation, and Morrison Formation. The Colorado Group is designated M/B for lightweight aggregate potential. The Triassic-Permian Lyons Sandstone and Lykins Formation bear sporadic interbedded shale that may be suitable sources for Leca; these units are assigned L/B for lightweight aggregate potential.

Claystone and bentonite (lower member) beds of the Cretaceous Pierre Shale bear highly expansive illite and montmorillonite, which are favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential. The Smoky Hill Shale Member of the Niobrara Formation is composed of 95 percent silt and clay and contains slightly to highly expansive illite and montmorillonite; this shale member may be a suitable resource for Leca (Hansen and Crosby, 1982). The Niobrara Formation is designated L/B for lightweight aggregate occurrence potential.

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). There are two past vermiculite occurrences at the contact of the Precambrian San Isabel granite to granodiorite and Precambrian metamorphic rocks (USGS MRDS, 2013). The relatively unweathered San Isabel pluton is designated L/B, and older, highly weathered felsic and hornblendic gneisses (derived from volcaniclastic host rocks) are designated M/C, for lightweight aggregate potential. A couple of outcrops of mostly felsic tuffs and breccias derived from Tertiary volcanic activity may host perlite, scoria, or pumice (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.32.23 Clay

Considerable clay has been mined from Pueblo County since the 1890s; production between 1951 and 1958 amounted to 612,000 tons of clay (Del Rio, 1960; Waagé, 1953). There have been numerous clay producers in a dozen Pennsylvanian through Tertiary shale-bearing rock units (USGS MRDS, 2013). The best quality refractory clays in the RGFO region are found in the Cretaceous Dry Creek Canyon Member (Dakota Sandstone) and Glencairn Shale Member (Purgatoire Formation); many prospects occur in these units in this and other counties (Arbogast et al., 2011; Patterson, 1968; Spence, 1980; Waagé, 1953). Bentonite (montmorillonite formed from altered volcanic ash) and multicolored claystones (principally composed of illite) are abundant in the Jurassic Morrison Formation (Brady, 1969; Cappa et al., 2007; Hosterman and Patterson, 1992). The undifferentiated Morrison Formation, Dakota Sandstone, and Purgatoire Formation are designated H/D for clay occurrence potential; the Morrison Formation alone is assigned M/C for clay potential.

Most prospects developed in the Graneros Shale (Colorado Group), as well as the overlying Niobrara Formation, throughout the RGFO region have produced a low-grade clay suitable for brick making (Patterson, 1968; Spence, 1980). Several Pueblo County clay quarries produce from the Colorado Group and Niobrara Formation; these units are assigned M/D in areas of reported mines and M/C elsewhere for clay potential.

The Cretaceous Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay is produced from this unit in Pueblo and other counties (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential. There are several clay prospects developed in the Permian-Triassic Lykins Formation along the Front Range; this unit has been occasionally mined for brick and tile clay in eastern Colorado (Arbogast, 2011; Patterson, 1968; USGS MRDS, 2013). The Lykins Formation is designated M/C for clay occurrence potential.

4.32.24 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Pueblo County hosts igneous and sedimentary rocks that have potential to be quarried for dimension and building stone, including Precambrian Silver Plume-aged granite, Ordovician to Mississippian limestones and sandstones, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

Silver Plume-aged granite has been quarried for dimension stone in other counties, although where weathered, fractured, or highly jointed, granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The alkalic San Isabel pluton and satellites, which range from granite to granodiorite, are designated H/C for dimension stone potential; Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Dimension and building stone production is reported from the Ordovician Harding Sandstone and Mississippian Leadville Limestone in this and other counties (Del Rio, 1960; Schwochow, 1981). Partially metamorphosed and marbleized Leadville Limestone is quarried in Pueblo, Fremont, and Chaffee Counties; stone from the ‘Beulah marble’ in Pueblo County adorns the Colorado State Capital building (Arbogast et al., 2011; Schwochow, 1981). Undifferentiated Ordovician to Mississippian rocks, mapped as MDO, are designated H/D for dimension stone potential.

Significant production of high-quality dimension stone is reported from the undifferentiated Lyons Sandstone and Lykins Formation, as well as the Dakota Sandstone, throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Sharps (1963) described over 30 sandstone quarries in the Lyons Sandstone, in Larimer and Boulder Counties that provided dimension and building stone material to the University of Colorado-Boulder campus. The Lykins Formation and Lyons Sandstone are assigned H/D for dimension stone potential. The Dakota Sandstone is designated H/D for dimension stone potential in the Front Range portion of Pueblo County where dimension stone has been quarried and H/C along the southern county border; the underlying, sandstone-bearing Jurassic Morrison Formation is assigned M/B for potential. The Permian-Pennsylvanian Fountain Formation hosts sandstone and conglomerate beds throughout its extent; building stone production is reported from the Fountain Formation in other counties (Arbogast et al., 2011; Cappa and Bartos, 2007; Lindvall, 1968; Schwochow, 1981). The Fountain Formation is assigned M/C for dimension stone potential.

The Cretaceous Fort Hays Member of the Niobrara Formation has been sporadically quarried for limestone dimension stone in Pueblo and other counties (Wolfe, 1968; USGS MRDS, 2013). The Fort Hays Member has also been used as building stone in New Mexico (Austin et al., 1990). The Niobrara Formation is designated L/C for dimension and building stone occurrence potential.

4.33 Saguache County

4.33.1 Geothermal

Traditional / EGS Geothermal

The portion of Saguache County within the RGFO is designated as M/C for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and moderate traditional geothermal favorability (Williams et al., 2008). An area in the east is considered H/B because of high EGS favorability.

Direct-Use / Low Temperature Geothermal

The portion of Saguache County within the RGFO contains no known springs or wells. All but the northeastern corner is below the temperature threshold and is designated as M/B. The northeastern corner is considered H/B.

4.33.2 Gold

The small portion of the northeastern edge of Saguache County that occurs within the RGFO management area touches on the Bonanza (Kerber Creek) mining district. Production quantity from this area is uncertain, but gold was recovered from quartz veins in fractures and fissures in the Rawley Andesite of the Bonanza Caldera complex (Cappa and Wallace, 2007). The Kismuth mine, located in the Rawley Andesite south of Silver Creek, reportedly produced gold in the 1930s (USGS MRDS, 2013). Rawley Andesite, including the area around the Kismuth mine, is designated M/C for gold occurrence potential.

4.33.3 Silver

The RGFO portion of Saguache County borders the highly mineralized and productive Bonanza district. Within the RGFO portion of the county, the Kismuth mines produced base metals, including silver, from quartz veins in the Rawley Andesite during the 1930s (USGS MRDS, 2013). The area surrounding the Kismuth mines is considered M/C for silver occurrence potential. The Precambrian felsic metamorphic rocks are assigned M/B due to silver occurrences in similar rocks in neighboring counties (Chaffee and Fremont).

4.33.4 Copper-Lead-Zinc

Lead, copper, and zinc have been mined in the Bonanza (Kerber Creek) district, which is southeast of the portion of Saguache County which lies in the RGFO region (Henderson, 1926; Cappa and Wallace, 2007). Vanderwilt (1947) reports production of 4.8 million pounds of lead, 2.9 million pounds of zinc, and 1.9 million pounds of copper between 1932 and 1945. The Rawley andesite is the productive unit (Vanderwilt, 1947), and it is designated M/C. Other Tertiary and Precambrian rocks in this portion of the county within the RGFO area are designated M/B.

4.33.5 Iron

There is no iron production reported in the RGFO portion of Saguache County; however, iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks are designated L/B for iron occurrence potential.

4.33.6 Manganese

There are no known manganese deposits in the RGFO region of Saguache County; however, the Tertiary igneous rocks are designated M/B for manganese potential due to occurrences in similar rocks in nearby Chaffee County, as well as proximity to the ‘manganese belt’ (e.g., Pershing mine) in Tertiary intrusives of the nearby Bonanza district outside the RGFO region (Dunn, 2003; Henderson, 1926; Muilenburg, 1919; Wells et al., 1952).

4.33.7 Molybdenum

There are no known molybdenum prospects in the RGFO portion of Saguache County, but the Tertiary intrusive rocks are designated M/B, and Precambrian metamorphic rocks are L/B since molybdenum occurs in the same rocks in nearby Chaffee and Fremont Counties.

4.33.8 Nickel

There are no known occurrences of nickel in the RGFO portion of Saguache County, but Precambrian metamorphic and igneous rocks are designated L/B for nickel potential due to minor occurrences in similar rocks in nearby Fremont and Custer Counties.

4.33.9 Tungsten

There are no known tungsten prospects in the RGFO portion of Saguache County, but the Precambrian metamorphic rocks are designated L/B since minor tungsten occurs in the same rocks in nearby Chaffee County.

4.33.10 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Saguache County; however, potential for gallium-germanium-indium occurrences exists in areas of sphalerite mineralization. Vanderwilt (1947) reports production of 2.9 million pounds of zinc from the nearby Bonanza district between 1932 and 1945, primarily from the Rawley andesite. Buffers around known zinc mines are assigned M/B for gallium, germanium, and indium occurrence potential.

4.33.11 Tellurium

There is no reported production of tellurium in the RGFO region of Saguache County; however, Precambrian rocks are designated L/B for tellurium potential due to occurrences of gold and copper mineralization in these rocks in this and other counties.

4.33.12 Uranium

Uranium deposits along the north-trending Chester group of thrust faults in northern Saguache County and southern Gunnison County were discovered in 1955 within what is now known as the Marshall Pass Uranium district (Olson, 1988; Wright and Everhart, 1960). This district is partially located in the RGFO portion of Saguache County, and the source rock for the uranium is likely Tertiary siliceous tuffs (Olson, 1988). Nearly 500 pounds of uranium were recovered from about 160 tons of 0.144 percent U_3O_8 at the Bonita group of mines (Nelson-Moore et al., 1978). The deposit is hosted by an 8-inch thick carbonaceous seam filling a fracture between

Precambrian granite and overlying Tertiary trachyte porphyry (Nelson-Moore et al., 1978). Tertiary tuffs are designated M/C for uranium occurrence potential.

4.33.13 Vanadium

In the RGFO portion of Saguache County, 5 pounds of V_2O_5 were produced at the Bonita claims from a uranium-bearing carbonaceous seam filling a fracture between Precambrian granite and overlying Tertiary trachyte porphyry (Nelson-Moore et al., 1978). Buffers along faults in Tertiary rocks are designated L/C for vanadium occurrence potential.

4.33.14 Fluorspar

There is no documented fluorite production in the RGFO portion of Saguache County; however, average fluorine content (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, as well as in Tertiary intrusives (Wallace, 2010). Precambrian Boulder Creek Granite is designated H/C, Tertiary intrusives are assigned M/C, and Precambrian hornblende gneiss is assigned M/B, for fluorspar occurrence potential in Saguache County.

4.33.15 Pegmatite Minerals

There are no known occurrences of pegmatites or reported production of feldspar or mica in the RGFO portion of Saguache County. However, Precambrian felsic metamorphic rocks are designated M/B for pegmatite mineral potential due to occurrences in the same rock types in other counties.

4.33.16 Industrial Abrasives

There is no reported production of industrial abrasives in the RGFO portion of Saguache County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks elsewhere in Colorado, these rocks are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950).

4.33.17 Limestone and Dolomite

In the RGFO portion of Saguache County, there are no limestone quarries; however, Paleozoic limestones have been used as flux material for the Colorado Fuel and Iron Corporation steel plant (D. A. Carter, 1968). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). The sole undifferentiated Paleozoic limestone mapped unit is designated H/C for limestone and dolomite occurrence potential.

4.33.18 Crushed Stone Aggregate

Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). Dense limestones and dolomites comprise about 70 percent of production nationwide (Langer and Knepper, 1995; Knepper et al., 1999). Cambrian to Mississippian limestones and quartzites, mapped as MDO in the RGFO portion of Saguache County, are assigned H/C for crushed stone potential.

Dense, fine-grained, Tertiary igneous rocks like basalt (traprock) satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Tertiary rocks mapped as Taf and Tmi are assigned H/C for crushed stone potential. Tertiary andesitic lavas and breccias may, in part, be too porous with abundant deleterious constituents to meet the requirements of crushed stone aggregate (Knepper et al., 1999); Tertiary rocks mapped as Tpl are assigned M/B for crushed stone potential.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The typically weathered, foliated, and jointed Precambrian Boulder Creek Granite is classified as a ‘fair’ source rock by Knepper et al., (1999). Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Boulder Creek Granite is assigned M/C, and Precambrian felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Tertiary Dry Union Formation may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). These sedimentary rocks are assigned L/B for crushed stone aggregate occurrence potential.

4.33.19 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which commonly occurs in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). In the RGFO portion of Saguache County, a small outcrop of Boulder Creek Granite is assigned M/B for lightweight aggregate potential, and felsic and hornblendic gneisses (derived from volcanic rocks) are assigned M/C. Outcrops of mostly mafic tuffs and breccias derived from Tertiary basaltic flows may host perlite, scoria, or pumice; two past DRMS-permitted perlite operations are noted (Arbogast et al., 2011; Knepper et al., 1999; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.33.20 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). There is no dimension stone production reported for the RGFO portion of Saguache County; however, production is reported from the Ordovician Harding Sandstone and Mississippian Leadville Limestone in several counties from undifferentiated rock units mapped as MDO (Del Rio, 1960; Schwochow, 1981; Tweto, 1979a). This unit is designated H/D for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B; Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.34 Sedgwick County

4.34.1 Geothermal

Traditional / EGS Geothermal

The entirety of Sedgwick County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The entire county has moderate favorability for EGS (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Sedgwick County contains no known springs or wells. The majority of Sedgwick County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. A few areas in the north and the southeastern corner are below the temperature threshold and are designated M/B.

4.34.2 Industrial Sand

Quaternary eolian sands in Sedgwick County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and one quarry is developed in eolian sands in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications;

however, several past and current DRMS-permitted industrial sand operations are noted in other counties, especially along the South Platte River; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.34.3 Helium

Southwestern Sedgwick County is designated L/C for helium due to its proximity to the Denver Basin.

4.34.4 Sand and Gravel

High-quality sand and gravel deposits in Sedgwick County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Sand and gravel operations are developed in the lower sandstone and conglomerate unit of the Oligocene White River Formation in this and other counties (Cullen, 1960); this unit is designated L/C for sand and gravel occurrence potential. Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.34.5 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Sedgwick County; however, well-cemented and unweathered sandstone units in the Tertiary White River and Ogallala Formations may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The White River and Ogallala Formations are assigned L/B for crushed stone aggregate occurrence potential.

4.34.6 Lightweight Aggregate

There is no reported production of lightweight aggregate in Sedgwick County; however, the Tertiary Ogallala Formation is highly weathered in part, resulting in loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds; production of volcanic ash is reported from this unit in Yuma County (Knepper et al., 1999; Schwochow, 1981). The Tertiary White River Formation is composed of ashy claystone and sandstone, which may also be a suitable source for Leca (Knepper et al., 1999). The Ogallala Formation is designated M/C, and the White River Formation is designated L/B, for lightweight aggregate occurrence potential.

4.34.7 Clay

There are two USGS MRDS (2013) clay occurrences in Sedgwick County, both developed in the Tertiary White River Formation, which is known to host occasional claystones suitable for brick clay; this unit is assigned L/B for clay occurrence potential (Vanderwilt, 1947). A few sand and/or gravel pits also produce clay from the alluvium along the South Platte River in this and other counties; the alluvium mapped unit is designated L/C for clay potential.

4.34.8 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Sedgwick County, the Tertiary White River Formation, Arikaree Group, and Ogallala Formation host sandstones in part, but have no documented production of dimension stone. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the White River Formation and Arikaree Group are designated M/B, for dimension and building stone occurrence potential.

4.35 Teller County

4.35.1 Geothermal

Traditional / EGS Geothermal

The majority of Teller County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). Moderate traditional favorability in the north-central portion of the county leads to a designation of M/C.

Direct-Use / Low Temperature Geothermal

Teller County contains one known well called Marigold (75°F), in the extreme southwestern corner. This location is considered H/D for direct use. The entirety of Teller County is below the temperature threshold and is designated M/B for low temperature and co-produced geothermal resources.

4.35.2 Gold

The Cripple Creek district in southern Teller County is Colorado's greatest gold-producing district. The Cripple Creek district is composed of alkalic rocks from a Tertiary diatreme-intrusive complex, the remnants of a composite volcanic subsidence basin (Cappa, 1998). Some discoveries of gold were made around Mount Pisgah in 1874, and the miners misidentified sylvanite as galena. Finally, large strikes were made in 1891; however, peak production was not achieved until after the turn of the century. At least 21 million ounces of gold were produced in this district between 1891 and 1998, predominantly from the Cresson mine (Cappa, 1998). Since 1994, the Cripple Creek & Victor Gold Mining Company has produced approximately 250,000 ounces of gold annually. The historic, and currently active, Cripple Creek district is assigned H/D for gold occurrence potential. Tertiary volcanic rocks related to the Cripple Creek complex are designated H/C. The region of creeks draining the Cripple Creek complex is labeled L/B for placer gold occurrence potential.

Mineralization (primarily fluorite with minor gold) in the Mt. Rosa alkalic intrusive center of the Pikes Peak batholith may be related to the Tertiary intrusion of the Cripple Creek volcanic complex (Cappa, 1998; Smith et. al., 1999; Stevens, 1949). Several gold occurrences are reported in the El Paso portion of this area on the USGS MRDS (2013), and a buffer around these occurrences and the Mount Rosa district is assigned M/C. The Pikes Peak batholith is assigned M/B due to scattered mines in this and other counties (e.g., El Paso and Douglas). Several gold occurrences in the West Creek district earn it a designation of M/C.

4.35.3 Silver

Teller County has been a major producer of silver, as well as gold, with a total of 2,173,760 ounces reported from 1891 through 1958 (Del Rio, 1960; Vanderwilt, 1947). Virtually all of that production has come from the Tertiary diatreme-intrusive complex in the Cripple Creek district (Cappa, 1998). The Morning Glory-Doctor-Jack Pot shafts, for example, host a high-grade tetrahedrite ore that yields up to 200 ounces of silver per ton (Lovering and Goddard, 1950). The Cripple Creek district is currently the leading silver-producing area in the State and is considered H/D for silver occurrence potential. Outlying bodies of related volcanics peripheral to the main subsided complex without established mines are designated H/B. The Pikes Peak batholith is designated M/B for silver occurrence potential due to sporadic silver occurrences in this and nearby El Paso and Park Counties.

4.35.4 Copper-Lead-Zinc

Although Teller County has historically been a major producer of gold and silver in the Cripple Creek district, only small amounts of lead (612 pounds) and copper (451 pounds) were reportedly produced between 1909 and 1923 in the county (Vanderwilt, 1947). The Cripple

Creek and Mount Rosa districts are given M/C for occurrence potential and the remainder of the Precambrian and Tertiary rocks in the county are considered L/B.

4.35.5 Iron

There is no iron production reported for Teller County; however, late-stage syenite, fayalite, phonolite, and other mafic intrusions into the Precambrian Pikes Peak batholith host iron-rich minerals (Smith et al., 1999); these units are designated M/B for iron occurrence potential. Elsewhere, the Pikes Peak batholith is designated L/B for iron potential. Precambrian Silver Plume-aged granites (Cripple Creek pluton) host magnetite as a primary accessory mineral, and production of iron as a tertiary commodity is reported in Clear Creek and Larimer Counties (Carten et al., 1988; Eggler, 1968). The Cripple Creek pluton is assigned L/B for iron potential. Also, iron-bearing minerals are reported in pegmatites and stratabound sulfide deposits in Precambrian metamorphic rocks throughout the RGFO region (Sheridan and Raymond, 1984a). Precambrian metamorphic rocks are designated L/B for iron occurrence potential.

4.35.6 Manganese

No production of manganese is reported in Teller County; however, anomalous concentrations of hydrous manganese oxides (wad) are reported in breccia pipes at the Ironclad and the new Cresson deposits of the Victor project (Cappa, 1998; Lovering and Goddard, 1950; USGS MRDS, 2013). Analysis shows a manganese content of up to 5,000 ppm (Gott et al., 1969). Muilenburg (1919) describes this occurrence as a deposit of manganiferous iron ore, assayed at 32.25 percent MnO_2. Eckel (1961) reports mallardite (hydrous $MnSO_4$) in the Moon Anchor mine of the Cripple Creek district. The Tertiary volcanic rocks of the Cripple Creek vicinity are designated M/C for manganese potential. Precambrian crystalline rocks in the rest of the county are assigned L/B due to reported occurrences in the same rocks in other counties (e.g., El Paso and Lake).

4.35.7 Molybdenum

Molybdenum is reported in a pegmatite of Pikes Peak Granite at the Snowflake feldspar mine in northern Teller County (USGS MRDS, 2013). Precambrian igneous and metamorphic rocks, including the Snowflake mine area, are designated L/B since molybdenum occurs in the same rocks in nearby Park, Jefferson, and Douglas Counties.

4.35.8 Nickel

Nickel was mined at past-producing Emma L mine, although no data are available (USGS MRDS, 2013). The mine is located in or adjacent to pyrrhotite-bearing Windy Point granite, a segregation of the Mount Rosa intrusive complex, both of which intruded the Pikes Peak batholith (Gross and Heinrich, 1965; USGS MRDS, 2013). Precambrian metamorphic and igneous rocks throughout the county are designated L/B for nickel potential due to this occurrence and others in similar rocks in nearby Jefferson County.

4.35.9 Tungsten

There are a few occurrences (Heavystone prospect and lode) of wolframite in a shear zone within the Pikes Peak granite associated with the Mount Rosa alkalic intrusive center, although no production is reported (Lemmon and Tweto, 1962; USGS MRDS, 2013). The tungsten occurrence potential is M/C in the Mount Rosa area; Pikes Peak granite elsewhere is assigned L/B.

4.35.10 Beryllium

The beryllium silicate, phenakite, occurs in abundance at the Crystal Peak (Florissant) area and the Gold King mine at Cripple Creek in Teller County (Eckel, 1961; Heinrich, 1957). Beryl occurs in zoned pegmatites in the Pikes Peak batholith at the Black Cloud mine and the Comanche Group and Tracie Group prospects (Meeves et al., 1966; USGS MRDS, 2013). The Pikes Peak batholith, as well as the Cripple Creek mining district, is designated M/B for beryllium potential. Granitic rocks elsewhere in the county are assigned L/B.

4.35.11 Rare Earth Elements

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, including the sodic Mount Rosa intrusive complex, all of which are enriched in REEs, especially LREEs (Gross and Heinrich, 1965; Persson, 2016; Simmons et al., 1999; Smith et al., 1999). Allanite, bastnaesite, cerianite, fergusonite, monazite, xenotime, and yttrium fluorite are reported from the many pegmatites of the Mount Rosa complex, which spans Teller and El Paso Counties (Adams, 1968; Gross and Heinrich, 1966; Olson and Adams, 1962; Persson, 2016; Smith et al., 1999; Stevens, 1949). Samples from Mount Rosa dikes assayed upwards of 1,018 ppm total REE oxides (Smith et al., 1999). The region around the Mount Rosa complex is designated H/C for REE occurrence potential.

Simmons and Heinrich (1980) report production of 15 tons of REE ore from pegmatites in Pikes Peak granite at the Snowflake feldspar claims northwest of Woodland Park. Allanite, fergusonite, xenotime, yttrian fluorite, and the uncommon yttrium silicate, thalenite, occur in perthitic microcline; thalenite samples assayed up to 32.6 percent yttrium (Adams et al., 1962). A buffer around the Snowflake mines area is assigned H/D for REE potential.

The Black Cloud mine is developed in a zoned feldspar pegmatite that hosts xenotime, monazite, cerian fluorite, gadolinite, samarskite, fergusonite, and the rare yttrotantalite in Pikes Peak granite (Heinrich and Gross, 1960). The pink Pikes Peak granite assayed up to 853 ppm total REE oxides, almost 4 times the normal crustal abundance (Smith et al., 1999). Gray Pikes Peak monzogranite in the northern part of the batholith assayed up to 519 ppm total REE oxides

(Smith et al., 1999). The potassic Windy Point granite and sodic Lake George syenite intrusions assayed up to 980 and 904 ppm total REE oxides respectively (Smith et al., 1999). Outside the Mount Rosa and Snowflake mine areas, the composite Pikes Peak batholith is designated M/C for REE potential.

4.35.12 Niobium-Tantalum

Though just two niobium-tantalum occurrences and no production are reported for Teller County, euhedral fergusonite crystals, as well as microlite, pyrochlore, and samarskite, are reported from zoned pegmatites in the Pikes Peak batholith of Jefferson, El Paso, and Douglas Counties (Haynes, 1965; Simmons and Heinrich, 1980). Pegmatites are vertical pipe-like to ellipsoidal lenses occurring at elevations between 6800 and 7800 feet within the Pikes Peak granite and quartz monzonite (Simmons and Heinrich, 1980). Niobium-tantalum minerals are reported from pegmatites in the St. Peters Dome area and around the perimeter of the Mount Rosa intrusive center (Parker, 1968). Buffers along pegmatite zones in Pikes Peak Granite of El Paso County are designated L/B for niobium-tantalum occurrence potential.

4.35.13 Tellurium

The Tertiary volcanic complex of the Cripple Creek district hosts gold-tellurides. Tellurium is present where gold is present as calaverite ($AuTe_2$), but more exotic telluride minerals including coloradoite (HgTe), melonite ($NiTe_2$), and petzite (Ag_3AuTe_2) are often present in host rocks. The alkalic volcanic rocks associated with gold mineralization in this district are assigned a tellurium occurrence potential of H/D. Precambrian rocks in the remainder of the county are considered L/B for tellurium occurrence.

4.35.14 Titanium

Late-stage alkalic and mafic intrusions into the Precambrian Pikes Peak batholith host titanium-rich minerals, and several past producers are noted from this and El Paso Counties (Smith et al., 1999; USGS MRDS, 2013). Ilmenite and microscopic rutile are reported from the Cripple Creek complex (Eckel, 1961). Alkalic and mafic units in the Pikes Peak batholith in Teller County are designated L/B for titanium potential.

4.35.15 Uranium

About 400 tons of ore yielding 1,200 pounds of U_3O_8 have been produced in Teller County from five mines or prospects (Nelson-Moore et al., 1978). All of the known production stems from the Tallahassee Creek Conglomerate in association with the underlying Tertiary Wall Mountain Tuff and overlying lower member of the Thirtynine Mile Andesite (Hon, 1984; Nelson-Moore et al., 1978). Most of the production (965 pounds) was recovered from 0.16 percent U_3O_8 ore in the Tallahassee Creek Conglomerate near Grouse Mountain west of Victor (Nelson-Moore et al., 1978). Samples from various past-producing mines in this unit assayed up to 0.44 percent U_3O_8 (Nelson-Moore et al., 1978). The Tallahassee Creek Conglomerate, Echo Park Formation, Wall Mountain Tuff, and Thirtynine Mile Andesite are designated H/D in areas of reported production and H/B elsewhere for uranium occurrence potential.

Mineralized veins host uranium in the Precambrian Mount Rosa alkaline granite, and some production is reported from mines in El Paso County (Nelson-Moore et al., 1978). The Teller County portion of the Mount Rosa intrusive complex is designated H/C for uranium occurrence potential. The late-stage Windy Point alkalic intrusions and into the Pikes Peak granite are assigned L/B for uranium potential. Tertiary siliceous tuffs are source rocks for uranium leached and reprecipitated in nearby fractures and faults (Olson, 1988). Production of nearly 500 pounds of uranium is reported from a seam underlying Tertiary tuffs in Saguache County (Nelson-Moore et al., 1978). Tertiary tuffs and phonolites in Teller County are designated L/B for uranium occurrence potential.

4.35.16 Thorium

Thorium in monazite occurs in veins and pegmatites along faults in the Precambrian Pikes Peak batholith at several mines in Douglas and Jefferson Counties, as well as several mines in the St. Peters Dome area of El Paso County; some production is reported (Heinicke, 1960; Schwochow and Hornbaker, 1985; USGS MRDS, 2013). Buffers along faults in Precambrian crystalline rocks are designated M/C in the St. Peters Dome area and L/C elsewhere for thorium occurrence potential.

4.35.17 Vanadium

In Teller County, about 2 pounds of V_2O_5 were produced from 5 tons of ore containing 0.02 percent V_2O_5 in the Oligocene Tallahassee Creek Conglomerate at the Genevieve Lode (Nelson-Moore et al., 1978). Significant uranium and vanadium production is reported from the Eocene Echo Park Formation and overlying Tallahassee Creek Conglomerate in Fremont County (Nelson-Moore et al., 1978). The Echo Park Formation and Tallahassee Creek Conglomerate are designated H/C for vanadium potential in Teller County.

Tyuyamunite is reported from a shear zone between Tertiary volcanic breccia and a phonolite dike at the Lady Stith (Globe Hill) claim, although no production is reported (Nelson-Moore et al., 1978). Also, roscoelite is associated with gold tellurides at the Cripple Creek gold mine (Cappa, 1998; Lovering and Goddard, 1950). Tertiary tuffs, phonolites, and other intrusives in the area surrounding this mine and the greater Cripple Creek gold mining district are assigned L/B for vanadium occurrence potential.

4.35.18 Fluorspar

Average content of fluorine (ppm) in Central Colorado measured anomalously high in Precambrian igneous and metamorphic rocks, as well as in Tertiary intrusives, all of which are found in Teller County (Wallace, 2010). The Pikes Peak composite batholith comprises the main granitic body plus numerous late-stage peraluminous to peralkaline granitic plutons and pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999; Tweto, 1987). Fluorite is a primary accessory mineral in all phases of the Pikes Peak composite batholith and related pegmatites; the composite batholith averaged 2,140 to 3,500 ppm fluorine and ranged up to 100,000 ppm (Wallace, 2010). Several fluorspar prospects are developed in the Teller County portion of the batholith (USGS MRDS, 2013). The Crystal Peak pegmatites, famous for gem-quality minerals including crystals of fluorite up to 6 inches long, are located on the eastern perimeter of the sodic Lake George ring complex in western Teller County (Aurand, 1920; Eckel, 1961; Kile and Eberl, 1999; Smith et al., 1999). Violet-blue fluorite is a common accessory mineral of the Tertiary Cripple Creek mining district ores; samples assayed up to 24,000 ppm fluorine, averaging 1,700 ppm (Aurand, 1920; Wallace, 2010). Veins of massive fluorite are also reported from Cripple Creek, although no commercial production is reported (Brady, 1975). Precambrian igneous rocks, including all phases of the Pikes Peak batholith, are designated H/C for fluorspar occurrence potential; Precambrian biotite gneiss and Tertiary intrusives, including the Cripple Creek complex, are assigned M/C.

4.35.19 Diamond and Gemstones

The Pikes Peak composite batholith comprises numerous late-stage peraluminous to peralkaline granitic plutons, including the sodic Mount Rosa intrusive complex in eastern Teller County, all of which host pegmatites (Gross and Heinrich, 1966; Persson, 2016; Smith et al., 1999). Gem-quality fluorite, topaz, quartz, amazonite, and zircon are reported from the numerous pegmatites of the Mount Rosa complex and St. Peters Dome area (Eckel, 1961; Pearl, 1972; Persson, 2016; Scott, 1968b). A buffer around this region is designated H/D for gemstone occurrence potential.

The Crystal Peak pegmatites, famous for gem-quality amazonite, topaz, smoky quartz, amethyst, and fluorite, are located on the eastern perimeter of the sodic Lake George ring complex in western Teller County (Eckel, 1961; Kile and Eberl, 1999; Pearl, 1972; Smith et al., 1999). This area has been worked since 1865, having produced amazonite crystals up to 18 inches in length and smoky quartz crystals weighing up to 52 pounds (Eckel, 1961; Pearl, 1972). A buffer around the Lake George pluton, which spans the Teller-Park county line is designated H/D for gemstone occurrence potential.

Some of the largest known petrified tree stumps are found in a 5-meter-thick volcaniclastic debris flow within the 70-meter-thick Eocene Florissant Formation at the Florissant Fossil Beds National Monument, just south of the Crystal Peak region (Mustoe, 2008; Pearl, 1972). Silicified tree trunks, hosting opal and chalcedony and ranging up to 4 meters thick and tall, are found within a petrified forest near the center of the National Monument (Mustoe, 2008). The region around the Florissant Fossil Beds National Monument is designated M/C for gemstone occurrence potential.

At least a few hundred pounds of turquoise have been mined from the Florence Lode in the Cripple Creek mining district (Cappa et al., 2003; Del Rio, 1960; Scott, 1968b; USGS MRDS, 2013). Relatively small opal, fluorite, smoky quartz, and rhodochrosite crystals are also reported from vugs and veins throughout this district and constitute gangue minerals of the polymetallic ores (Lindgren and Ransome, 1906). Large, well-formed tourmaline crystals occur in a pegmatite near Rhyolite Mountain (Lindgren and Ransome, 1906). The greater Cripple Creek district is designated H/D for gemstone occurrence potential.

Pegmatites hosting amazonite, smoky quartz, topaz, and amethyst occur sporadically throughout the Pikes Peak region (Arbogast et al., 2011, Pearl, 1972). The Pikes Peak batholith outside the Mount Rosa complex, Lake George pluton, and Cripple Creek district areas is assigned M/C for gemstone potential.

Due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the nearby CMB, Precambrian biotite gneisses and schists are assigned M/B for gemstone potential (Lovering and Goddard, 1950). Zoned pegmatites are known to occur in Silver Plume-aged plutons, and the correlative Cripple Creek pluton in southwestern Teller County is assigned L/B for gemstone potential outside the Cripple Creek district (Boos, 1954). The Precambrian Boulder Creek Granite, which is relatively devoid of pegmatites, is designated L/A for gemstone occurrence potential (Boos, 1954).

4.35.20 Pegmatite Minerals

Meeves et al. (1966) report 14 tons of scrap mica production from Teller County through 1963. Six miles northwest of Woodland Park, the Snowflake mine is listed as a past producer of feldspar (microcline) from a pegmatite in Pikes Peak granite (USGS MRDS, 2013). The USGS MRDS (2013) reports 90 tons of feldspar ore being produced in 1942 at the Quartz Lode (Dands #2 Feldspar Quarry) from pegmatite near the Lake George pluton of the Pikes Peak batholith. The Black Cloud mine is also developed in zoned pegmatite near the Lake George pluton and has reported production of 585 tons of feldspar (microcline) in 1941 (USGS MRDS, 2013). The area around the Lake George pluton and reported past producers is designated H/C for pegmatite occurrence potential. Elsewhere in the county, Precambrian biotite gneiss and schists are assigned M/B for potential. Precambrian plutonic rocks are considered L/B except the Pikes Peak batholith which is designated M/C.

4.35.21 Industrial Abrasives

There is no reported production of industrial abrasives in Teller County; however, due to the preponderance of pegmatites in Precambrian metamorphic rocks and elevated mineralization in the CMB to the west, Precambrian metamorphic rocks in the county are designated M/C for industrial abrasive (garnet) potential (Lovering and Goddard, 1950). Precambrian igneous rocks, which are relatively devoid of pegmatites, are designated L/B for industrial abrasive occurrence potential (Boos, 1954).

4.35.22 Limestone and Dolomite

There are no limestone quarries in Teller County; however, the Leadville, Williams Canyon, and Manitou Limestones have historically been used as flux for smelting both iron and lead ores (D. A. Carter, 1968; Vanderwilt, 1947). The Leadville Limestone was also used in the sugar refining process, and the un-dolomitized portions are suitable for cement production (Wolfe, 1968; Schwochow, 1981). These units are designated H/C for limestone and dolomite occurrence potential in northeastern Teller County.

4.35.23 Industrial Sand

Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium throughout the RGFO region, including several in Teller County (Schwochow, 1981); Quaternary alluvium is assigned M/C for industrial sand potential along Crystal Creek and around an additional isolated occurrence.

4.35.24 Sand and Gravel

Several sand and gravel prospects are developed in Quaternary deposits in Teller County (USGS MRDS, 2013). High-quality sand and gravel deposits are found in youngest floodplain and low-elevation terraces mapped as Qg (gravel) (Arbogast et al., 2011; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; pockets of glacial drift (Qd) are assigned H/C for potential (Arbogast et al., 2011).

In central Teller County, Tertiary gravels near Divide are sometimes mapped as the Pliocene Ogallala Formation. Weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered M/C for sand and gravel potential. The Pennsylvanian-Permian Fountain Formation, which host sporadic sand and gravel operations in this and other counties, is designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968). Additionally, several DRMS-permitted quarries and USGS MRDS (2013) occurrences are scattered in various rock units throughout the county, principally along creek beds; buffers along these creek beds are assigned M/C, and around other individual occurrences are designated L/C, for sand and gravel occurrence potential.

4.35.25 Crushed Stone Aggregate

In Teller County, Cambrian to Mississippian limestones and quartzites are excellent source rocks for crushed stone aggregate, being relatively hard and free from fractures with no deleterious chemical constituents (Knepper et al., 1999). Dense limestones and dolomites are excellent sources of crushed stone aggregate, comprising about 70 percent of production nationwide (Langer and Knepper, 1995; Knepper et al., 1999). Cambrian to Mississippian limestones and quartzites, mapped as Or, MC, or OC in Teller County, are assigned H/D for crushed stone aggregate occurrence potential.

Dense, fine-grained Tertiary volcanic rocks like basalt (traprock) satisfy the physical and chemical standards for high-quality crushed stone aggregate, although welded tuffs typically contain microcrystalline quartz which is detrimental to cement-making (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Significant production of high-quality crushed stone from basaltic flows is reported from other counties (Arbogast, 2011). Tertiary andesitic lavas and breccias (mapped as Tpl) may be too porous with abundant deleterious constituents in part to meet the requirements of crushed stone aggregate (Knepper et al., 1999). Tertiary intrusive rocks are assigned H/C for crushed stone potential, except andesitic rocks mapped as Tpl, which are assigned M/B.

Dense, consolidated granite, where lightly jointed, faulted, and weathered, may meet the physical and chemical requirements for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). Silver Plume-aged granites, like the Cripple Creek pluton in Teller County, make excellent crushed stone aggregate source rocks (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The older, more weathered and jointed Precambrian Boulder Creek plutons and satellites were classified as only ‘fair’ source rocks by Knepper et al., (1999). Arbogast et al. (2011) categorized the younger Pikes Peak Granite as a good-quality source for crushed stone aggregate, but Knepper et al. (1999) classified it as unsuitable due to the degree of weathering. Some Precambrian metamorphic rocks in the RGFO region have also been quarried for crushed stone aggregate, although foliation typical of schist renders a rock unsuitable (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Cripple Creek pluton is designated H/C, the Boulder Creek Granite is assigned M/C, and the Pikes Peak Granite is assigned MB, for crushed stone aggregate potential. Precambrian Idaho Springs Formation biotite schist is assigned L/B, and felsic and hornblendic gneisses are assigned H/B, for crushed stone aggregate occurrence potential.

Most sandstones and siltstones are too soft to meet the physical specifications of crushed stone aggregate; however, well-indurated and unweathered sandstone units in the Fountain and Morrison Formations may satisfy the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Fountain and Morrison Formations are designated L/C for crushed stone potential.

4.35.26 Lightweight Aggregate

The natural lightweight aggregate, vermiculite, forms from the weathering of micas, which are common in Precambrian granitic igneous and metamorphic rocks (Arbogast et al., 2011). Pegmatites and syenite dikes are abundant in the Precambrian igneous and metamorphic rocks of Teller County, and vermiculite is commonly associated with them (Bush, 1968; Heinrich, 1957). There are a couple past DRMS-permitted vermiculite operations developed in these rocks (Del Rio, 1960). The relatively unweathered Pikes Peak and Cripple Creek granitic plutons are designated L/B, and the older, more weathered Boulder Creek Granite is designated M/B, for lightweight aggregate potential. Precambrian metamorphic rocks are designated M/C for lightweight aggregate potential.

Numerous outcrops of felsic to mafic tuffs and breccias derived from Tertiary volcanic activity may host pumice, scoria, or perlite; several developed occurrences are noted (Arbogast et al., 2011; Knepper et al., 1999; USGS MRDS, 2013; Vanderwilt, 1947). These rocks are assigned H/C for lightweight aggregate occurrence potential.

4.35.27 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). Teller County hosts rock units of all ages that have been quarried for dimension stone, including the Precambrian Pikes Peak Granite, Cambrian to Mississippian quartzites, sandstones, and limestones, the Pennsylvanian-Permian Fountain Formation (conglomerate), the Permian-Triassic Lyons Sandstone, and the Cretaceous Dakota Sandstone (Arbogast et al., 2011; Cappa et al., 2003; Lindvall, 1968; Schwochow, 1981).

The Precambrian Pikes Peak and Cripple Creek granitic plutons have been quarried for dimension stone in the RGFO region, although where weathered or highly jointed, these granites are more suited for use as crushed stone (Arbogast et al., 2011; Lindvall, 1968; Schwochow, 1981). The Pikes Peak and Cripple Creek plutons are designated H/C for dimension and building stone occurrence potential. The older and more weathered Boulder Creek Granite is designated M/C for dimension stone potential. Precambrian metamorphic rocks have no documented production of dimension stone; however, the occurrence potential is considered M/B.

Significant production of high-quality dimension stone is reported from the Cambrian Sawatch Quartzite, the Ordovician Manitou Limestone and Harding Sandstone, and the Mississippian Leadville Limestone throughout the Front Range (Arbogast et al., 2011; Cappa et al., 2003; Del Rio, 1960; Lindvall, 1968; Schwochow, 1981). Partially metamorphosed and marbleized Leadville Limestone is quarried in Pueblo, Fremont, and Chaffee Counties, and Pueblo County 'Beulah marble' adorns the Colorado State Capital building (Arbogast et al., 2011; Schwochow, 1981). Undifferentiated Cambrian through Mississippian rock units, mapped as Or, OC, or MC, are designated H/D for dimension and building stone occurrence potential. The Fountain Formation is the only conglomerate quarried (in Fremont County) for dimension stone in the RGFO region (Lindvall, 1968; Schwochow, 1981); the Fountain Formation is assigned M/C for dimension stone potential.

The Wall Mountain Tuff is a welded rhyolitic ash-flow tuff that occurs as isolated remnants in Teller County (Arbogast et al., 2011; Del Rio, 1960; Scarbrough, 2001; Tweto, 1979a). The Wall Mountain Tuff has been quarried in Douglas County for high-quality dimension and building stone (Del Rio, 1960). The Wall Mountain Tuff is designated H/D for dimension stone potential; other Tertiary intrusive bodies are assigned L/B for dimension stone potential.

4.36 Washington County

4.36.1 Geothermal

Traditional / EGS Geothermal

The eastern portion of Washington County is designated as L/A for high temperature/EGS geothermal resources due to it not being analyzed for traditional geothermal favorability (Williams et al., 2008). The entire county has moderate favorability for EGS (Augustine, 2011) and the western portion has low traditional favorability (USGS 2008); the western portion is therefore considered M/B.

Direct-Use / Low Temperature Geothermal

Washington County contains no known springs or wells. The majority of Washington County, which lies outside named COGCC fields, is considered H/B for low temperature and/or co-produced geothermal resources. Small, scattered areas within named fields are designated as H/C. An area in the east-central portion is below the temperature threshold and is designated M/B.

4.36.2 Gold

Parker (1974) reports a placer gold occurrence northwest of Akron that is likely a reconcentration of a fossil placer in the Ogallala Formation. The small remnant of Ogallala Formation near the noted occurrence is designated M/C.

4.36.3 Industrial Sand

Widespread Quaternary eolian sands in Washington County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and one occurrence is noted for this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium in other counties; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, and there is one permitted operation noted in Washington County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.36.4 Helium

Most of Washington County is designated L/C for helium due to its location in the Denver Basin.

4.36.5 Sand and Gravel

High-quality sand and gravel deposits in Washington County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Sand and gravel operations are developed in the lower sandstone and conglomerate unit of the Oligocene White River Formation in this and other counties (Cullen, 1960); this unit is designated L/C for sand and gravel occurrence potential. Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.36.6 Crushed Stone Aggregate

There is one reported past DRMS-permitted crushed stone aggregate operation developed in limestone of the Tertiary White River Formation in northern Washington County. Well-cemented and unweathered sandstone or limestone units in the White River and overlying Ogallala Formations may meet the requisite qualifications for crushed stone aggregate (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The White River and Ogallala Formations are assigned L/B for crushed stone aggregate occurrence potential.

4.36.7 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported from the Tertiary Ogallala Formation in Washington and other counties (Schwochow, 1981; USGS MRDS, 2013). The Ogallala Formation is a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981). The underlying White River Formation is composed of ashy claystone and sandstone and may also be a suitable source rock for Leca (Knepper et al., 1999). The Ogallala Formation is designated M/C, and the White River Formation is assigned L/B, for lightweight aggregate occurrence potential.

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Pierre Shale is assigned H/C for lightweight aggregate potential.

4.36.8 Clay

There are no USGS MRDS (2013) or DRMS clay occurrences in Washington County; however, the Cretaceous Pierre Shale crops out in the western half of the county; the Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it elsewhere (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C for clay occurrence potential. Fuller’s earth is reported north of Akron by Patterson (1968); based on the map by Tweto (1979a) the occurrence may be hosted by the Pierre Shale or Tertiary White River Formation. The White River Formation is known to host occasional claystones suitable for use in making bricks; this unit is assigned L/B for clay potential (Vanderwilt, 1947). A few sand and/or gravel pits also produce clay from the alluvium along the South Platte River in other counties; the alluvium mapped unit is designated L/C for clay potential.

4.36.9 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Washington

County, the Tertiary White River Formation and Ogallala Formation host sandstones in part, but have no documented production of dimension stone. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the White River Formation is designated M/B, for dimension and building stone occurrence potential.

4.37 Weld County

4.37.1 Coal

The RGFO portion of the Cheyenne Basin of the Denver Coal Region (see section 3.1.1 of this MPR) lies in north-central Weld County. Southern Weld County contains the northern extent of the Denver Basin and Boulder-Weld coal field, also of the Denver Coal Region. Production of 68.7 million tons of coal is reported between 1864 and 2002 from the Cretaceous Laramie Formation at 68 past-producing mines, predominantly in the Denver Basin (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). There are two inactive CDRMS coal exploration permits in the county. Weld County also hosts the only active coal mine in the Denver Basin, the Keenesburg Strip mine operated by Coors Energy Company.

Of an estimated 1.7 billion tons of original coal resources under 3,000 feet of overburden in the county, roughly 137 million tons are depleted, implying reserves of 1.56 billion tons of subbituminous coal (Brandt, 2015; Carroll and Bauer, 2002; Landis, 1959). The Denver Basin in Weld County is designated H/D for coal occurrence potential around the area of producing mines and H/C elsewhere. The Cheyenne Basin is designated H/C for coal occurrence potential around the producing mines and H/B elsewhere. RGFO management area coal occurrence potential is depicted on Map 7-1 in section 7.

4.37.2 Geothermal

Traditional / EGS Geothermal

The majority of Weld County is designated as M/B for high temperature/EGS geothermal resources due to the combination of moderate-high EGS favorability (Augustine, 2011) and low traditional geothermal favorability (Williams et al., 2008). The west-central portion has high favorability for EGS, and is therefore designated as M/C. The northeastern corner has low EGS favorability and a designation of L/B.

Direct-Use / Low Temperature Geothermal

Weld County contains no known springs or wells. The southwestern portion of Weld County is dominated by named COGCC fields of the Denver Basin and, along with other scattered areas, is designated H/C. Areas in the northern and northeastern parts of the county are below the temperature threshold for low temperature and co-produced geothermal resources and are designated M/B. The rest of the county, which lies outside named COGCC fields and is above the temperature threshold, is considered H/B.

4.37.3 Iron

No iron production is reported in Weld County; however, thin beds containing abundant siderite, hematite, and limonite concretions above a coal seam in the Laramie Formation are reported from this and Boulder County, and significant production was reported from a Boulder County mine (Harrer and Tesch, 1959; Reade, 1978). The Laramie Formation is designated L/B for iron occurrence potential in Weld County.

4.37.4 Manganese

There is one known occurrence of manganese in Weld County, located at the Furney Manganese prospect. MRDS (2013) lists this prospect as a past producer of manganese, and the Prospect is situated in the Tertiary White River Formation, which stratigraphically overlies the upper Dawson Arkose where manganese occurs in other counties (e.g., Arapahoe and Douglas). Potentially the manganese was mined at depth in the Dawson Arkose, but no further information is available. The area around this prospect is designated L/C for manganese potential.

4.37.5 Gallium-Germanium-Indium

There are no reported occurrences or production of gallium, germanium, or indium in Weld County; however, the Cheyenne and Denver Basins of the Denver Coal Region in the county (see sections 3.1.1 and 4.37.1 of this MPR) are designated L/B for germanium occurrence potential.

4.37.6 Titanium

Although no titanium production is reported for Weld County, economical concentrations of fossil heavy-mineral placer deposits, including rutile and ilmenite, occur at Titanium Ridge in the Late Cretaceous Fox Hills Sandstone of Elbert County (Arbogast et al., 2011; Pirkle et al., 2012). The Fox Hills Sandstone in Weld County is designated L/B for titanium occurrence potential.

4.37.7 Uranium

Several significant uranium deposits within the Cheyenne Basin of Weld County were mined in the 1970s and early 1980s, and at least one area is currently proposed for in situ solution mining. Interest in uranium started in 1970 when a rancher reported anomalous uranium shows in cuttings from seismic shotholes. An extensive leasing and drilling effort followed, and between 1970 and 1972 over 3,000 exploration test holes with total footage in excess of 1 million feet were drilled (Reade, 1978). Four solution-front uranium deposits were discovered by the project: the Grover, Keota, Pawnee, and Sand Creek deposits.

The Grover and Sand Creek uranium deposits are in the Cretaceous Laramie Formation, and the Keota and Pawnee deposits are in the Cretaceous Fox Hills Sandstone. Reade (1978) reported the Grover deposit contained over 1 million pounds of U_3O_8 at a grade of 0.05 percent U_3O_8. Wyoming Minerals Corporation conducted a pilot-scale in situ solution mine at the Grover deposit in 1977 and 1978 (DRMS Permit No. M1977-159). Power Resources and Union Oil Company of California proposed a full-scale in situ solution mine at the Keota deposit and hoped to start mining in 1980 or 1981 (DRMS Permit No. M1981-045). They expected the mine to produce 5 to 10 million pounds of U_3O_8 during the 10 to 20 years of anticipated production (Wyoming Minerals Corporation, 1978; Kirkham and Ladwig, 1980). However, although the mine was in the licensing and permitting phase, the price of uranium dropped and the mine never opened. Using a cutoff grade of 0.05 percent U_3O_8, Reade (1978) reported the Sand Creek deposit contained about 150,000 pounds of U_3O_8, and the Pawnee deposit was described as having about 1 million pounds of U_3O_8, but neither deposit has yet been mined.

Powertech (USA) Inc. (a.k.a. Powertech Uranium or Azarga Uranium Corporation) recently developed the advanced-stage exploration project (Centennial Project) along the western margin of the Cheyenne Basin between the towns of Nunn and Wellington. SRK Consulting (2010) describes the project as a proposed in situ solution mining or in situ recovery project that potentially could produce about 10 million pounds of U_3O_8 from several different solution roll-front deposits in the Fox Hills Sandstone.

Numerous other uranium occurrences are known in Weld County. All are within the Cheyenne Basin and associated with either the Laramie Formation (called the Lance Formation in some references) or Fox Hills Sandstone. Note that the Lance Formation is incorrectly correlated with the Fox Hills Sandstone in some publications.

The Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin area are assigned H/D for uranium resources. These units elsewhere in the county are designated H/B.

4.37.8 Vanadium

No vanadium is known to have been produced in Weld County; however, three occurrences are reported in the USGS MRDS (2013): the Grover, King Solomon, and Pawnee Buttes N.E. uranium deposits, all of which are developed in the Cretaceous Laramie Formation or underlying Fox Hills Sandstone. Carnotite and tyuyamunite are reported at the Grover and Pawnee Buttes N.E. deposits (Nelson-Moore et al., 1978). Minor amounts of vanadium are associated with uranium reserves in the western Cheyenne Basin as reported by SRK Consulting (2010). Based on estimated uranium reserves (see Weld County uranium, section 4.37.7 above), future uranium production could possibly yield significant vanadium as a byproduct in these units. The Laramie Formation and Fox Hills Sandstone are designated L/B for vanadium occurrence potential.

4.37.9 Diamonds and Gemstones

Abundant pale to deep blue euhedral barite crystals up to 6 inches long occur singly or in clusters in calcite veins and cavities in the Oligocene Chadron Formation of the White River Group in northeastern Weld County (Modreski et al., 1990; Pearl, 1972). Thousands of barite crystals and clusters with outstanding color, clarity, and luster have been recovered along a northwest-trending reverse fault that cuts montmorillonite clay (altered volcanic ash) beds about 6 miles northeast of Stoneham (SW¼ section 15, T8N, R56W) (Modreski et al., 1990). Barite crystals are also reported from other outcrops of the Chadron Formation in Weld County (Modreski et al., 1990). A northwest-trending buffer around the occurrence in this area is designated H/D for gemstone occurrence potential; the White River Group elsewhere in this region of the county is assigned M/C.

4.37.10 Industrial Sand

Widespread Quaternary eolian sands in Weld County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and a few quarries are developed in eolian sands in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are noted in Weld County along Cottonwood Creek, Box Elder Creek, Boulder Creek, and the South Platte River; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Tertiary Dawson Arkose and Ogallala Formation throughout the RGFO region, and two permitted operations occur in Weld County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C, and the Dawson Arkose is designated L/C, for industrial sand potential.

4.37.11 Helium

The eastern and southern parts of Weld County are designated L/C for helium due to its location in the Denver Basin.

4.37.12 Sand and Gravel

Abundant high-quality sand and gravel deposits in Weld County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) and Qg (gravel) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential; older Quaternary gravels and alluvium (Qgo), which are more deeply weathered and friable, are assigned H/C for potential (Arbogast et al., 2011). Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). In Weld County, the undifferentiated Tertiary Dawson Arkose, Denver Formation, and Arapahoe Formation, as well as the White River Formation, Cretaceous Fox Hills Sandstone and Laramie Formation, all of which host sporadic sand and gravel operations in this and other counties, are designated L/C for sand and gravel occurrence potential (W. D. Carter, 1968; Schwochow, 1981). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in some areas (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered M/D for sand and gravel potential.

4.37.13 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Weld County; however, well-cemented and unweathered sandstone units in the Cretaceous Fox Hills Sandstone, as well as the Tertiary Dawson Arkose, White River Formation, and Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Fox Hills Sandstone is designated L/C, and the Dawson Arkose, White River Formation, and Ogallala Formation are assigned L/B, for crushed stone aggregate occurrence potential.

4.37.14 Lightweight Aggregate

The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The overlying Fox Hills Sandstone, which is composed of 20 to 40 percent clay and silt, as well as the Laramie Formation, composed of highly expansive claystones, host mixed-layer illite-montmorillonite clay (with some deleterious kaolinite) and may be suitable resources for Leca (Hansen and Crosby, 1982; Knepper et al., 1999). The Fox Hills Sandstone is designated L/B, the Laramie Formation is designated M/B, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

Often mapped together, the Arapahoe and Denver Formations and Dawson Arkose contain claystone beds bearing up to 95 percent (in the Denver Formation) of moderately to highly expansive illite and montmorillonite clay and silt, suitable for Leca production (Bush, 1968; Hansen and Crosby, 1982). However, expandable clay occurrence potential may vary region-wide in the Dawson Arkose due to the lack of lateral persistence of claybeds and the occurrence of kaolinite (Hansen and Crosby, 1982). The undivided Denver and Arapahoe Formations (mapped as TKda) are designated M/C, and the undivided Denver Formation and Dawson Arkose (mapped as TKdl) are designated M/B, for lightweight aggregate potential.

Production of volcanic ash (pumice or pumicite) is reported in other counties from the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981; USGS MRDS, 2013). Suitable expandable clays may be found in the underlying Arikaree Formation, which hosts abundant volcanically derived clasts, and the White River Formation, which is composed of ashy claystones and sandstones (Knepper et al., 1999). The Ogallala Formation is designated M/C, and the White River and Arikaree Formations are assigned L/B, for lightweight aggregate occurrence potential.

4.37.15 Clay

The Cretaceous Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). Abundant kaolinite with significant montmorillonite occurs in shales of the Cretaceous Laramie Formation, although quartz impurities result in a PCE below 20, relegating the quarried clay to the brick industry (Spence, 1980). As many as 40 clayrock units have been mined in the Laramie Formation, which was estimated to be the largest source of structural clay in the State by Hansen and Crosby (1982). The Tertiary Dawson Arkose, correlative with the Denver Formation and often undifferentiated from the underlying Arapahoe Formation, commonly hosts mica clay in sandstone pockets or lenses: kaolinite is abundant, but quartz impurities restrict PCE values to between 19 and 21 (Spence, 1980). The Pierre Shale and Laramie Formation are designated H/C, and the Dawson Arkose is designated M/C, for clay potential.

Shale interbeds of the Cretaceous Fox Hills Sandstone host clay suitable for brick making; there is one clay prospect developed in this unit (Vanderwilt, 1947). A few sand and/or gravel pits also produce clay from the alluvium along the South Platte River in this and other counties (USGS MRDS, 2013); the Fox Hills Sandstone and alluvium mapped unit are designated L/C for clay potential. The Tertiary White River Formation is known to host occasional claystones suitable for use in making bricks; this unit is assigned L/B for clay potential (Vanderwilt, 1947).

4.37.16 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Weld County, the Cretaceous Fox Hills Sandstone, as well as the Tertiary Denver Formation, Dawson Arkose, White River Formation, and Ogallala Formation host sandstones in part but have no documented production of dimension stone. The Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B, and the other sandstone units are designated M/B for dimension and building stone occurrence potential.

4.38 Yuma County

4.38.1 Geothermal

Traditional / EGS Geothermal

The entirety of Yuma County is designated L/A for high temperature/EGS geothermal resources due to a lack of analysis indicating traditional geothermal favorability (Williams et al., 2008). The whole county does have moderate favorability for EGS (Augustine, 2011).

Direct-Use / Low Temperature Geothermal

Yuma County contains no known springs or wells. The majority of Yuma County is below the temperature threshold for low temperature and/or co-produced geothermal resources and is designated M/B. The western part of the county, which lies outside named COGCC fields, is considered H/B. Small, scattered areas within named fields are designated as H/C.

4.38.2 Industrial Sand

Widespread Quaternary eolian sands in Yuma County are composed of well-sorted and well-rounded quartz grains; significant production is reported from eolian sands in El Paso County, and one eolian sands quarry occurs in this county (Arbogast, 2011; Cappa et al., 2003; Carroll et al., 2001; USGS MRDS, 2013). Eolian sands are designated H/B for industrial sand occurrence potential. Quaternary alluvium (Qa) does not typically meet industrial sand specifications; however, several past and current DRMS-permitted industrial sand operations are developed in alluvium in Yuma County along the North and South Forks of the Republican River and the Arikaree River; Quaternary alluvium is assigned M/C for industrial sand potential. Sporadic DRMS-permitted industrial sand pits and limited production are reported from the Pliocene Ogallala Formation throughout the RGFO region, and several permitted operations are noted in Yuma County (Arbogast et al., 2011). The Ogallala Formation is assigned M/C for industrial sand potential.

4.38.3 Helium

Most of Yuma County is designated L/D for helium due to its location in the Denver Basin.

4.38.4 Sand and Gravel

High-quality sand and gravel deposits in Yuma County are found in youngest floodplain and low-elevation terraces mapped as Qa (alluvium) (Arbogast et al., 2011; Del Rio, 1960; Tweto, 1979a). These units are designated H/D for sand and gravel occurrence potential. Widespread Quaternary eolian deposits (Qe) are considered just M/C for sand and gravel potential due to a high concentration of fine-grained sediments (Arbogast et al., 2011).

Sedimentary rocks of all ages host sand and gravel occurrences throughout the RGFO region (USGS MRDS, 2013). Throughout eastern Colorado, weathering of the Pliocene Ogallala Formation resulted in loosely consolidated sandstone and conglomerate which have been extensively quarried in this and other counties (W. D. Carter, 1968; Del Rio, 1960; Schwochow, 1981); this unit is considered H/D for sand and gravel potential.

4.38.5 Crushed Stone Aggregate

There is no reported production of crushed stone aggregate in Yuma County; however, well-cemented and unweathered sandstone units in the Tertiary Ogallala Formation may meet the requisite qualifications (Arbogast et al., 2011; Knepper et al., 1999; Langer and Knepper, 1995). The Ogallala Formation is assigned L/B for crushed stone aggregate occurrence potential.

4.38.6 Lightweight Aggregate

Production of volcanic ash (pumice or pumicite) is reported in Yuma County (Schwochow, 1981). A couple of quarries are developed in the Tertiary Ogallala Formation, a highly weathered, loosely consolidated, clay-bearing sandstone and conglomerate, with occasional ash beds (Knepper et al., 1999; Schwochow, 1981). The Cretaceous Pierre Shale is composed of abundant claystones and some bentonite (lower member); the clay type is mixed-layer illite-montmorillonite, which is favorable for the production of Leca (Bush, 1968; Hansen and Crosby, 1982; Knepper et al., 1999). The Pierre Shale has been quarried to produce Leca, and its thickness (up to 2,500 meters) suggests a sizeable resource for expandable clay (Bush, 1968; Hansen and Crosby, 1982). The Ogallala Formation is designated M/C, and the Pierre Shale is assigned H/C, for lightweight aggregate occurrence potential.

4.38.7 Clay

There are a few USGS MRDS (2013) clay occurrences in Yuma County, likely developed in the upper unit of the Cretaceous Pierre Shale, which is overlain by alluvium from the North Fork of the Republican River. The Pierre Shale hosts clay beds ranging from 900 to 2,500 meters thick in the northeastern quarter of the State (Hansen and Crosby, 1982). The Pierre Shale hosts abundant illite with complementary montmorillonite, as well as bentonite interbeds, and clay quarries are mined in it throughout the RGFO region (Arbogast, 2011; Landis, 1959b; Schultz, 1978). The Pierre Shale is designated H/C, and the alluvial unit around the North Fork of the Republican River is assigned L/C, for clay occurrence potential.

4.38.8 Dimension and Building Stone

To qualify as dimension or building stone, a rock must meet the proper physical and chemical attributes such as durability, strength, resistance to weathering, color, texture, and ability to take a polish (Arbogast et al., 2011). Though the most common types of building and dimension stone (granite, sandstone, limestone, marble, and rhyolite) are found throughout the RGFO region, not all varieties meet the qualitative attributes (Mead and Austin, 2006). In Yuma County, the Pliocene Ogallala Formation is partially composed of a highly weathered and loosely consolidated sandstone unsuited for use as dimension stone (Arbogast et al., 2011; W. D. Carter, 1968). The Ogallala Formation is designated L/B for dimension and building stone occurrence potential.

5. OVERVIEW OF MINERAL RESOURCE ECONOMICS

This section provides additional detail related to the market demand of mineral commodities, economic and geopolitical trends involving minerals, and the anticipated future need and usage of minerals both nationally and internationally. The following information provides a broad outlook of the role of mineral commodities now and into the near future. This information was obtained by reviewing available literature on mineral developments and markets; communication with industry experts and government representatives familiar with specific mineral resources and mining activities within the RGFO management area; consideration of the mineral occurrence potential and historical development previously described in this MPR; and evaluation of commodity pricing, supply, demand, and other relevant market factors.

5.1 Coal

- The "usable" characteristics of the material[1]
  - Abundant
  - Stored chemical energy released by burning

- What technology/industrial practice it is used for currently[1,2]
  - Electricity generation
  - Heating
  - Steel making (coke coal)

- What technology/industrial practice it might be used for in the future[2]
  - Gasification of coal to produce hydrogen, synthetic fuels, plastics, and to produce electricity

- Local, regional and worldwide reserves—both in the ground and stockpiled[2]
  - Worldwide, in the ground proved recoverable reserves of coal were ~979.8 billion short tons in December 2011
  - In January 2015, the U.S. had estimated recoverable reserves of 255.8 billion short tons of coal
  - As of January 1, 2015, producing mines in the U.S. had recoverable reserves of 19.4 billion short tons
  - There are no primary producing uranium mines in the RGFO

- Local, regional and worldwide markets and why[2]
  - The four largest total coal producing nations in 2014 were:
    - China (4.27 billion short tons)
    - United States (1.0 billion short tons; Figure 5-1)
    - India (0.736 billion short tons

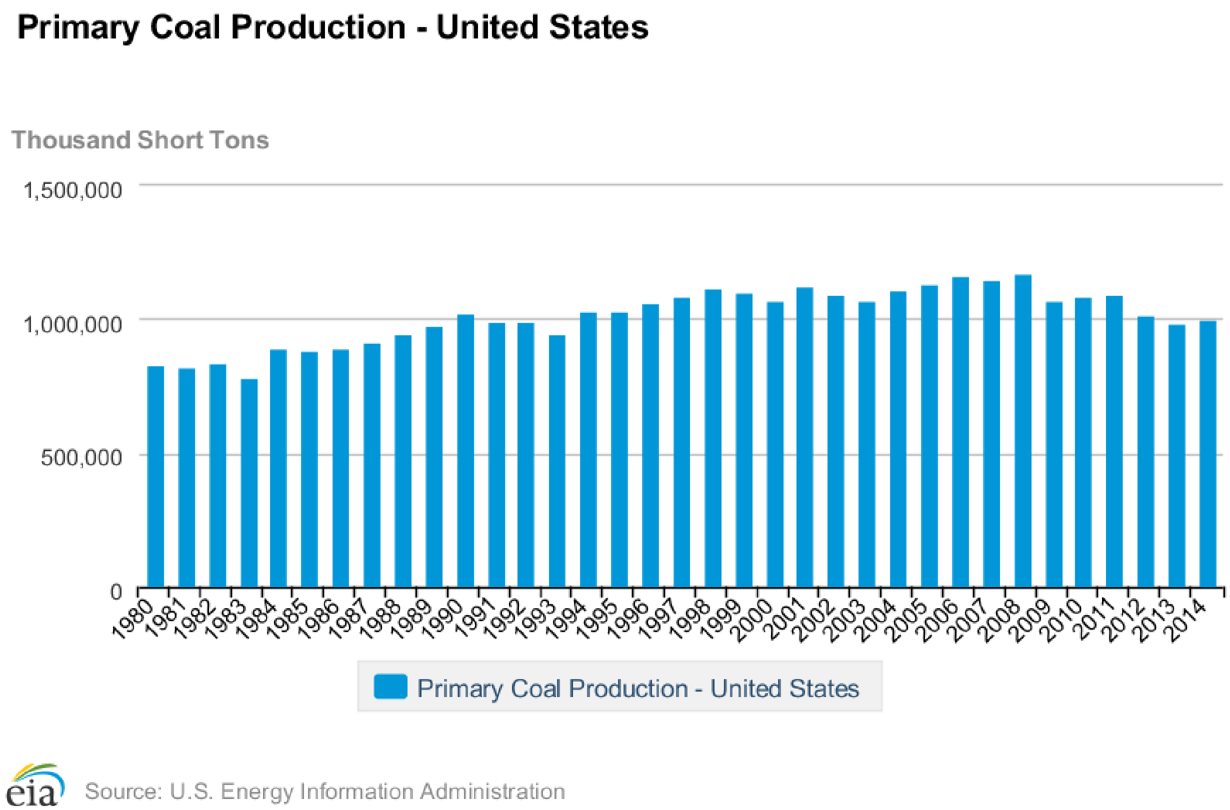


Figure 5-1. Annual U.S. production of coal from 1980 to 2014.

- Australia (0.553 billion short tons)
- The five largest total coal producing States in 2014 were (in descending order):
  - Wyoming (0.40 billion short tons)
  - West Virginia (0.11 billion short tons)
  - Kentucky (0.08 billion short tons
  - Pennsylvania (0.06 billion short tons)
  - Illinois (0.06 billion short tons)
- Coal is produced in ~65 countries around the world; Coal is widely but unevenly distributed, and the grade of coal varies significantly from deposit to deposit and sometimes even within a single deposit.
- In 2015, 1159 mines produced coal in the U.S.
- In 2012, the five States that used the most Colorado coal were Tennessee, Kentucky, Utah, Alabama, and Illinois (CU Leeds, 2013).
- 91 percent of coal consumed in 2015 went to the electric power sector; 33 percent of electricity generated in 2015 came from coal
- As of 2013, there was one coal mine with an active permit in the RGFO area on private land[3]

- Reasons for demand fluctuations[2]
    - Growing demand for non-fossil fuel options
    - The Clean Power Plan, announced in 2015, aims to reduce carbon emissions from power plants, the leading source of greenhouse gas emissions in the U.S. One of the suggested emission-reduction "building blocks" is to shift electricity generation from higher emitting, fossil fuel-fired steam power plants (generally coal-fired) to lower emitting natural gas-fired power plants. The implementation of the plan was stayed in February 2016 pending judicial review (U.S. EPA, 2016a)
    - Price of coal (Figure 5-2)
    - Sales of Colorado-mined coal to Alabama, Kentucky, and Tennessee have fallen significantly as the Tennessee Valley Authority reduced its consumption of Colorado coal by 2.8 million tons per year between 2008 and 2012 (CU Leeds, 2013)

- Reasons for market fluctuations[2]
    - Declining worldwide demand leads to lower production
    - Lower mining costs shift the market towards near-surface, thick coal deposits such as those in Wyoming and away from thinner, deeper deposits such as those in Appalachia

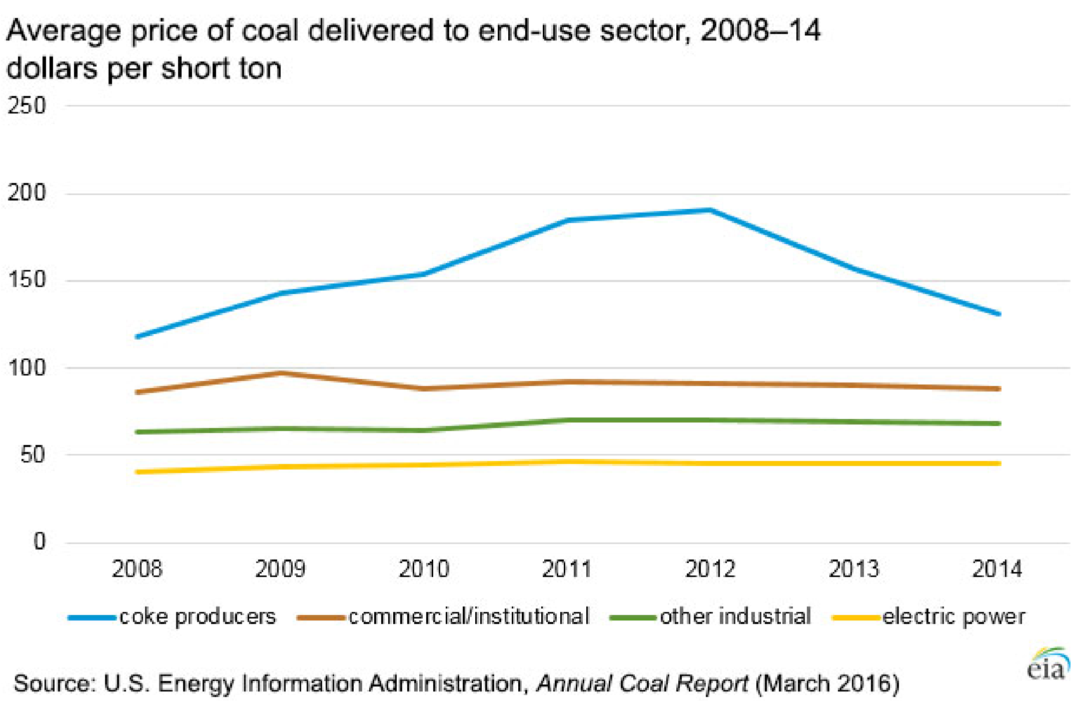


Figure 5-2. Annual average price of coal from 2008 to 2014.

  - Increased transportation costs can increase prices of long shipping distances, pricing western producers out of eastern markets

- Current and projected trends for demand and why[2]
  - Demand for clean energy is likely to continue to increase, reducing demand for coal
  - If the Clean Power Plan is permanently disbanded or there are other legislative changes, coal demand could remain steady or rise

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for coal, high occurrence potential areas in the RGFO (e.g., the Raton Basin) could become economic

Summarized from:
[1]MEC, 2016
[2]U.S. EIA, 2014a
[3]CDRMS, 2016

5.2 Geothermal

- The "usable" characteristics of the material[1]
  - Renewable
  - Fairly abundant
  - Small above-ground footprint

- What technology/industrial practice it is used for currently[1,2]
  - Electricity generation
  - Direct heating of residential/commercial buildings
  - Food dehydration
  - Gold Mining
  - Milk Pasteurizing
  - Geothermal heat pumps for heating/cooling buildings

- What technology/industrial practice it might be used for in the future[2]
  - Enhanced geothermal systems
  - New technologies for low-temperature geothermal resources

- Local and regional and worldwide resources[1,2]
  - Geothermal resources are defined by the co-occurrence of heat found in rocks at depth, fluid to carry the heat, and permeability of the rocks. Areas where these three properties occur together have a high potential for geothermal resources.

        - The western U.S., including the Basin and Range Province, the Cascade Mountains, the Colorado Rockies, and the California coast, are areas with high geothermal resources
    - Colorado is dominated by low-temperature (<100°C) surface geothermal resources, but higher temperatures within a reasonable subsurface distance could provide potential power-generating capacity
        - 15 Colorado communities are within 5 miles of a geothermal resource with a temperature of at least 50°C, making them candidates for district heating (U.S. DOE, 2005)
    - There were no geothermal power plants in Colorado in 2016, but there were several hot springs in the RGFO region

- Local, regional and worldwide markets and why[1,3]
    - The four States that have the most summer capacity at installed geothermal electricity generation plants in September 2016 were :
        - California (1934 Megawatts)
        - Nevada (460 Megawatts)
        - Utah (73 Megawatts)
        - Hawaii (43 Megawatts)
    - Geothermal energy is currently produced in 7 States. Geothermal resources are unequally distributed and are concentrated mainly in the western U.S.
    - In 2014, the U.S. had 64 operating conventional geothermal power plants (U.S. EIA, 2014b)

- Reasons for demand fluctuations[1,2]
    - Growing demand for non-fossil fuel options can increase demand, but the increased use and potentially lower cost of other renewable energies such as solar could decrease demand (see U.S. renewable energy supply in Figure 5-3)
    - Federal and State incentives for using renewable energy, including geothermal, are reducing the up-front cost for consumers
    - Price of geothermal energy
        - The initial up-front cost for a geothermal plant can be relatively high compared to other energy sources
        - Geothermally generated electricity isn't vulnerable to shifts in coal or natural gas prices: once the plant is set up, all resources are in place
        - Over the lifetime of a geothermal plant, the cost per megawatt hour is competitive with or lower than natural gas
        - In December 2016, geothermal energy from The Geysers plants in California was sold at \$0.03 to \$0.035 per kWh. A new power plant was estimated to cost \$0.05 per kWh

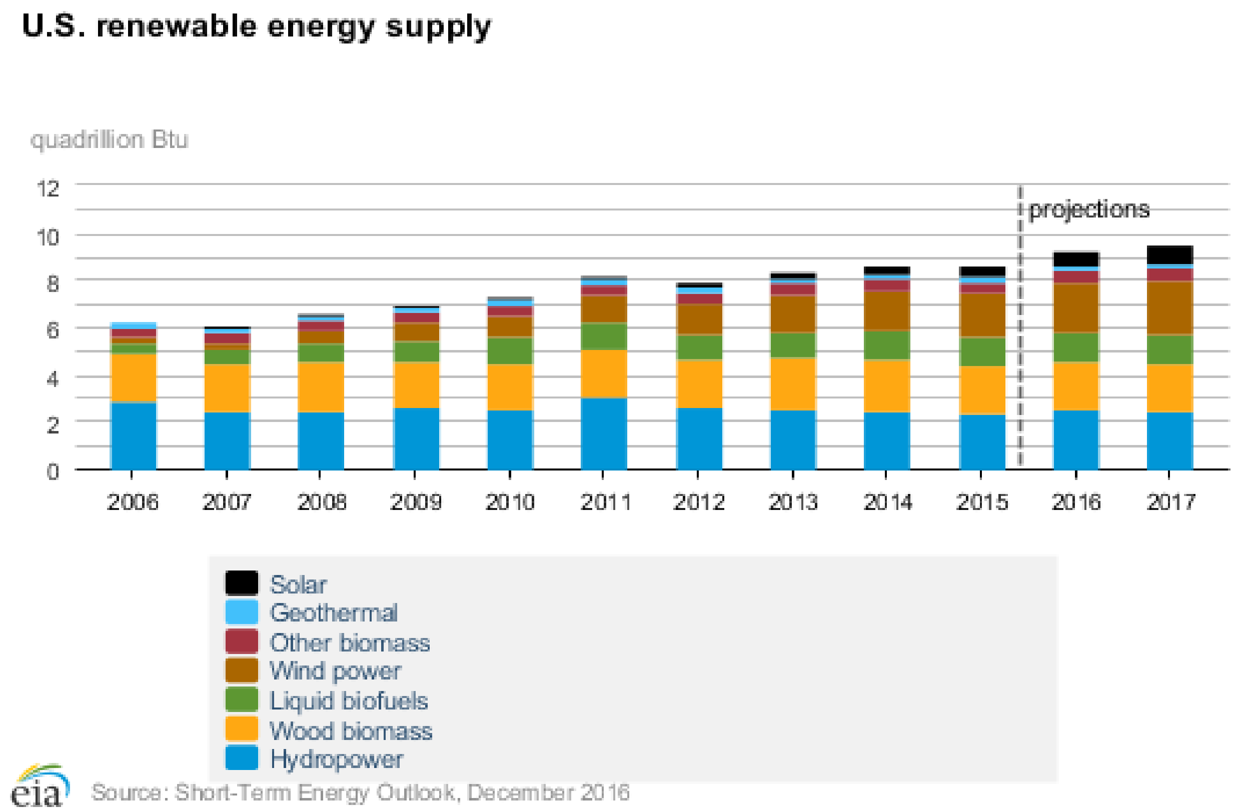


Figure 5-3. U.S. renewable energy supply from 2006 through 2017. Note: Hydropower excludes pumped storage generation. Liquid biofuels include ethanol and biodiesel. Other biomass includes municipal waste from biogenic sources, landfill gas, and other non-wood waste.

- Reasons for market fluctuations[1,2]
    - Initial cost of exploration and setup of geothermal plants can be expensive, and drilling may be risky, as characterization of underground, conventional geothermal resources is limited
    - Development of “unconventional” geothermal resources like Enhanced Geothermal Systems, low-temperature resources, co-produced resources, and direct use systems are making geothermal energy an option in non-ideal geologic settings
    - Production declined at the U.S.’s largest geothermal field, The Geysers, in the late 1980s due to accelerated development and reduced steam pressure. To correct the problem, treated wastewater from the surrounding communities was pumped into the field, restoring production and ensuring long-term sustainability (Geysers, 2016)
    - Lower oil prices have led to cheaper exploration costs and more drill rig availability for geothermal exploration; however, the number of developing

projects decreased in 2016 due to economic uncertainty and higher interest rates (GEA, 2016).

- Current and projected trends for demand and why[2]
  - Demand for clean energy is likely to continue to increase, and at least some part of that will be provided by geothermal energy
  - Increasing use of “unconventional” geothermal resources may increase availability and decrease price

- Any influence of these trends that may directly affect the RGFO region
  - There are several hot springs in the RGFO region that may be used for direct or low temperature use if there is sufficient demand and community support. There is also potential for EGS if demand is high enough.

Summarized from:
[1]U.S. EIA, 2014a
[2]U.S. EERE, 2016
[3]U.S. EIA, 2016

5.3 Precious Metals

5.3.1 Gold

- The "usable" characteristics of the material[1,3,4]
  - Native element, occurring in a pure to mixed-element state naturally
  - Ductile, meaning it can be drawn into wires
  - Malleable, meaning it can be flattened into very thin sheets
  - Corrosion resistant and has limited chemical reactivity, meaning it is resistant to chemical wear and is chemically stable
  - Prized for its intrinsic value, beauty, and rarity; it has been coveted for centuries as material for jewelry and coinage

- What technology/industrial practice it is used for currently[1,3,4]
  - Jewelry
  - Electronics and electrical components such as cell phone circuitry
  - Coinage
  - Dentistry
  - Aerospace
  - Medical
  - Electrolyte in electro-plating
  - Ingots for investing

- What technology/industrial practice it might be used for in the future[4]
    - Further uses in aerospace-spacecraft and spacesuit shielding, radiation shielding, lubrication
    - Gold nanoparticles for disease treatment
    - Nanotechnology
    - Fuel cells
    - Catalytic converters

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
    - Worldwide, 2016 in-the-ground reserves were 56,000 tonnes of gold
    - In 2015, the U.S. government stockpile was 8,140 tonnes
    - As of December 31, 2015, Cripple Creek and Victor (CC&V), the only major gold producing mine in Colorado, had proven reserves of 1.290 million ounces in the ground and probable reserves of 1.150 million ounces in the ground, 230,000 ounces in stockpile, and 1.160 million ounces in leach pad. CC&V is located in the RGFO management area (Newmont, 2016)
    - The Dawson Mountain Project, located in the RGFO region southwest of Cañon City, has estimated resources of 150,800 ounces of gold (Guilinger and Keller, 2015)

- Local, regional and worldwide markets and why[1,2]
    - Worldwide gold production is depicted in Figure 5-4. The four largest gold producing nations in 2015 were:
        - China (490 tonnes)
        - Australia (300 tonnes)
        - Russia (242 tonnes)
        - United States (200 tonnes)
    - Gold is produced on every continent except Antarctica. The demand for gold is equally distributed around the globe.
    - Nevada produces 74 percent, and Alaska produces 14 percent, of U.S. gold. The remaining gold is produced from Colorado, Utah, Washington, California, Montana, South Dakota, Arizona, and New Mexico (in decreasing order of production)
    - In the U.S., 43 percent of gold went to jewelry, 37 percent to electrical and electronics, 15 percent to official coins, and 5 percent to other industries.
        - Top jewelry manufacturing locations were New York, NY, and Providence, RI
- Reasons for demand fluctuations[1,2,4]
    - Economic uncertainty, especially in large markets like India and China
    - Price of gold (Figure 5-5)

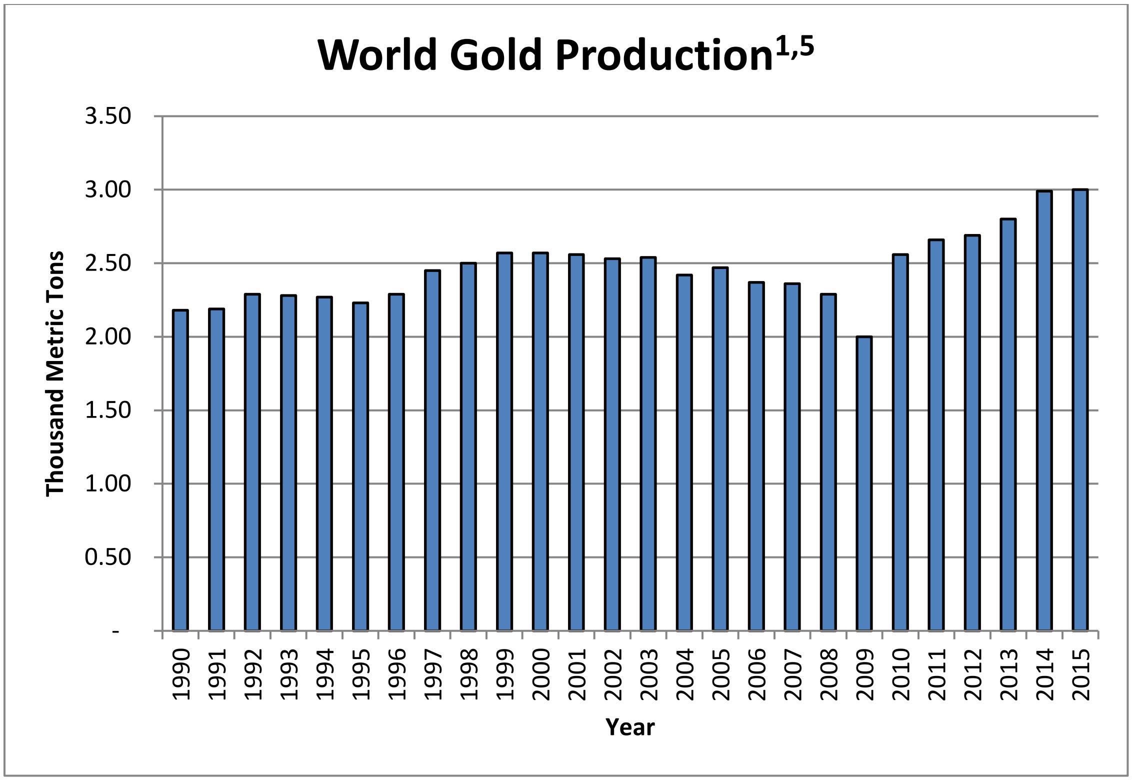


Figure 5-4. Annual world gold production from 1990 to 2015.

Figure 5-5. Fluctuation in price of gold between 1969 and 2015.

    - Amount of gold that comes from recycled sources
    - New and less expensive gold substitutes (e.g., gold plating)

- Reasons for market fluctuations[1,2,4]
    - Economic uncertainty affects gold price
    - Variable ore grades at producing mines affects production totals
    - Closure of smaller mines due to price decrease
    - Passage of rules by SEC requiring publicly traded companies to ensure their gold is not sourced as a conflict mineral from Congo or surrounding areas (conflict minerals are those that may be funding armed groups)
    - Drop in gold price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 31 percent decrease in exploration budgets for gold from 2013 to 2014 and a 14 percent drop from 2014 to 2015 (Wilburn and Karl, 2015).

- Current and projected trends for demand and why[1,2,4]
    - The year-on-year change for investment gold was +141 percent, mostly due to Western investors of all backgrounds
        - Investment was the largest component of gold demand for the first two quarters of 2016, the first time in history this had happened.
        - General economic and political uncertainty has led people back to physical gold investments
    - The year-on-year change for technological applications of gold was –3 percent. Thrifting of gold and gold substitutes are causing a reduction in the use of gold for electronics and dentistry.

- Any influence of these trends that may directly affect the RGFO region
    - The largest influence on the RGFO region will likely be the Dawson Mountain project. If the project moves forward, it would be a large addition of gold production to the RGFO region. This project is smaller and more likely to be influenced by market conditions and gold price. CC&V is backed by a large multi-national corporation, and, therefore, is less subject to market fluctuations and more likely to maintain steady production.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]WGC, 2016
[5]Barry et al., 2013

5.3.2 Platinum-Group Metals

- The "usable" characteristics of the material[1,3]
  - Platinum-group Metals (PGMs) include platinum, palladium, rhodium, ruthenium, osmium, and iridium
  - All of the metals are excellent catalysts
  - Platinum is wear and tarnish resistant, making it ideal for fine jewelry
  - All of the metals are anti-corrosive
  - All of the metals have excellent high-temperature characteristics
  - All of the metals have stable electrical properties
  - Only platinum and palladium are found pure in nature, all the other PGMs are found as alloys

- What technology/industrial practice it is used for currently[1,3]
  - Platinum, platinum alloys, and iridium are used as crucible materials for growth of single crystals
  - Platinum or platinum-rhodium alloys are used in the production of nitric oxide (used for fertilizer)
  - Ruthenium dioxide is used for coating titanium anodes used in the production of chlorine
  - Platinum supported catalysts are used in refining crude oil and in the production of high-octane gasoline
  - Palladium, platinum, and rhodium are used in catalytic converters to treat automobile exhaust
  - PGM alloys are used in low-voltage and low-energy contacts, thick- and thin-film circuits, thermocouples and furnace components, and electrodes.
  - Iridium is used in the manufacture of LED lights

- What technology/industrial practice it might be used for in the future[1,2]
  - Biomedical devices
  - Fuel cells
  - Continued use in catalytic converters as developing nations adopt stricter emissions regulations

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Worldwide, in the ground reserves in 2016 were 66,000 tonnes of PGMs
  - In 2015, the U.S. government stockpile was 18 kg of iridium and 261 kg of platinum. U.S. palladium stocks were exhausted in 2004.

- As of December 31, 2014, Stillwater Mining Company (SMC), the only major PGM producing mine in the U.S., had proven and probable reserves of 691,000 kg of PGMs with a palladium-to-platinum ratio of 3.6:1.
- There are two mining projects in the initial stages of exploration in the Duluth complex in Minnesota.
- There are no active PGM mines within the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - Worldwide production of PGMs is depicted in Figure 5-6. The four largest platinum producing nations in 2015 were:
    - South Africa (125,000 kg)
    - Russia (23,000 kg)
    - Zimbabwe (12,500 kg)
    - Canada (9,000 kg)
  - The four largest palladium producing nations in 2015 were (in descending order):
    - Russia (80,000 kg)
    - South Africa (73,000 kg)
    - Canada (24,000 kg)
    - United States (12,500 kg)
  - PGMs are produced mainly from South Africa, with major palladium supplies also coming from Russia. The U.S. is approximately the fourth largest producer of combined PGMs.
  - In the United States, there is only one commercial PGM producer, the Stillwater Mining Company. They produce out of the East Boulder and Stillwater mines near Nye, MT.
  - In 2014, catalytic converters accounted for 84 percent of rhodium consumption, 65 percent of palladium consumption, and 45 percent of platinum consumption. The automobile industry is the largest consumer of PGMs.
  - In 2014, 65 percent of palladium was used in the catalytic converter industry, 14 percent in the electronics industry, 8 percent in the dental industry, 5 percent in the jewelry industry, and 5 percent in the chemical industry.
  - In 2014, 45 percent of platinum went to the catalytic converter industry, 34 percent to the jewelry industry, 9 percent to chemical and petroleum refining, and 3 percent to electronics.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty, especially in large markets like India and China
  - Demand for automobiles
  - Amount of PGMs that come from recycled sources
  - Demand for PGM-containing electronics (cell phones, tablets, etc.)

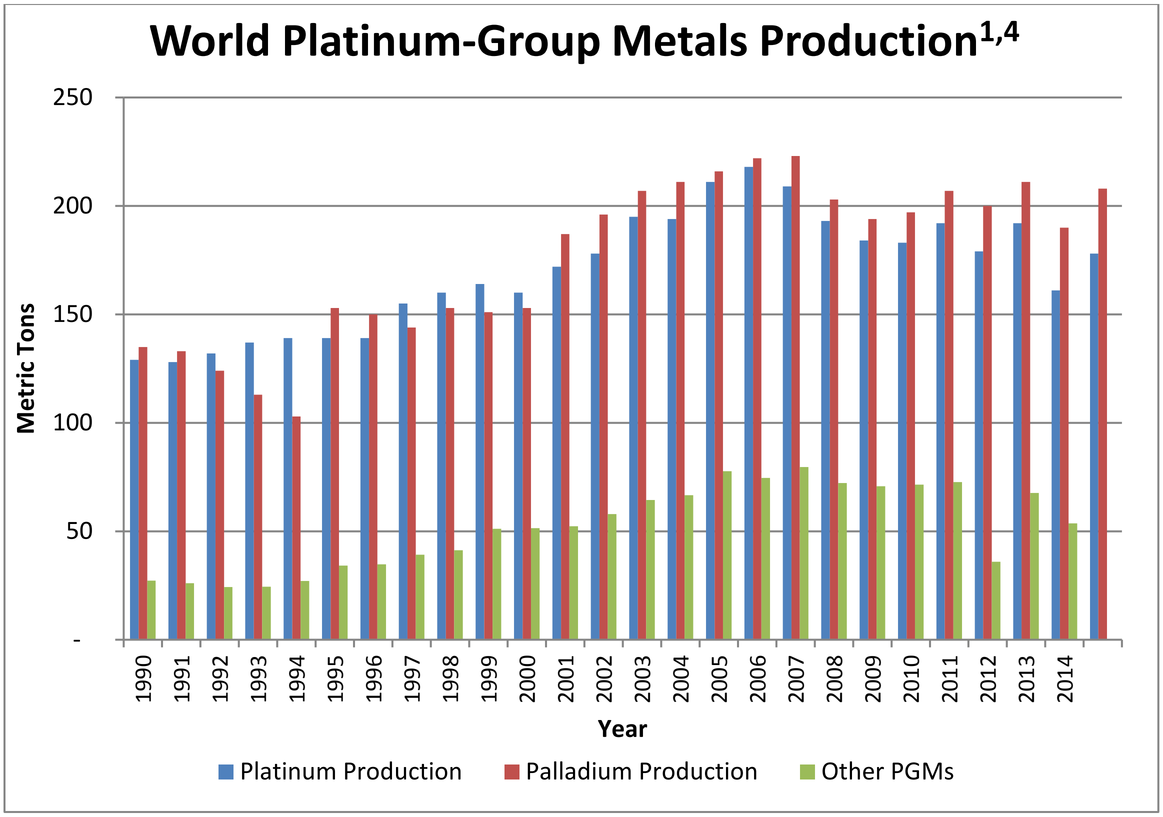


Figure 5-6. Annual world production of platinum-group metals between 1990 and 2015.

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects PGM prices (Figure 5-7)
  - A worker strike in South Africa in early 2014 resulted in ~$2.3 billion in lost revenue for the mining industry and 33,600 kg lost platinum production
  - Sanctions on Russia due to the ongoing political situation in Ukraine could affect palladium supply and price
  - From 2014 to 2015, there was a 33 percent decrease in PGM exploration budgets, from $179 million to $120 million, meaning the number of prospects being discovered is decreasing. PGM exploration budgets account for only ~ 1 percent of global exploration budgets (Wilburn and Karl, 2015)

- Current and projected trends for demand and why[1,2]
  - Global automobile production is expected to increase, especially in emerging markets like China and India, meaning there will be continued demand for catalytic converters and PGMs
  - Demand for PGM-containing electronics is expected to rise in emerging markets
  - Iridium demand may increase as more consumers switch to energy-efficient LED lights
  - Increased recycling of PGMs may decrease demand from mines

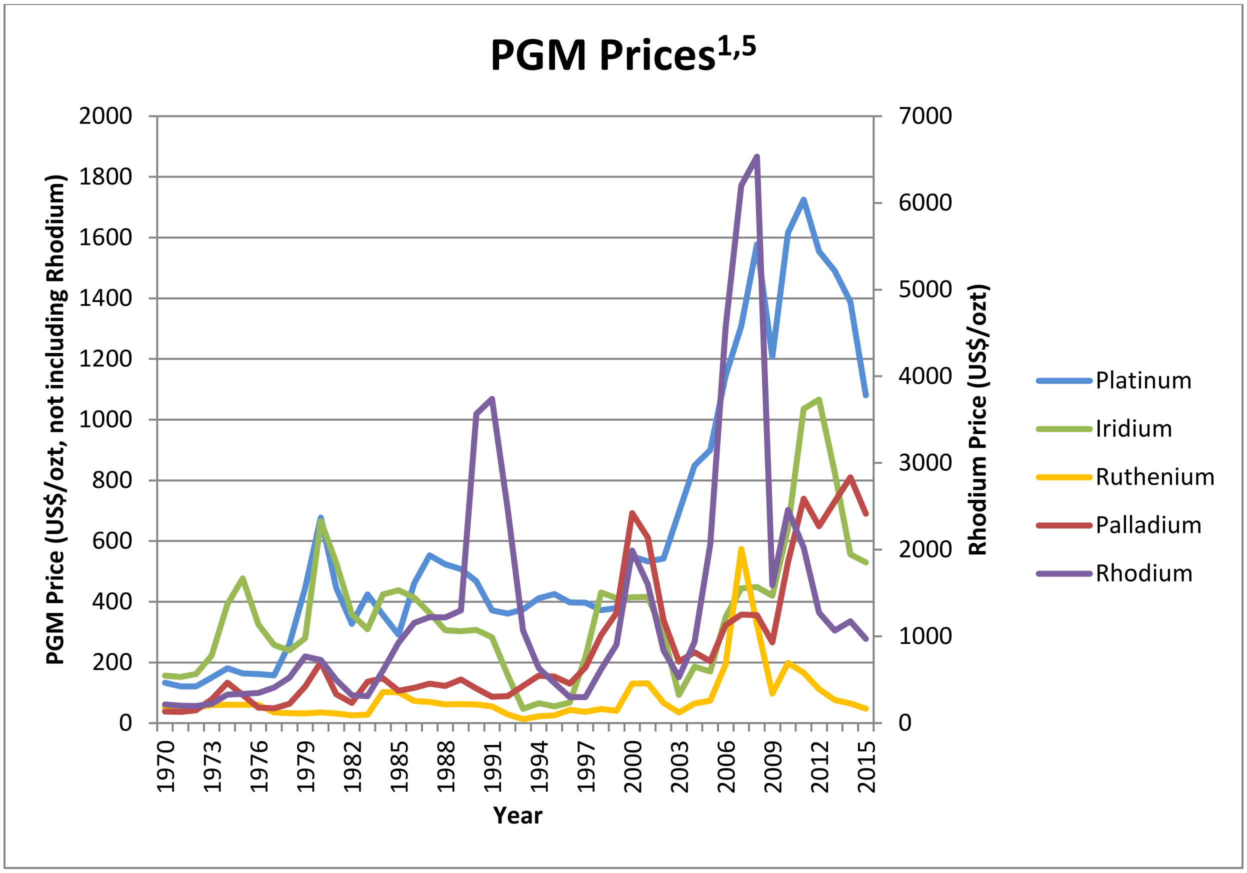


Figure 5-7. Annual average price of platinum-group metals from 1970 to 2015.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for PGMs, high occurrence potential areas in the RGFO could become economically viable

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013

5.3.3 Silver

- The "usable" characteristics of the material[1,2,3,6]
    - Native element, occurring in a pure to mixed-element state naturally
    - Ductile, meaning it can be drawn into wires
    - Malleable, meaning it can be flattened into very thin sheets
    - Prized for its intrinsic value, and beauty it has been sought for centuries as material for jewelry, eating utensils, and coinage

- What technology/industrial practice it is used for currently[1,3,6]
    - Jewelry
    - Electronics and electrical components
    - Brazing and soldering
    - Coinage
    - Dentistry
    - Photography
    - Mirrors
    - Water filtration
    - Photovoltaic cells
    - Ingots for investing
    - Used in production of ethylene oxide

- What technology/industrial practice it might be used for in the future[2,6]
    - Molten salt energy generation and storage
    - Antibacterial applications
    - Nanotechnologies
    - Energy-saving window coatings
    - Temperature-regulating clothing

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
    - Worldwide, in the ground reserves in 2016 were 570,000 tonnes of silver
    - In 2015, the U.S. Treasury stockpile was 498 tonnes
    - U.S. in the ground reserves were estimated at 25,000 tonnes in for 2016
    - The Revenue mine in Ouray County Colorado, owned by Fortune Minerals Ltd., has a measured and indicated resource of 16.3 million ounces of silver (Guilinger and Keller, 2015)
    - The Cripple Creek and Victor mine (CC&V) in the RGFO region produces silver as a byproduct of its gold mining operation. Estimated reserves were not available, but silver production in 2014 was 110,373 ounces (Guilinger and Keller, 2015)

- Local, regional and worldwide markets and why[1,2]
    - Annual worldwide silver production has increased since 1994 (Figure 5-8)
    - The four largest silver producing nations in 2015 were:
        - Mexico (5,400 tonnes)
        - China (4,100 tonnes)
        - Peru (3,800 tonnes)
        - Australia (1,700 tonnes)
    - Silver is mined in ~65 countries and has a global demand.

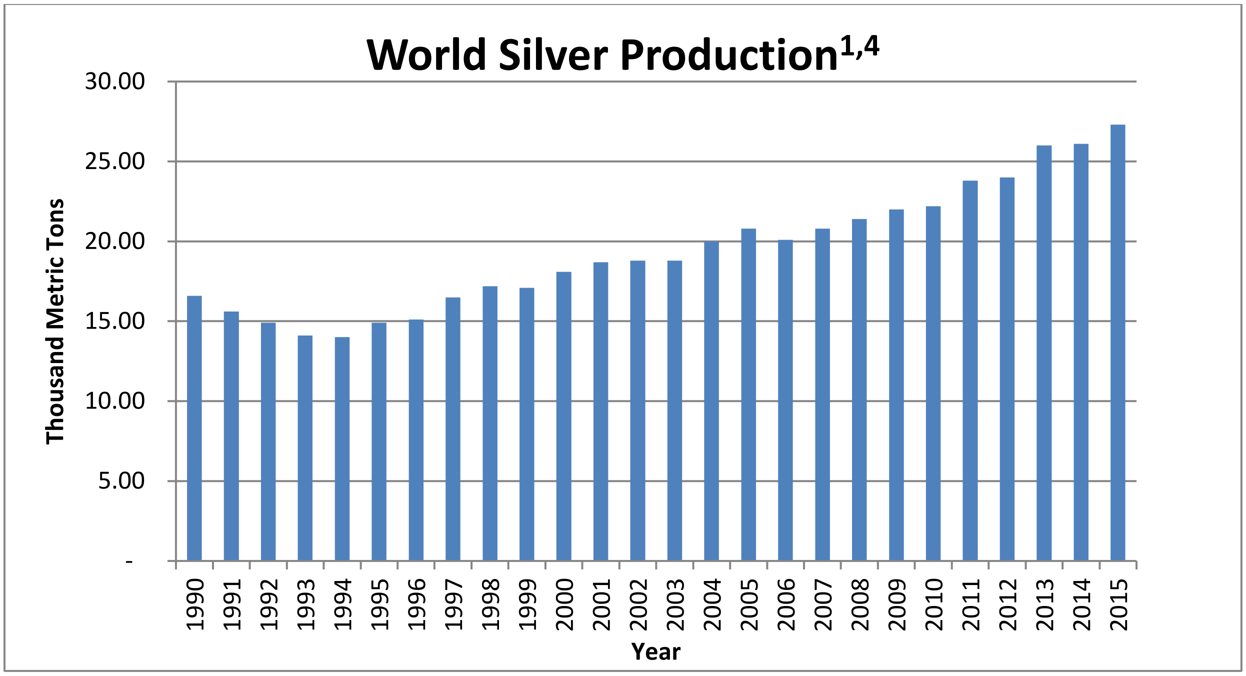


Figure 5-8. Annual world silver production from 1990 to 2015.

- In the United States, Alaska is the largest silver-producing State, followed by Nevada and Idaho.
- Globally, 5 percent of silver went to silverware, 19 percent to jewelry, 25 percent to coins and bars, and 50 percent to industrial fabrication

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty, especially in large markets like India and China
  - Price of silver (Figure 5-9)
  - Amount of silver that comes from recycled sources
  - Continued decline of film-based photography
  - Rise in use of photovoltaic solar cells
  - Increased used of molded plastics, which are based on ethylene oxide

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects silver price
  - 13 percent decline from 2015 to 2016 in scrap available for recycling
  - Reduced grades and throughput at U.S. mines and mills
  - Lower price led to increased jewelry demand
  - Drop in silver price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was an 18 percent drop in budget from 2014 to 2015 (Wilburn and Karl, 2015)

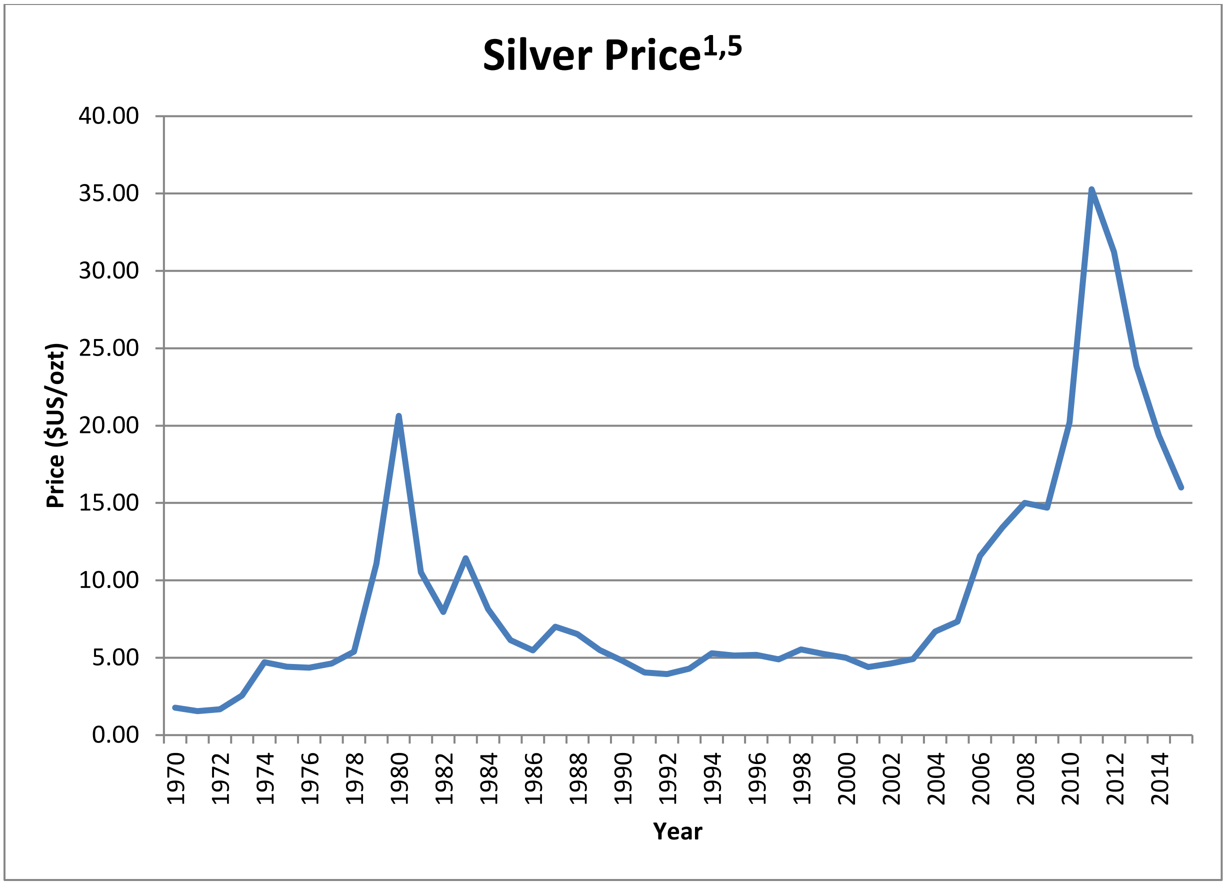


Figure 5-9. Annual average silver price from 1970 to 2015.

- Current and projected trends for demand and why[1,2,6]
  - Expected continued growth in solar energy industry
  - Expected continued decline of film-based photography, including conversion to digital X-rays
  - Increase in jewelry demand in countries such as India and Thailand if prices remain steady
  - Demand for silver-containing electronics is expected to rise in emerging markets
- Any influence of these trends that may directly affect the RGFO region
  - CC&V is the largest producer of silver in the RGFO region. Silver is produced as a byproduct of gold, and is subject to the gold:silver ratio and economic viability of recovering.

Summarized from:
[1] USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013

[6]Silver Institute, 2016

5.4 Base Metals

5.4.1 Copper

- The "usable" characteristics of the material[1,3]
  - Native element, occurring in a pure to mixed-element state naturally
  - Ductile, meaning it can be drawn into wires
  - Malleable, meaning it can be flattened into very thin sheets
  - Resistant to corrosion
  - Electrical conductivity

- What technology/industrial practice it is used for currently[1,3,6]
  - Wiring for buildings, power transmission, motors, consumer electronics, etc.
  - Telecommunication cables
  - Electronic circuitry
  - Plumbing
  - Heating and air conditioning tubing
  - Roofing, flashing, and other construction applications
  - Electroplated coatings
  - Used in alloys to make brass and bronze

- What technology/industrial practice it might be used for in the future[1,6,7]
  - Copper circuitry in silicon chips
  - Antimicrobial medical equipment
  - High speed trains
  - Electric and hybrid vehicles
  - Copper-based intermetallic photovoltaic cells
  - High efficiency heat pumps
  - Copper-refractory metal composites used for rocket motors

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - 2016 worldwide in-the-ground reserves were 720 million tonnes of copper
  - In 2015, the U.S. had reserves of 33 million tonnes of copper
  - As of December 31, 2015, Freeport-McMoRan (one of the largest copper producers in the U.S.) had reserves in North America of 15.2 million tonnes (Freeport McMoRan, 2015)
  - There are no primary producing copper mines in the RGFO region

- Local, regional and worldwide markets and why[1,2,7]

- o Annual worldwide copper production is depicted in Figure 5-10 (mined) and Figure 5-11 (refined).
- o The four largest copper producing nations in 2015 were:
  - Chile (5.7 million tonnes)
  - China (1.75 million tonnes)
  - Peru (1.6 million tonnes)
  - United States (1.25 million tonnes)
- o Copper is produced in 52 countries around the world, and demand for copper is widely distributed across the globe.
- o In the United States, Arizona is the largest copper producer followed by Utah, New Mexico, Nevada, and Montana.
- o In 2014, copper recovered from scrap accounted for 35 percent of the total U.S. copper supply.
- o In the U.S., 43 percent of copper went to building and construction, 19 percent went to the transportation equipment sector, 18 percent went to electric and electronic products, 12 percent went to general consumer products, and 7 percent went to the industrial machinery and equipment sector

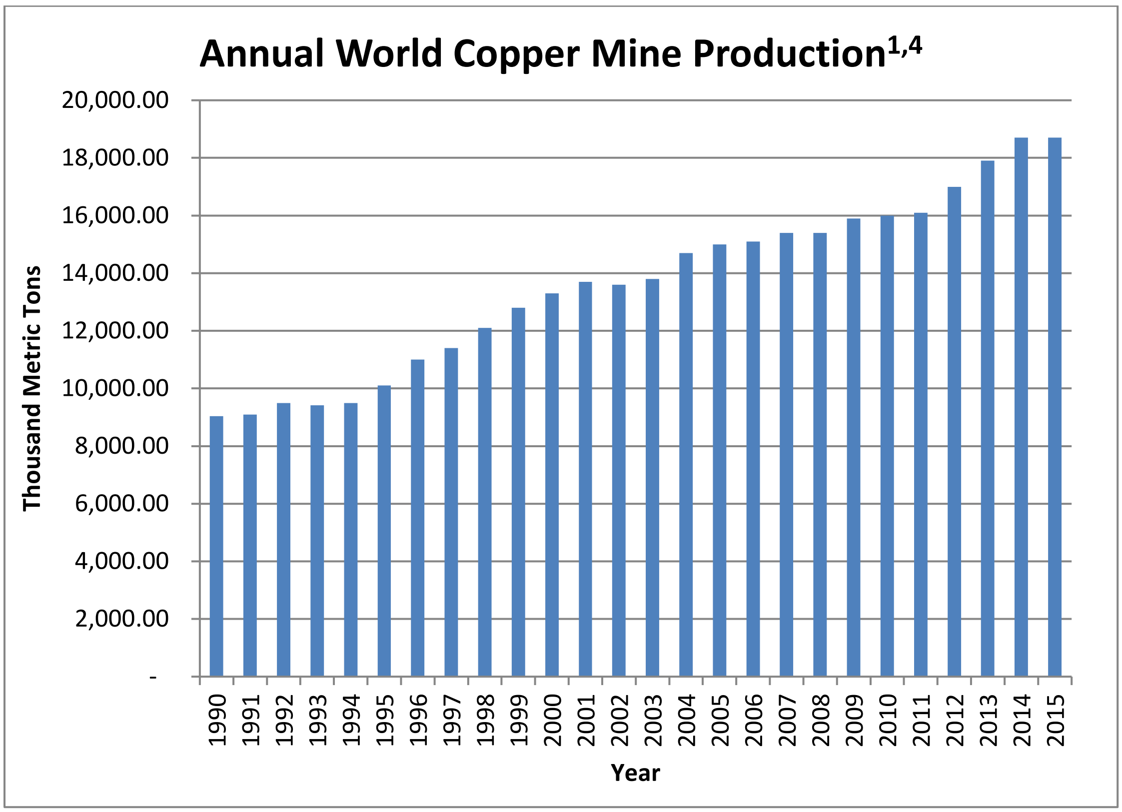


Figure 5-10. Annual world copper mine production from 1990 to 2015.

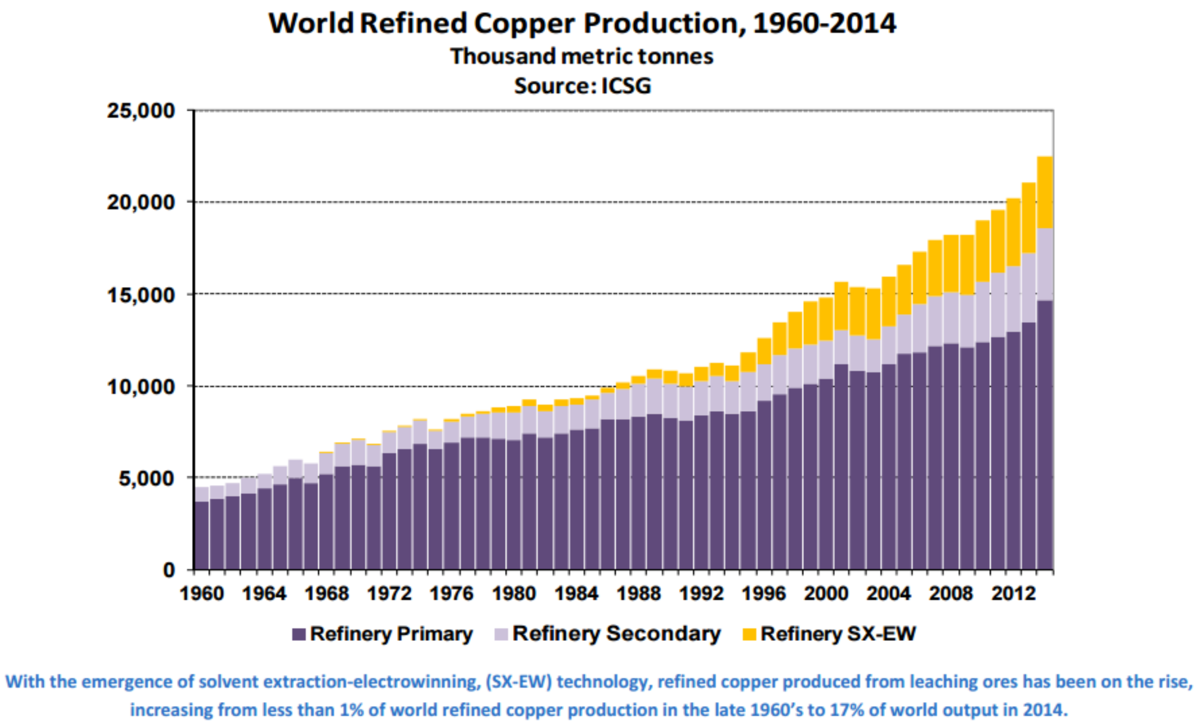


Figure 5-11. Annual world refined copper production from 1960 to 2014.

- Reasons for demand fluctuations[1,2,7]
    - Economic uncertainty and reduced housing construction, especially in large markets like China
    - Price of copper (Figure 5-12)
    - Amount of copper that comes from recycled sources
    - New and less expensive copper substitutes (e.g., plastic piping and plumbing)

- Reasons for market fluctuations[1,2]
    - Economic uncertainty affects copper price
    - Highwall failure at Bingham Canyon mine affected U.S. production
    - Closure of smaller mines due to price decrease
    - Drop in copper price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 22 percent decrease in exploration budgets for copper from 2014 to 2015 (Wilburn and Karl, 2015).

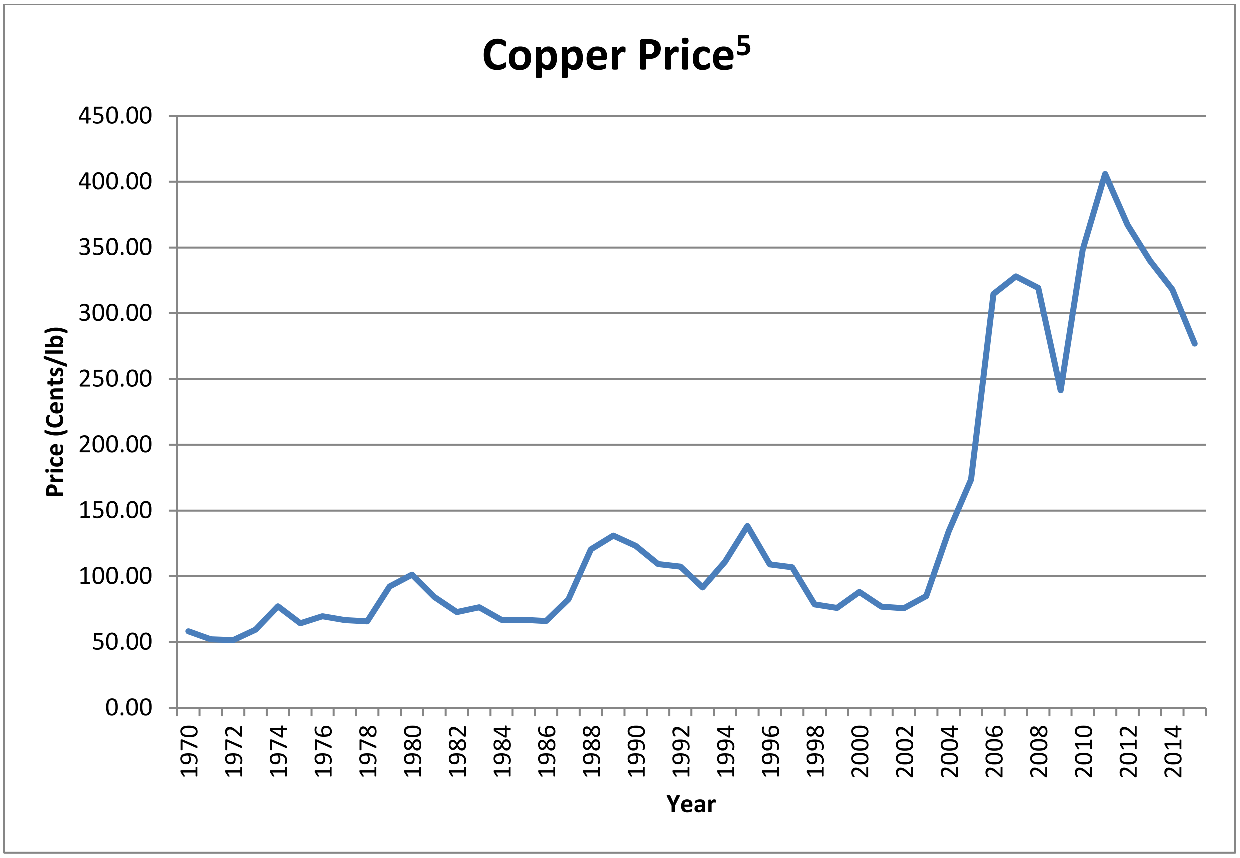


Figure 5-12. Annual average price of copper from 1970 to 2014.

- Current and projected trends for demand and why[1,2,6,7]
    - Demand for copper is closely tied to the housing and construction industries, which are highly linked to economic prosperity or downturns
        - The status of China's economy will likely have a large effect on copper demand
    - New uses for copper in the transportation industries could increase demand

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for copper, high occurrence potential areas in the RGFO area could become economically viable
- Summarized from:
- [1]USGS MCS, 2016
- [2]USGS MYB, 2014
- [3]MEC, 2016
- [4]Barry et al., 2013
- [5]USGS, 2013
- [6]CDA, 2016

- [7]ICSG, 2016

5.4.2 Lead

- The "usable" characteristics of the material[1,3]
  - Almost never found as elemental lead, but as compounds, often sulfides
  - Very soft and workable (malleable and ductile)
  - High density
  - Resistance to corrosion
  - Ability to react with organic chemicals
  - Relatively low melting temperature for metal

- What technology/industrial practice it is used for currently[1,3,6]
  - Batteries
  - Cable sheathing
  - Extruded products like pipes
  - Ammunition
  - Medical shielding
  - Pigments for paints
  - Leaded crystal
  - Solder

- What technology/industrial practice it might be used for in the future[1,7]
  - Lead-acid batteries for electric and hybrid vehicles
  - Energy storage from renewable energy sources
  - X-ray shielding
  - Transportation and storage of radioactive waste and elements

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - 2016 worldwide in-the-ground reserves were 89 million tonnes of lead
  - In 2015, the U.S. had reserves of 5 million tonnes of lead
  - As of March 1, 2016, Teck Alaska Inc., one of the largest lead producers in the U.S., had reserves at the Red Dog mine of 56.6 million tonnes of ore grading 4.1 percent lead (Teck, 2016).
  - There are no primary producing lead mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - World production of lead is depicted in Figure 5-13. The four largest lead producing nations in 2015 were:
    - China (2.3 million tonnes)
    - Australia (633,000 tonnes)

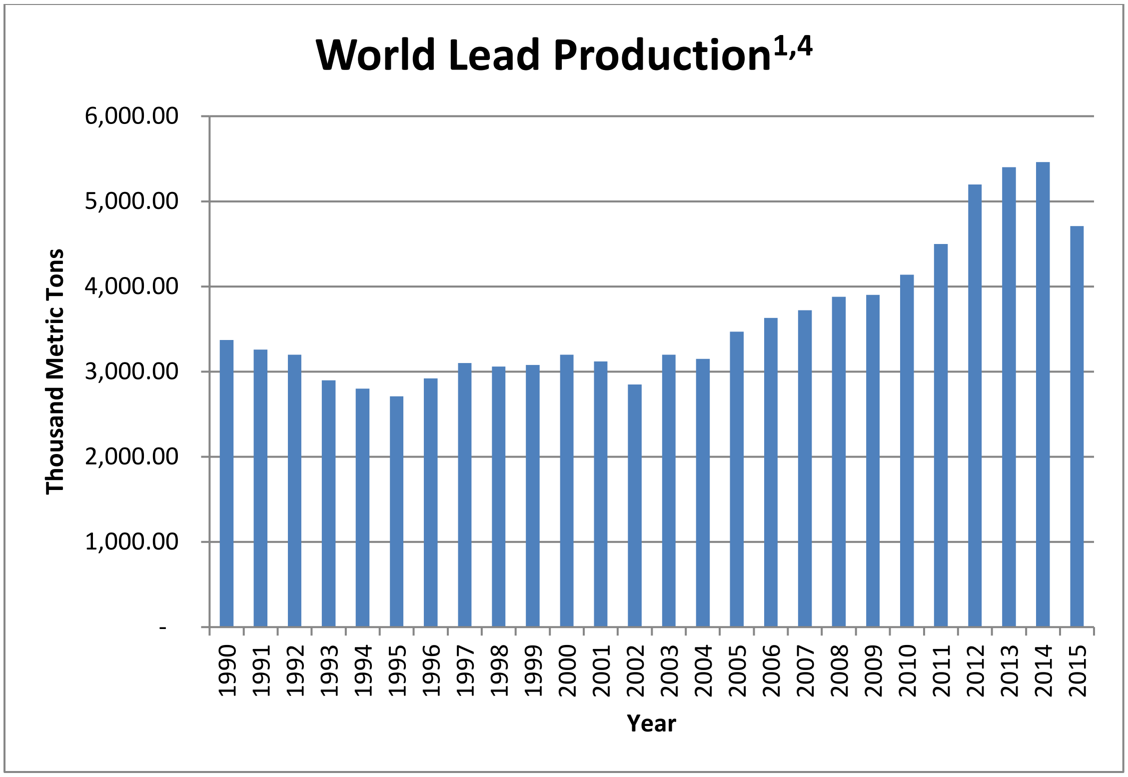


Figure 5-13. Annual world lead production.

- United States (385,000 tonnes)
- Peru (300,000 tonnes)

- Lead is produced in ~36 countries around the world.
- In the United States, Alaska is the largest lead producer, followed by Missouri, Idaho, and Washington.
- In 2013, secondary lead (recycled, recovered from scrap, etc.) accounted for 52 percent of the total world lead production.
- In the U.S., 90 percent of reported lead consumption was for lead-acid batteries.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty, especially in large markets like China
  - Price of lead (Figure 5-14)
  - Amount of lead that comes from recycled sources
  - New and more environmentally friendly lead substitutes—tin in solder, steel and zinc for wheel weights, plastic for cable covers

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects lead price
  - Closure of U.S. primary and secondary refineries

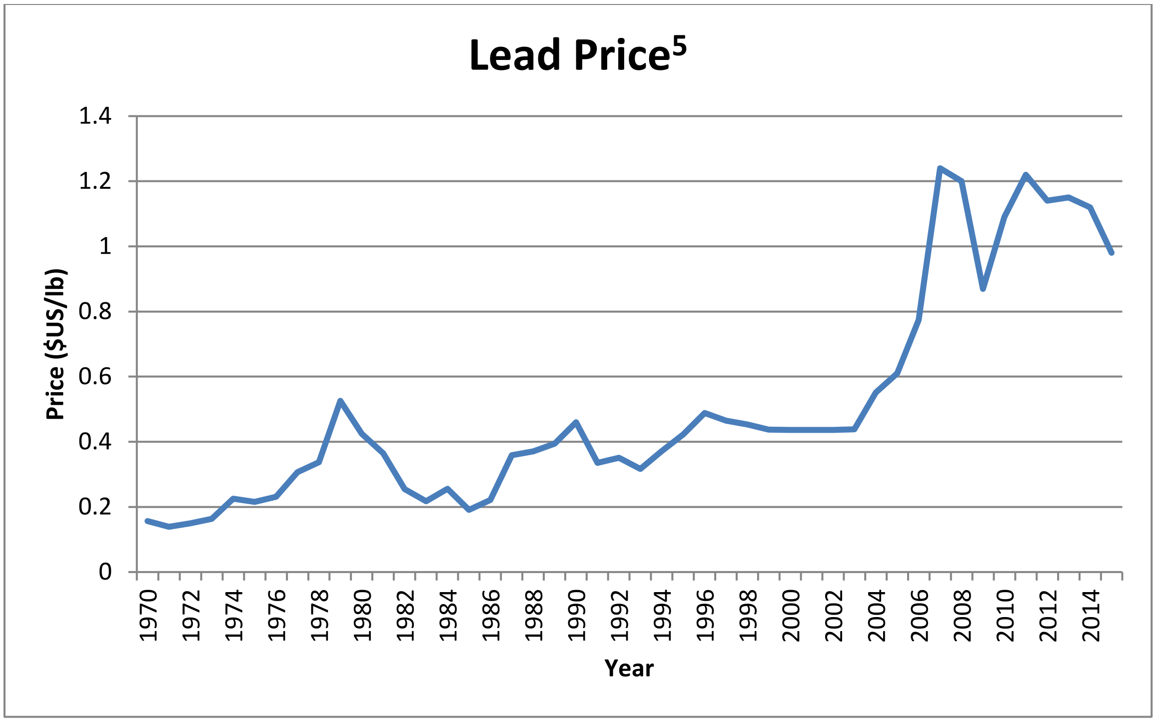


Figure 5-14. Annual average price of lead from 1970 to 2015.

- Opening of Pend Oreille mine (2015) in Washington boosted domestic production
- Drop in lead price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 22 percent decrease in exploration budgets for lead from 2014 to 2015 (Wilburn and Karl, 2015)

- Current and projected trends for demand and why[1,2,6]
  - Demand for lead is closely tied to the automotive industry, which is highly linked to economic prosperity or downturns:
    - The status of China's economy will likely have a large effect on lead demand.
  - As more alternative energies, especially solar, are developed, there may be an increase in demand for lead-acid batteries to store and smooth out supply of power.

- Any influence of these trends that may directly affect RGFO region
  - If there is sufficient demand for lead, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013

[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]ILZSG, 2016
[7]Doe Run, 2016

5.4.3 Zinc

- The "usable" characteristics of the material[1,3]
  - Almost never found as elemental zinc, but as compounds, often sulfides
  - Alloys very well with other metals
  - Ease of reactivity/oxidation

- What technology/industrial practice it is used for currently[1,3,6]
  - Making alloys (e.g., brass)
  - Anti-corrosive coatings (galvanization), plugs, and sacrificial anodes
  - Batteries
  - Pigments and paints
  - Rubber production
  - Nutritional supplements/cold remedies

- What technology/industrial practice it might be used for in the future[2,7]
  - Agriculture industries are looking to zinc as a new fertilizer
  - Flexible, printed zinc-base batteries
  - Batteries for medical devices

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Worldwide, in the ground reserves in 2016 were 200 million tonnes of zinc.
  - In 2015, the U.S. had reserves of 11 million tonnes of zinc.
  - As of March 1, 2016, Teck Alaska Inc. (one of the largest zinc producers in the U.S.) had reserves at the Red Dog mine of 56.6 million tonnes of ore grading 14.6 percent zinc (Teck, 2016).
  - There are no primary producing zinc mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - Annual world zinc production is depicted in Figure 5-15. The four largest zinc producing nations in 2015 were:
    - China (4.9 million tonnes)
    - Australia (1.58 million tonnes)
    - Peru (1.37 million tonnes)
    - United States (850,000 tonnes)

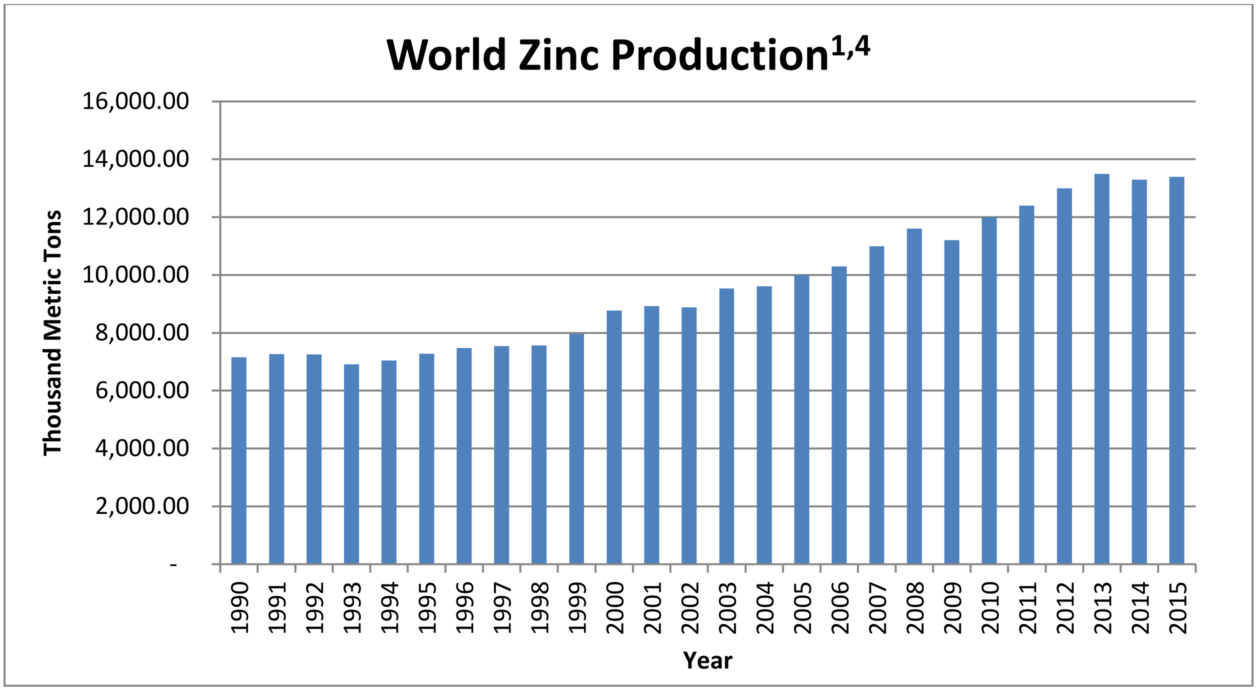


Figure 5-15. Annual world zinc production between 1990 and 2015.

  - Zinc is produced in ~47 countries around the world
  - In the United States, Alaska is the largest zinc producer, followed by Tennessee, Missouri, Idaho, and Washington
  - In 2015, 37 percent of zinc produced in the U.S. was from recycled material
  - In the U.S., 80 percent of zinc was used for galvanizing, 6 percent for brass and bronze, 5 percent in zinc-base alloys, and 9 percent for other uses

- Reasons for demand fluctuations[1,2,7]
  - Economic uncertainty, especially in large markets like China
  - Price of zinc (Figure 5-16)
  - Amount of zinc that comes from recycled sources
  - Substitutes for galvanization including aluminum and plastic

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects zinc price
  - Closure of U.S. refineries
  - Opening of Pend Oreille mine (2015) in Washington boosted domestic production
  - Drop in zinc price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 22 percent decrease in exploration budgets for zinc from 2014 to 2015 (Wilburn and Karl, 2015).

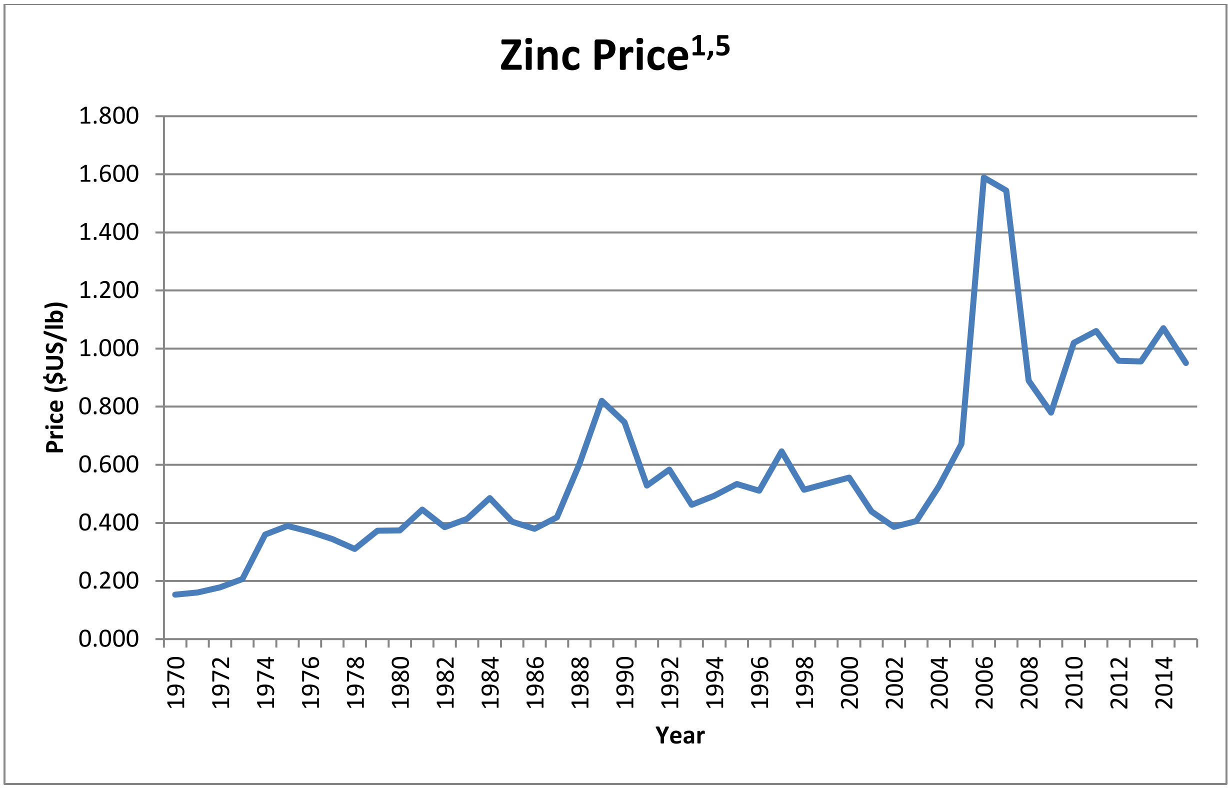


Figure 5-16. Annual average price of zinc from 1970 to 2015.

- Current and projected trends for demand and why[1,2,6,7]
    - Demand for zinc is closely tied to the housing and construction industries, which are highly linked to economic prosperity or downturns.
        - The status of China's economy will likely have a large effect on zinc demand.
    - Zinc is a critical micronutrient, and many countries are realizing their soils are zinc depleted; adverse health effects will increase demand for zinc fertilizer.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for zinc, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]ILZSG, 2016
[7]INN, 2016

5.4.4 Iron

- The "usable" characteristics of the material[1,3]
  - Naturally magnetic
  - Alloys very well with other metals
  - Abundant

- What technology/industrial practice it is used for currently[1,3,6]
  - Steel
  - Pigments for paints, plastics, dyeing
  - Fertilizer
  - Industrial catalyst
  - Water purification

- What technology/industrial practice it might be used for in the future[6]
  - Smaller and more powerful REE alloy magnets
  - Electric motors

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Worldwide, in the ground reserves in 2016 were 85,000 million tonnes of iron.
  - In 2016, the U.S. had reserves of 3,500 million tonnes of iron.
  - As of December 31, 2015, Cliffs Natural Resources, one of the largest iron producers in the U.S., had reserves at the United Taconite mine of 466.8 million long tons of ore grading 23 percent iron (Cliffs, 2015).
  - There are no primary producing iron mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - Annual world iron ore production is depicted in Figure 5-17. The four largest iron producing nations in 2015 were:
    - China (1,380 million tonnes)
    - Australia (824 million tonnes)
    - Brazil (428 million tonnes)
    - India (129 million tonnes)
  - Iron is produced in ~45 countries around the world
  - In the United States, the Lake Superior district (Michigan and Minnesota) is the largest source of iron production, with Indiana and Utah also contributing.
  - In 2015, 42.5 million tonnes of iron ore were produced in the U.S., and 7 million tonnes of scrap was recycled.
  - In the U.S., 98 percent of iron was used for steel making, and 2 percent for other uses.

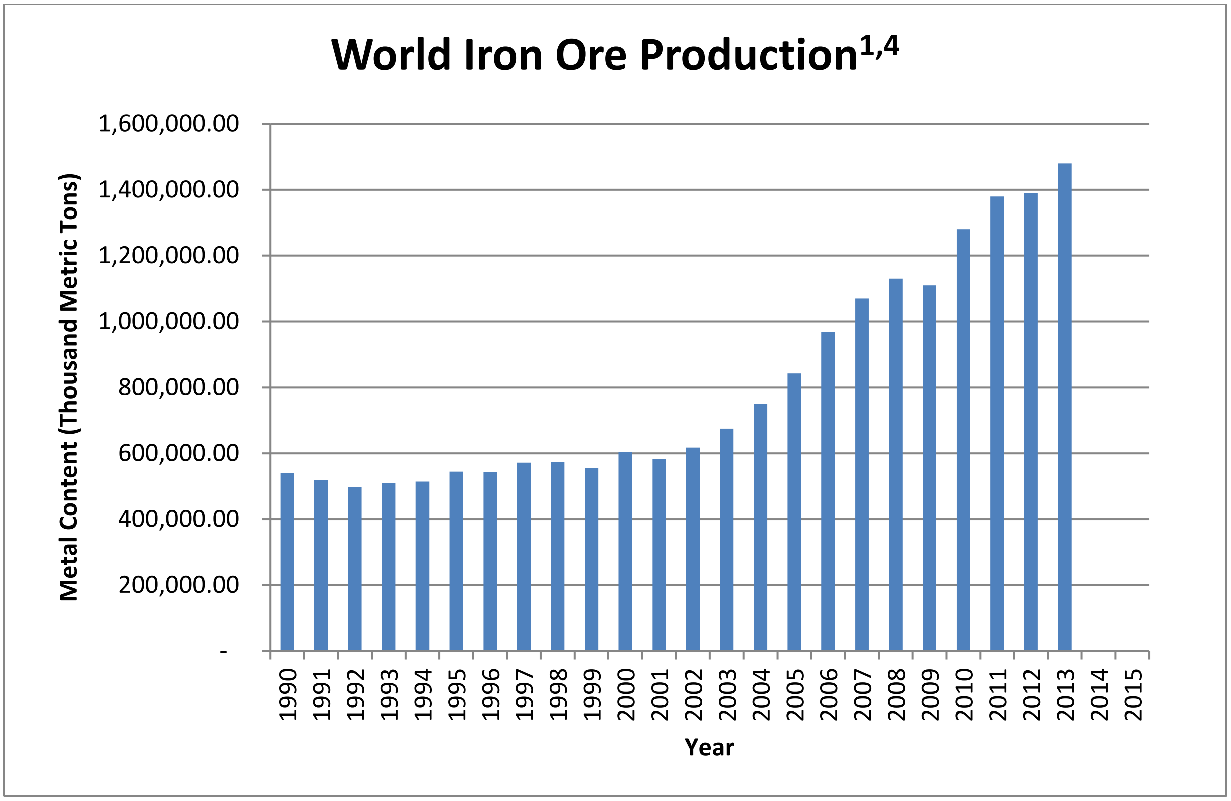


Figure 5-17. Annual world iron ore production from 1990 to 2013.

- Reasons for demand fluctuations[1,2,5]
    - Economic uncertainty, especially in large markets like China
    - Price of iron (Figure 5-18)
    - Amount of iron that comes from recycled (scrap) sources

- Reasons for market fluctuations[1,2]
    - Iron prices between 1986 and 2016 are depicted in Figure 5-18.
    - Economic uncertainty affects iron price, especially the growth or decline of the automotive and housing industries.
    - Closure/idling of U.S. mines and production facilities
    - Drop in iron price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 22 percent decrease in exploration budgets for iron from 2014 to 2015 (Wilburn and Karl, 2015).

- Current and projected trends for demand and why[1,2]
    - Demand for iron is closely tied to the automotive industry, which is highly linked to economic prosperity or downturn
        - The status of emerging market economies will likely have a large effect on iron demand

Figure 5-18. China import iron ore fines 62 percent FE spot (CFR Tianjin port) from 1986 to 2016, U.S. Dollars per Dry Metric Ton.

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for iron, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Barry et al., 2013
[5]Indexmundi, 2016
[6]Edison, 2016

5.4.5 Manganese

- The "usable" characteristics of the material[1,3]
  - Hard
  - Alloys well with other metals
  - Reacts easily with air and water
  - Never found on earth as elemental manganese, always in minerals

- What technology/industrial practice it is used for currently[1,2,3]
  - Steel hardening
  - Ferroalloys
  - Dry cell batteries

- Micronutrient in animal feed and fertilizer
- Brick and ceramic colorant
- Chemical oxidizer and catalyst

- What technology/industrial practice it might be used for in the future[6]
  - New types and uses for lithium manganese dioxide batteries (a type of lithium-ion battery)
  - Multiferroic alloys that convert heat directly to electricity

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Worldwide, in the ground reserves in 2016 were 620,000 million tonnes of manganese (gross weight).
  - In 2016, the U.S. had no reserves of manganese.
  - As of October 2016, there were no producing manganese mines in the U.S.
  - There are no primary producing manganese mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - Annual world manganese production is depicted in Figure 5-19. The four largest manganese producing nations in 2015 were:
    - South Africa (6.2 million tonnes)
    - China (3 million tonnes)
    - Australia (2.9 million tonnes)
    - Gabon (1.8 million tonnes)

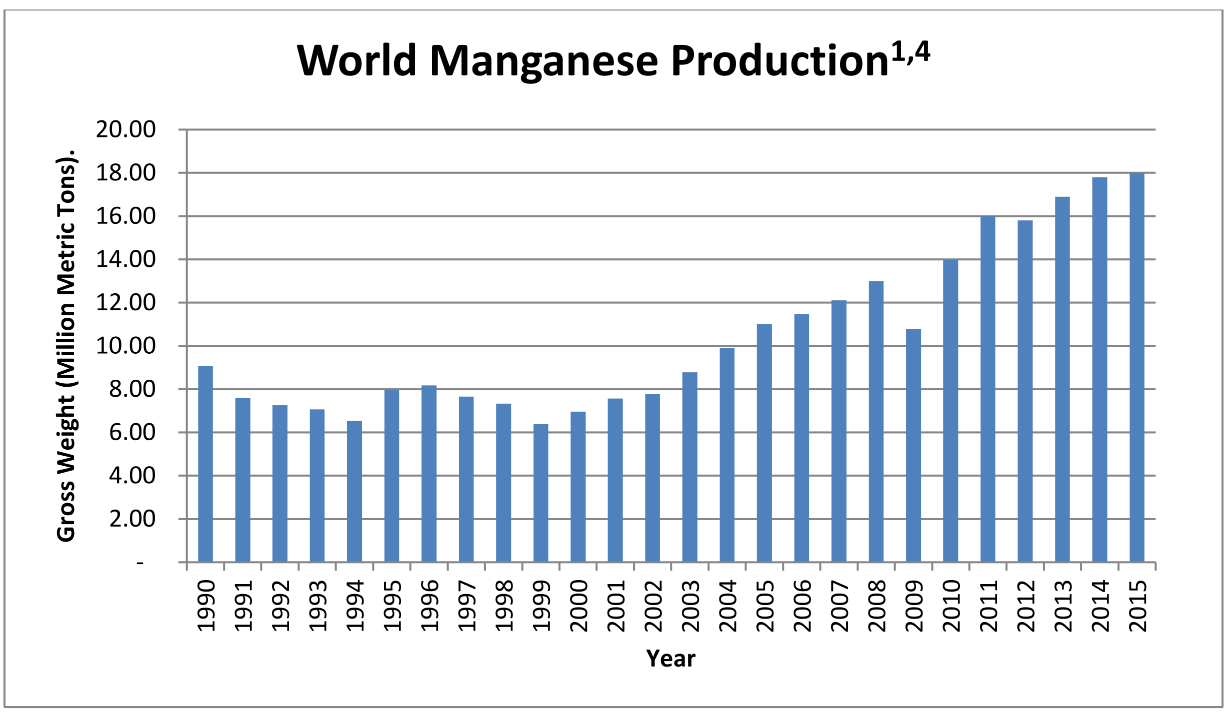


Figure 5-19. Annual world manganese production from 1990 to 2015.

  - Manganese is produced in ~12 countries around the world; deposits are unequally distributed.
  - In the United States, the Artillery Peak deposit in Arizona is likely the largest manganese deposit; American Manganese postponed plans to put the property into production after a pre-feasibility study indicated a poor economic return.
  - As of September 30th, 2015, the U.S. government had 292,000 tonnes of manganese ore and 286,000 tonnes of ferromanganese (high carbon) in stockpile.
  - In 2016, manganese was recovered incidentally as a part of ferrous and non-ferrous scrap, but intentional manganese recovery was negligible.
  - In the U.S. in 2015, 33 percent of manganese went to construction, 13 percent to machinery, 10 percent to transportation, with most of the rest going to other iron and steel applications

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty, especially in large markets like China
  - Price of and demand for steel

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects steel price, especially the growth or decline of the automotive and housing industries
  - Political unrest in major suppliers like South Africa and Ukraine
  - Drop in manganese price (Figure 5-20) led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 15 percent decrease in exploration budgets for manganese from 2014 to 2015 (Wilburn and Karl, 2015).
  - There are deposits of manganese-rich nodules on the ocean floor which may be mined if price and technology allow.

- Current and projected trends for demand and why[1,2,6]
  - Demand for manganese is closely tied to the steel industry, which is highly linked to economic prosperity or downturn
    - The status of emerging market economies will likely have a large effect on manganese demand
  - Manganese is being used in more batteries for solar-generated electricity storage and electric vehicles; these market will likely continue to expand.

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for manganese, high occurrence potential areas in the RGFO area could become economically viable.

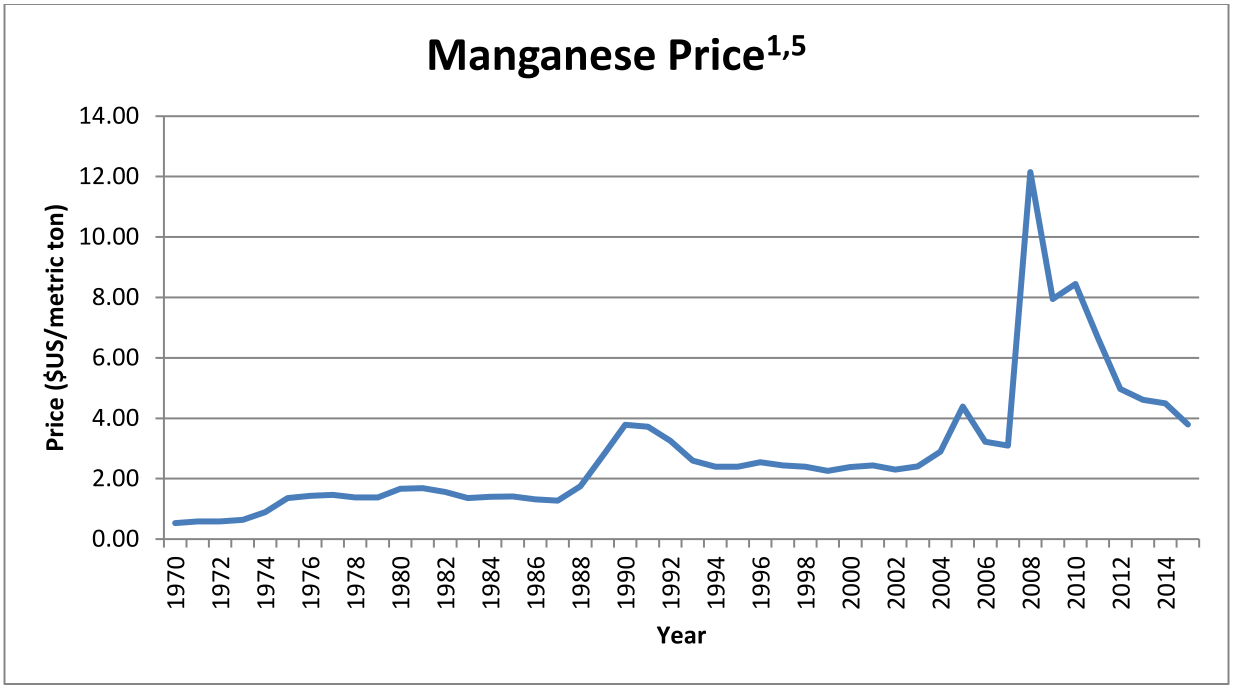


Figure 5-20. Annual average manganese price from 1970 to 2015.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Resource Investor, 2016

5.4.6 Molybdenum

- The "usable" characteristics of the material[1,3]
  - High melting point (4730° F)
  - Alloys well with other metals
  - Slippery, lubricating texture

- What technology/industrial practice it is used for currently[1,3,6]
  - Steel strengthening
  - Catalysts
  - Paint pigments
  - Corrosion inhibitors
  - Smoke and flame retardants

    - Dry lubricants
- What technology/industrial practice it might be used for in the future[2,6]
    - Catalyst in the production of low-sulfur diesel fuel
    - Solar electric systems
    - Dry lubricants on space vehicles

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves in 2015 were 11 million tonnes of molybdenum
    - In 2015, the U.S. had reserves of 2.7 million tonnes of molybdenum
    - As of 2015, molybdenum was produced as a primary product at 2 U.S. mines and as a byproduct at 8 U.S. copper mines
    - As of December 31, 2015, Freeport-McMoRan, one of the largest molybdenum producers in the U.S., had reserves in North America of 1.1 million tonnes of molybdenum (including reserves at the Henderson and Climax molybdenum mines located in the RGFO management area) (Freeport McMoRan, 2015).

- Local, regional and worldwide markets and why[1,2]
    - World molybdenum production is depicted in Figure 5-21. The four largest molybdenum producing nations in 2015 were:
        - China (101,000 tonnes)
        - United States (56,300 tonnes)
        - Chile (49,000 tonnes)
        - Peru (18,100 tonnes)
    - Molybdenum is produced in ~12 countries around the world; deposits are unequally distributed.
    - In the United States, molybdenum is mined as a primary or secondary metal in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, and Utah.
    - There are 2 primary molybdenum mines in the RGFO area, Henderson and Climax; in 2015 they produced a combined ~21,800 tonnes of recoverable molybdenum.
    - The U.S. government does not hold a molybdenum stockpile.
    - Molybdenum is recovered as part of recycled steel and other alloys. Though there is no process for the separate recovery and refining of secondary molybdenum, molybdenum recycled from scrap may be as much as 30 percent of apparent supply.

- Reasons for demand fluctuations[1,2]
    - Economic uncertainty, especially in large markets like China
    - Price of and demand for steel

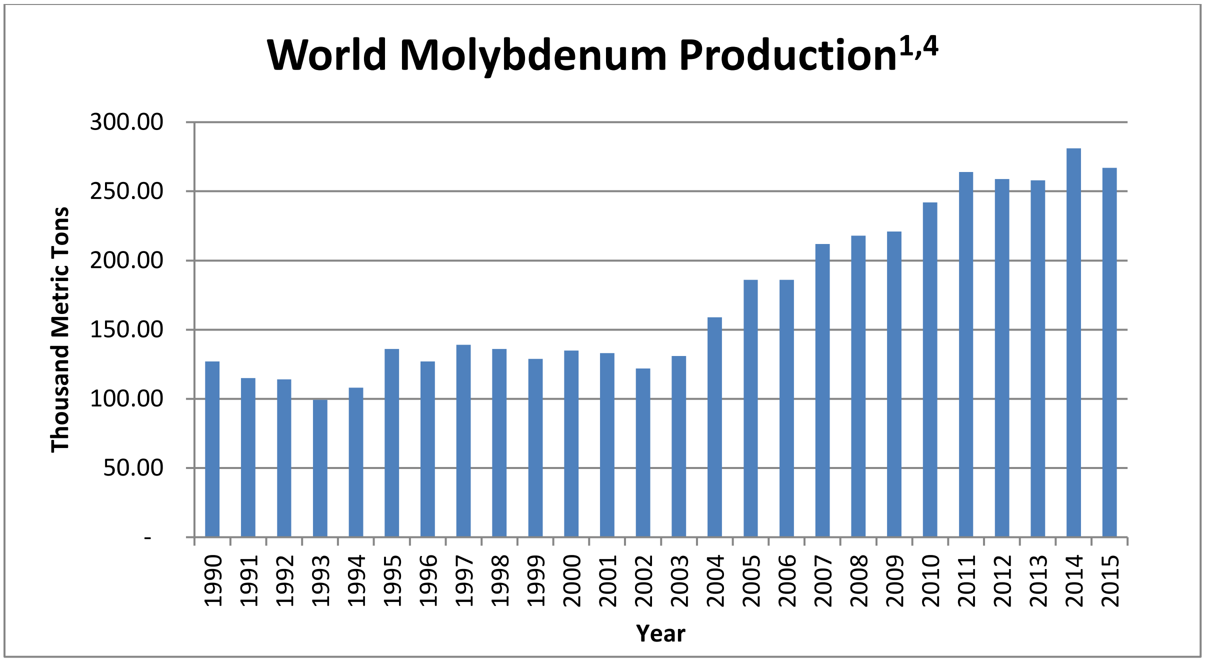


Figure 5-21. Annual world molybdenum production from 1990 to 2015.

- Reasons for market fluctuations[1,2]
    - Economic uncertainty, especially the growth or decline of the automotive and housing industries, affects steel price.
    - Production at the Ashdown (NV) and Questa (NM) mines continued to be suspended in 2015; the Thompson Creek (ID) and Mineral Park (AZ) mines were put on care and maintenance at year-end 2014 and were not reopened in 2015, significantly reducing U.S. production.
    - A drop in molybdenum price (Figure 5-22) led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 15 percent decrease in exploration budgets for molybdenum from 2014 to 2015 (Wilburn and Karl, 2015).

- Current and projected trends for demand and why[1,2]
    - Demand for molybdenum is closely tied to the steel industry, which is highly linked to economic prosperity or downturns.
        - The status of emerging market economies will likely have a large effect on molybdenum demand.
    - There is not a viable substitute for molybdenum in steel manufacturing, so if steel demand rises, so will demand for molybdenum.
    - In the U.S. in 2015, 74 percent of consumed molybdenum went to iron, steel, and superalloy producers.

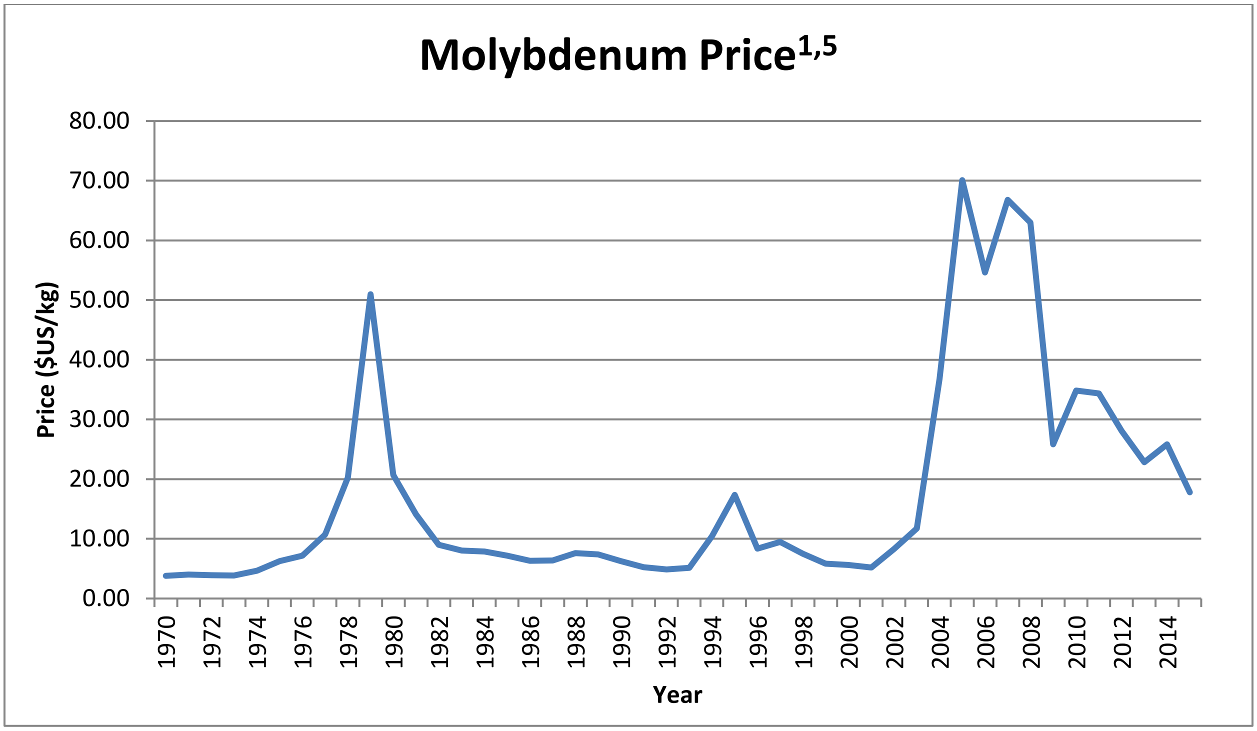


Figure 5-22. Annual average price of molybdenum from 1970 to 2015.

- Any influence of these trends that may directly affect the RGFO region[1,2]
    - The continued operation of Climax and Henderson mines depends upon their continued economic feasibility. Climax was on limited production or closed due to low molybdenum prices for almost two decades.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2015
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Climax Molybdenum, 2016

5.4.7 Nickel

- The "usable" characteristics of the material[1,3]
    - Malleable, meaning it can be flattened into very thin sheets
    - Naturally magnetic
    - Alloys well with other metals
    - Resistant to corrosion
    - Electrically and thermally conductive

- What technology/industrial practice it is used for currently[1,3]
    - Steel alloys, particularly Stainless Steel
    - Coinage
    - Nickel-cadmium and nickel-metal hydride batteries
    - Chemical catalyst
    - Glass pigment

- What technology/industrial practice it might be used for in the future[1,2,3]
    - Superalloys used in gas and steam turbines
    - Superalloy piping for geothermal energy infrastructure
    - Fuel cell anodes and cathodes
    - Superlight nickel microlattices for thermal insulation, battery electrodes, and impact protection

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves in 2015 were 79 million tonnes of nickel.
    - In 2015, the U.S. had reserves of 160,000 tonnes of nickel.
    - As of 2015, nickel was produced as a primary product at 1 U.S. mine in Michigan, with 3 projects in development in northern Minnesota:
        - The Eagle mine, the only U.S. primary producer of nickel, had reserves of 95,000 tonnes contained nickel as of June 30, 2016 (Lundin, 2016).
        - The NorthMet deposit at the western end of the Duluth Complex had estimated proven and probable reserves of 249 million tonnes of ore grading 0.082 percent nickel in 2013.
    - The U.S. government sold the last of the National Defense Stockpile in 1999, but the DOE holds 8,800 tons of nickel ingot and 5,080 tons of nickel scrap.
    - There are no primary producing nickel mines in the RGFO area.

- Local, regional and worldwide markets and why[1,2]
    - Annual world nickel production is depicted in Figure 5-23. The four largest nickel producing nations in 2015 were:
        - Philippines (530,000 tonnes)
        - Canada (240,000 tonnes)
        - Russia (240,000 tonnes)
        - Australia (234,000 tonnes)

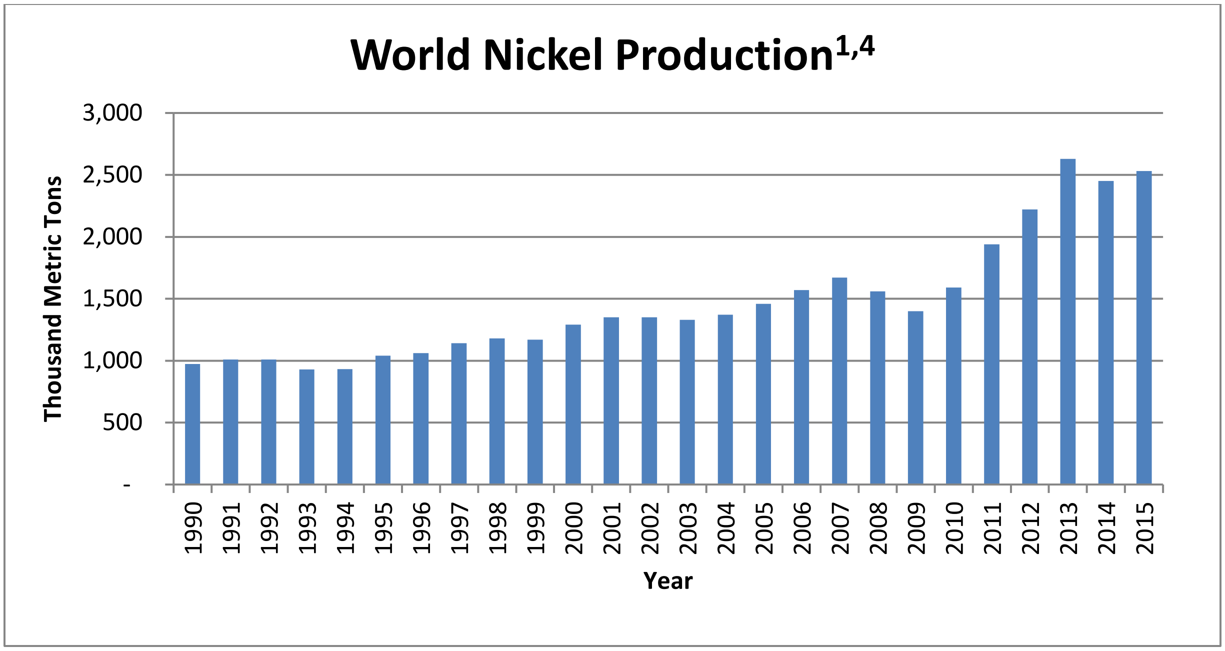


Figure 5-23. Annual world nickel production from 1990 to 2015.

  - Nickel is produced in ~32 countries around the world; deposits are unequally distributed. Laterite deposits in tropical regions require less processing than sulfide ores, which are more widely distributed.
  - In the United States, nickel is mined as primary ore in Michigan.
  - Nickel is recovered as part of recycled steel and other alloys. Nickel recycled from scrap may be as much as 45 percent of apparent consumption.
  - In the U.S. in 2015, 45 percent of primary nickel consumption went to stainless and alloy steel production, 43 percent to nonferrous alloys and superalloys, 7 percent to electroplating, and 5 percent to other uses.
    - End uses include: transportation and defense (34 percent), fabricated metal products (20 percent), electrical equipment (13 percent), chemical industry (7 percent), petroleum industry (7 percent), construction (5 percent), household appliances (5 percent), industrial machinery (5 percent), and other (4 percent).

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty, especially in large markets like China
  - Price of and demand for steel
  - Emerging uses of nickel, particularly batteries for electric and hybrid batteries
  - Amount of nickel from recycled sources

- Reasons for market fluctuations[1,2,6,7]
  - Economic uncertainty affects steel price, especially the growth or decline of the automotive and housing industries

- The London Metal Exchange had accrued stocks of 423,000 tons of nickel metal by October 2015, the highest ever level. This will provide a steady supply should mine production change.
- In January 2014, Indonesia banned export of direct shipping ores (DSO) of nickel in order to encourage construction of additional refining plants domestically. However, this caused China to increase importation of DSO from the Philippines.
    - As of September 2016, members of the Philippine's Congress were calling for an ore ban similar to Indonesia's.
    - As of September 2016, the Philippines Department of Environment and Natural Resources had suspended the licenses of ~8 nickel producers and recommended another ~10 for suspension or closure due to environmental concerns; if all recommendations are followed, mines accounting for 55 percent of the country's total nickel ore output could be closed.
- A drop in nickel price (Figure 5-24) led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 33 percent decrease in exploration budgets for nickel from 2014 to 2015 (Wilburn and Karl, 2015).

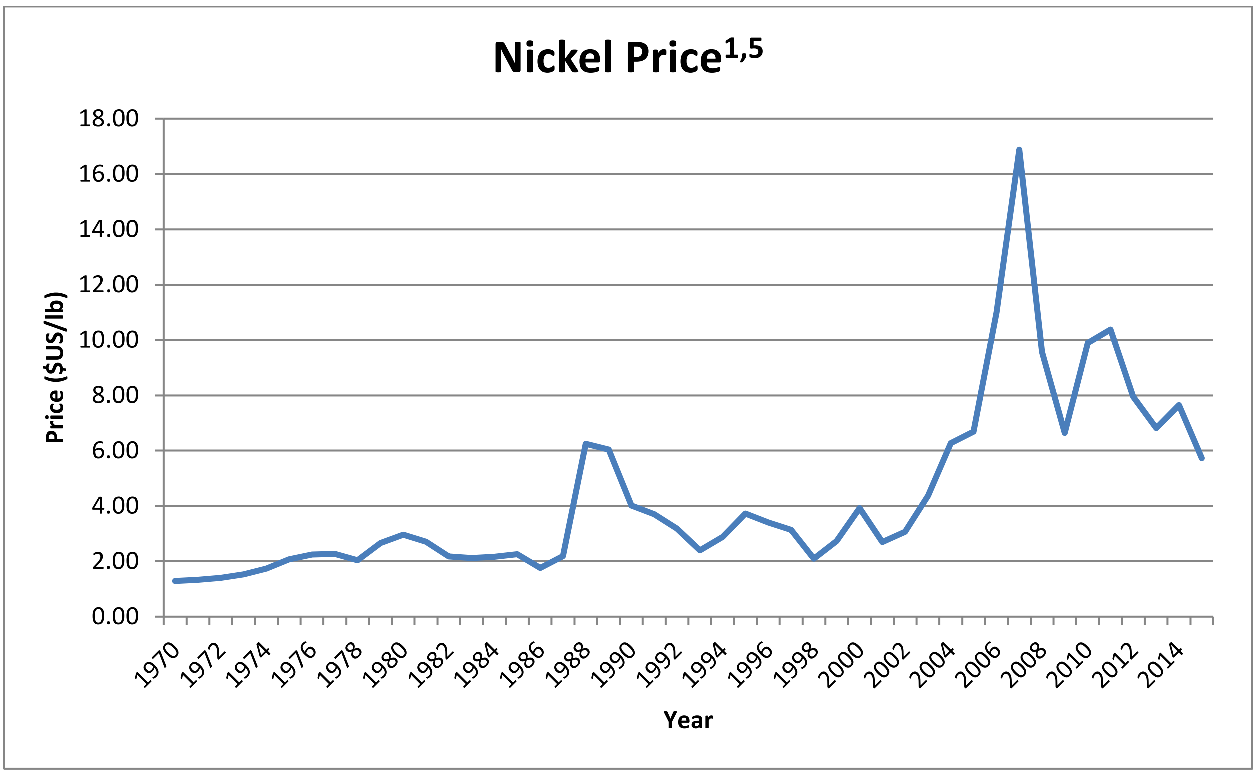


Figure 5-24. Annual average price of nickel from 1970 to 2015.

- Current and projected trends for demand and why[1,2]
    - Demand for nickel is closely tied to the steel industry, which is highly linked to economic prosperity or downturns.
        - The status of emerging market economies will likely have a large effect on nickel demand.
    - Demand in the energy industry is expected to continue to rise; both traditional and renewable energy projects require large tonnages of nickel-bearing steel.
    - The use of lithium-ion versus nickel-metal hydride batteries in the automotive industry could lower or raise demand.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for nickel, high nickel occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Dela Cruz and Serapio, 2016
[7]Mining.com, 2016

5.4.8 Tungsten

- The "usable" characteristics of the material[1,3]
    - Chemically stable
    - Highest melting point of any metal
    - Resistant to acids

- What technology/industrial practice it is used for currently[1,3]
    - Tungsten carbide cutting tools (e.g., micro drills for circuit boards, drill bit heads for resource exploration)
    - Military armor
    - Lightbulb filaments
    - Electrodes and wires
    - Welding
    - Superalloys for turbine engine parts

- What technology/industrial practice it might be used for in the future[3,5]
    - Bits for super-deep drilling

  - High efficiency gas turbines
  - Nuclear reactor parts
  - Semiconductors
  - Energy efficient lighting
  - Medical implants

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Worldwide, in the ground reserves in 2015 were 3.3 million tonnes of tungsten
  - In 2015, the U.S. did not report tungsten reserves in order to avoid disclosing company proprietary data for the only producing tungsten mine.
  - As of 2015, tungsten was produced as a primary product at 1 U.S. mine, in California, with 2 projects in development in Nevada.
    - The Andrew mine, the only U.S. primary producer of tungsten, did not have reported resources or reserves.
    - As of June 30, 2016, the Springer complex in Nevada held indicated and inferred resources of ~8,700 tonnes of tungsten (Silver Predator, 2016).
    - As of June 10, 2014, the Pilot Mountain project in Nevada held 21,000 tonnes of indicated and inferred tungsten (Thor, 2016).
  - At the end of 2014, the U.S. government National Defense Stockpile held 11,600 tonnes of tungsten ore and concentrates.
  - There are no primary producing tungsten mines in the RGFO area.

- Local, regional and worldwide markets and why[1,2]
  - Annual world tungsten production is reported in Figure 5-25. The four largest tungsten producing nations in 2015 were :
    - China (71,000 tonnes)
    - Vietnam (5,000 tonnes)
    - Russia (2,500 tonnes)
    - Canada (1,700 tonnes)
  - Tungsten is produced in ~20 countries around the world; deposits are widespread but the largest deposits are heavily concentrated in China.
  - In the United States, tungsten is mined as primary ore in California.
  - Tungsten recovered from scrap represented 59 percent of apparent consumption.
  - In the U.S. in 2015, 60 percent of tungsten was used in cemented carbide parts for cutting and wear-resistant materials.

- Reasons for demand fluctuations[1,2,5]
  - Economic uncertainty affects manufacturing sector and consumption of cemented carbides, the largest use of tungsten.

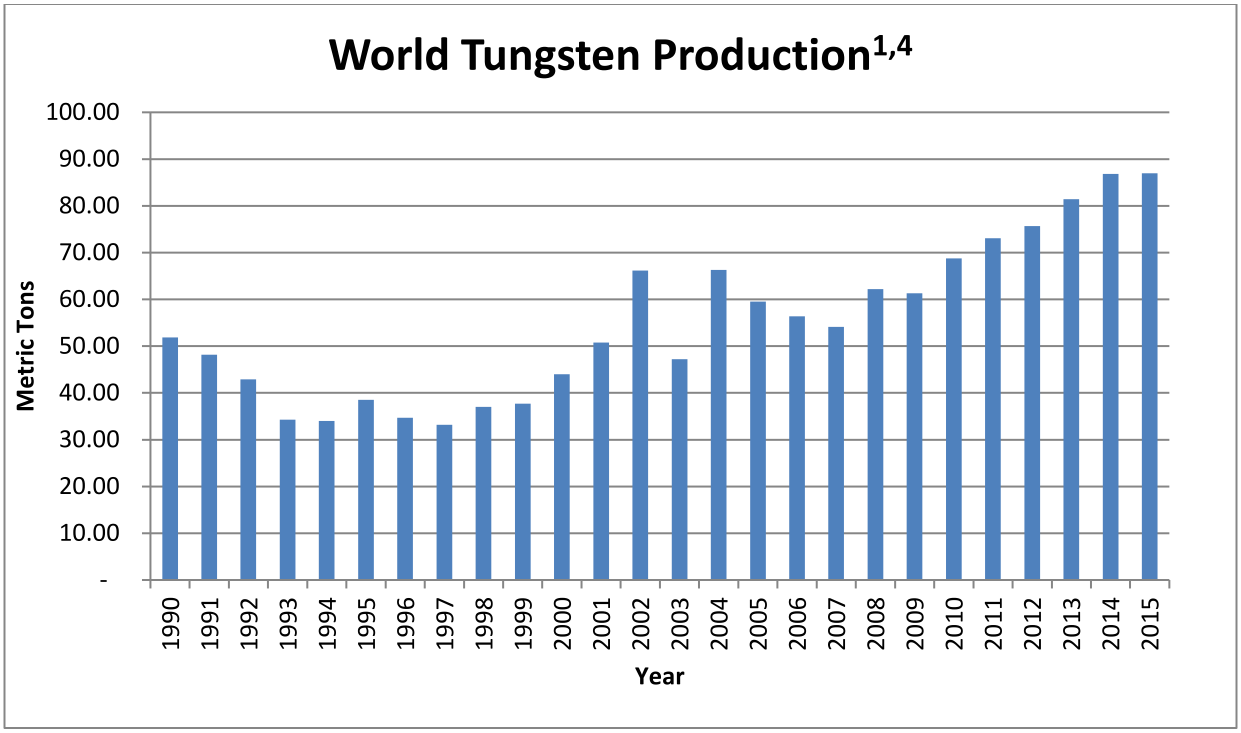


Figure 5-25. Annual world tungsten production from 1990 to 2015.

        - Commodities prices affect the amount of oil, gas, and mining exploration and drilling, which heavily use tungsten carbide bits
    - Price of tungsten (Figure 5-26)
    - Government spending budgets for defense applications
    - Amount of tungsten from recycled sources

- Reasons for market fluctuations[1,2]
    - Economic uncertainty affects the growth or decline of the automotive, electronics, and manufacturing industries.
    - Passage of rules by the SEC requiring publicly traded companies to ensure their tungsten is not sourced as a conflict mineral from Congo or surrounding areas (conflict minerals are those that may be funding armed groups).
    - A drop in tungsten price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was an 18 percent decrease in exploration budgets for tungsten from 2014 to 2015 (Wilburn and Karl, 2015).

- Current and projected trends for demand and why[1,2,5]
    - Demand for tungsten is tied to manufacturing, which is highly linked to economic prosperity or downturns.

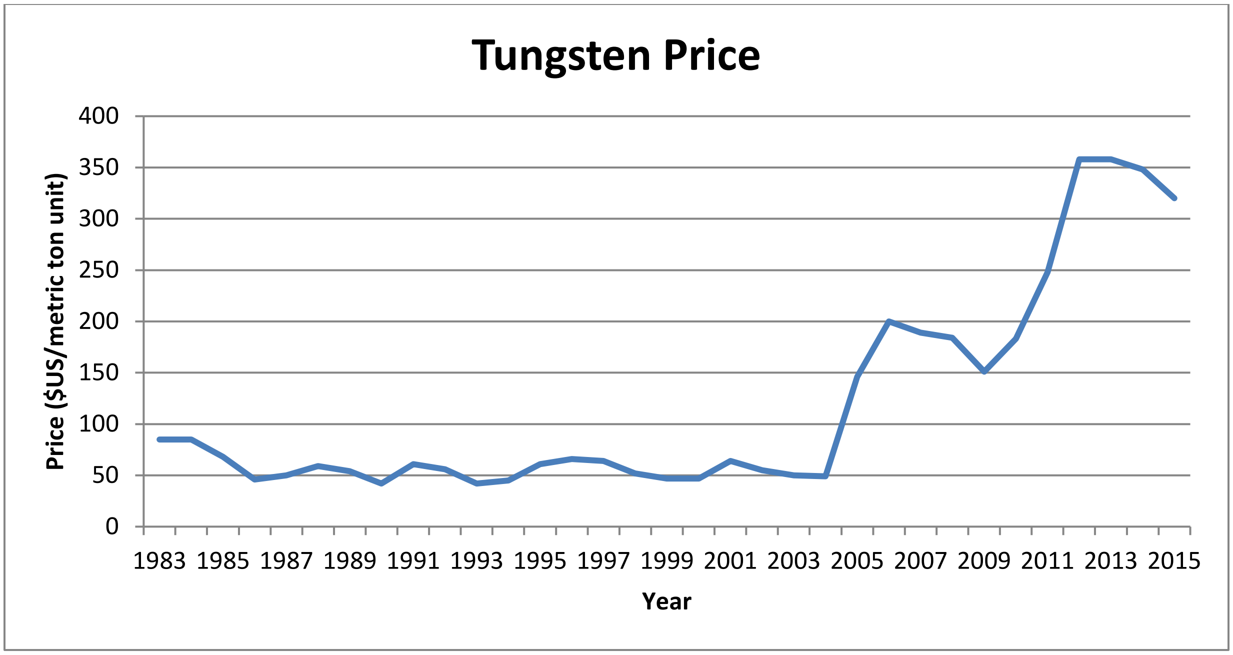


Figure 5-26. Annual average price of tungsten from 1983 to 2014. All data from USGS Mineral Yearbooks, 1983-2014; 1997-2014 U.S. spot quotation, annual average calculated from weekly prices reported by Platts Metals Week; 1983-1996 average equivalent price per metric ton unit of WO3 calculated from Metals Week; U.S. spot quotations, 65 percent WO_3 basis, c.i.f. U.S. ports, including duty.

        - The status of emerging market economies will likely have a large effect on tungsten demand.
    - Demand in the energy industry is expected to continue to rise; both traditional and renewable energy projects require tungsten alloys and tungsten carbide.
    - The use of tungsten in defense applications is variable, and industry changes could raise or lower demand.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for tungsten, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]ITIA, 2016

5.5 Minor Metals

5.5.1 Beryllium

- The "usable" characteristics of the material[1,3]
  - Lightweight
  - Hard
  - High strength
  - Excellent thermal conductivity
  - High melting point

- What technology/industrial practice it is used for currently[1,3,4]
  - Consumer electronic components
  - Alloys to make other metals stronger
  - Alloys to make springs
  - Alloys with copper to make spark-resistant metals
  - Windows for X-ray tubes
  - Nuclear reactor control parts

- What technology/industrial practice it might be used for in the future[4]
  - Aerospace components
  - Advanced nuclear reactors
  - Miniaturization of electrical components
  - Particle accelerators and other Ultra High Vacuum (UHV) applications

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Worldwide, in the ground reserves were not available. Worldwide beryllium resources in 2015 were estimated at 80,000 tonnes.
  - In 2015, there was only one producing beryllium mine in the U.S.
    - Materion reported combined proven and probable reserves of ~21,600 tonnes of beryllium as of December 31, 2015; this is essentially equal to the reserves for the U.S. (Materion, 2015).
  - As of September 30, 2015, the U.S. government National Defense Stockpile had 77 tonnes of beryllium metal.
  - There are no primary producing beryllium mines in the RGFO area.

- Local, regional and worldwide markets and why[1,2]
  - Annual world beryllium production is depicted in Figure 5-27. The three largest beryllium producing nations in 2015 were:
    - United States (275 tonnes)
    - China (20 tonnes)

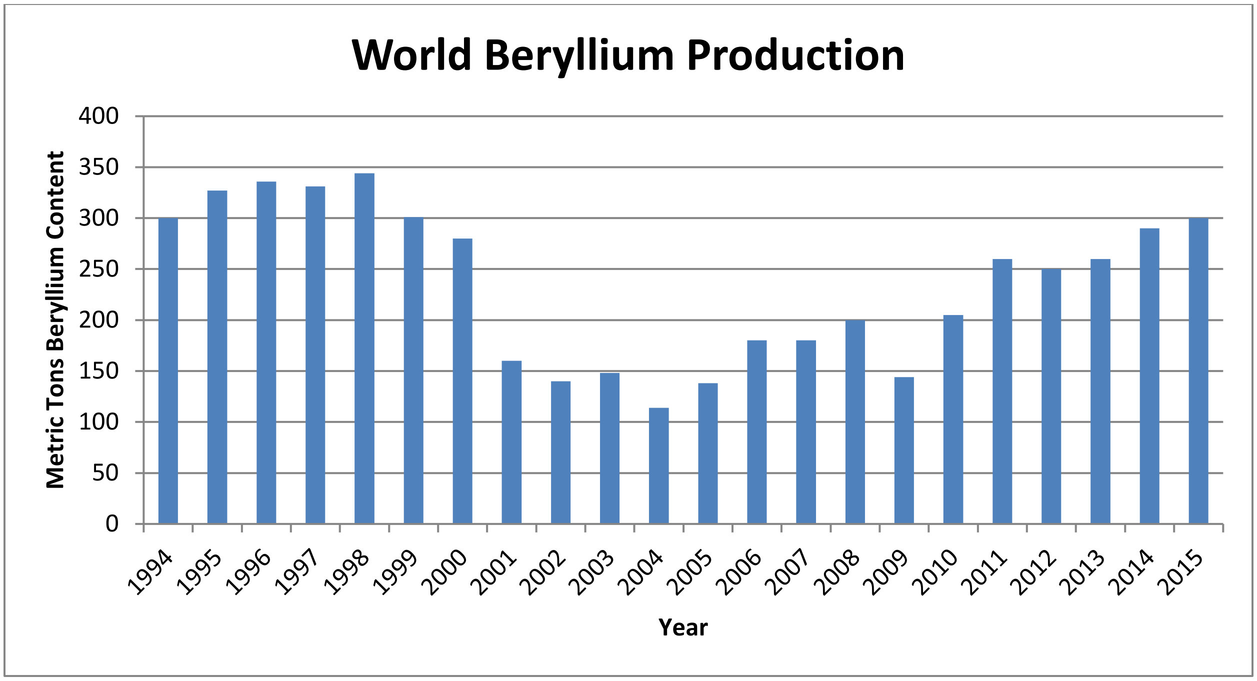


Figure 5-27. Annual world beryllium production from 1994 to 2015. All data from USGS MCS, 1996 to 2016.

        - Mozambique (2 tonnes)
    - Beryllium is produced in ~4 countries around the world; deposits are extremely limited.
    - In the United States, beryllium is mined as a primary ore in Utah.
    - Beryllium recovered from scrap may account for 20-25 percent of apparent consumption.
    - In the U.S. in 2015, 20 percent of beryllium products were used in industrial components, 18 percent in consumer electronics, 16 percent in automotive electronics, 8 percent in energy applications, 8 percent in telecommunications infrastructure, 6 percent in defense applications, 2 percent in medical applications, and 22 percent in other applications.

- Reasons for demand fluctuations[1,2]
    - Economic uncertainty affects demand for beryllium-containing products.
    - Price of beryllium (Figure 5-28)
    - Government spending budgets for defense applications
    - Amount of beryllium from recycled sources
    - Use of beryllium substitutes like metal matrices and alternative alloying metals

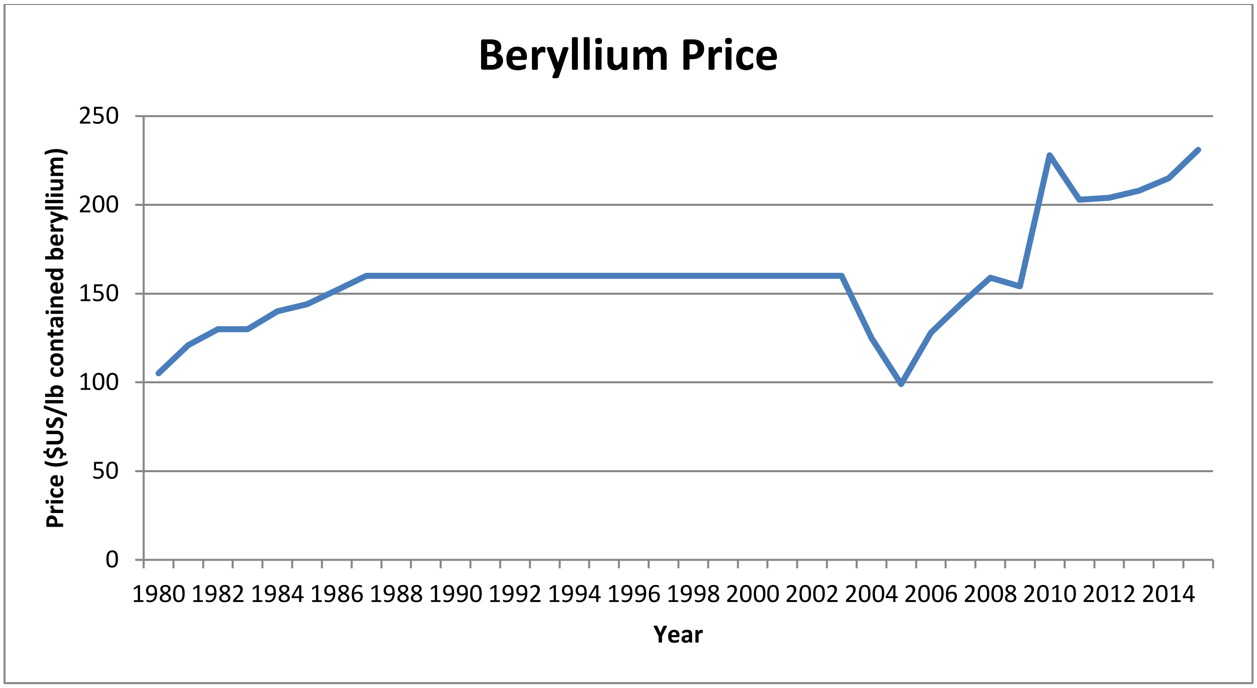


Figure 5-28. Annual average price of beryllium from 1980 to 2015 Data from USGS Mineral Yearbooks, 1983-1990; USGS Mineral Commodity Summaries 1991-2015. Unit value, annual average, beryllium-copper master alloy, dollars per pound contained beryllium.

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects the growth or decline of the automotive, electronics, and manufacturing industries
  - U.S. Government designated beryllium as a strategic and critical material, and took actions to maintain a long-term domestic supply
    - The DOD invested in a public-private partnership in 2008 to build a primary beryllium facility to process the ore from Utah
  - Russia is investing in beryllium production, with commercial production expected to begin in 2020

- Current and projected trends for demand and why[1,2,4]
  - Demand for beryllium is tied to manufacturing, which is highly linked to economic prosperity or downturns.
    - The status of emerging market economies will likely have a large effect on beryllium demand.
  - In certain applications, there are no appropriate beryllium substitutes, meaning the demand in those cases will remain steady or increase.
  - Continued growth of beryllium applications is expected, but miniaturization of products could mean beryllium consumption may lag behind application demand.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for beryllium, high occurrence potential areas in the RGFO region could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Materion, 2016

5.5.2 Gallium-Germanium-Indium

- The "usable" characteristics of the material[1,3]
    - Gallium
        - Low melting temperature (~84° F)
        - Unusually high boiling point (~4000° F)
    - Germanium
        - Semiconducting
    - Indium
        - Malleable
        - Ductile
        - Relatively low melting temperature (~313° F)
        - Semiconducting

- What technology/industrial practice it is used for currently[1,3]
    - Gallium
        - Cellphones
        - Wireless applications and infrastructure
        - LEDs and laser diodes
        - Semiconductors
        - Defense applications
    - Germanium
        - Semiconductors
        - Fiber optics
        - Infrared night vision systems
        - Polymerization catalysts
    - Indium
        - Fusible alloys and solders
        - Semiconductors
        - Thin films for LCD screens
        - Nuclear reactor control rods

- What technology/industrial practice it might be used for in the future[1,2,3]
    - Gallium
        - Aerospace components
        - Copper indium gallium selenide photovoltaic cells (currently available but not in widespread use)
        - Advanced defense applications in radar systems
    - Germanium
        - Nanowire production
        - High-efficiency solar cells
        - Possible use in organic compounds for pharmaceuticals
        - High speed telecommunications
    - Indium
        - Copper indium gallium selenide photovoltaic cells (currently available but not in widespread use)
        - Cryogenics
        - Ultra-High-Vacuum applications

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves were not available for gallium; it is recovered as a byproduct of bauxite and zinc ores. Since only part of the gallium present in those ores is recoverable, an estimate of reserves is not practicable.
    - Worldwide, in the ground reserves were not available for germanium; it is recovered as a byproduct of zinc ores. Since as little as 3 percent of the germanium present in those ores is recoverable, an estimate of reserves is not practicable.
    - Worldwide, in the ground reserves were not available for indium; it is recovered as a byproduct of zinc ores. Since only part of the indium present in those ores is recoverable, an estimate of reserves is not practicable.
    - As of November 2016, there are no primary producing gallium or indium mines in the U.S.
        - One indium-rich zinc project, the West Desert in Utah, had indicated resources of ~1600 tonnes of indium as of March 17, 2014. The project was not in production as of November 2016 (InZinc, 2016).
    - In 2016, germanium was produced as a byproduct of zinc mining at the Red Dog mine in Alaska, Pend Oreille mine in Washington, and the Middle Tennessee mine in Tennessee; there is an estimated 2,500 tonnes of germanium in U.S. zinc deposits (although only a fraction is recoverable).
    - There is no government stockpile for gallium or indium. Germanium is considered a strategic and critical material, and the National Defense Stockpile contained 13.4 tonnes of germanium as of September 30, 2015.

- There are no primary producing gallium, germanium, or indium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - Annual world production of gallium, germanium, and indium is depicted in Figure 5-29. The four largest gallium primary producing nations in 2015 were (no absolute individual primary production numbers available):
    - China
    - Germany
    - Japan
    - Ukraine
  - The three largest refined germanium (primary and new scrap) producing nations in 2015 were:
    - China (120 tonnes)
    - Russia (5 tonnes)
    - United States (withheld tonnage to avoid disclosing proprietary data)

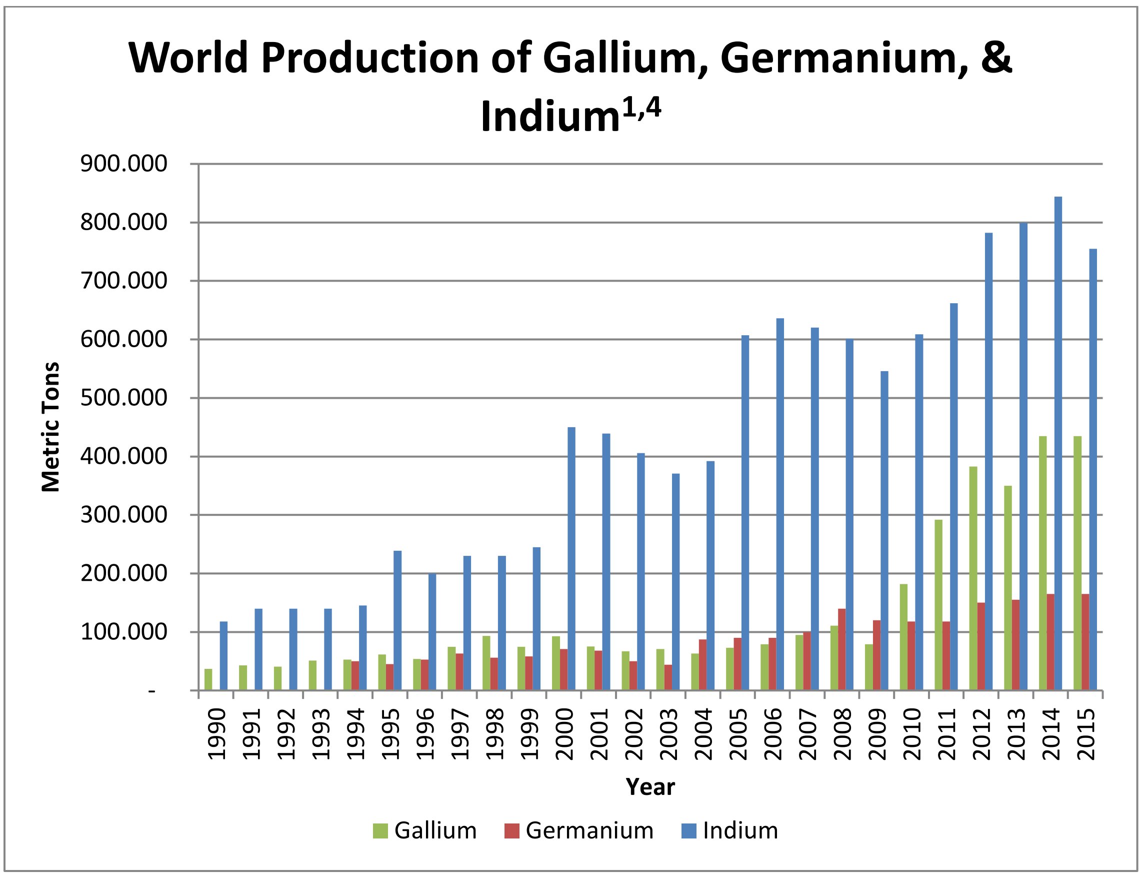


Figure 5-29. Annual world production of gallium, germanium, and indium from 1990 to 2015.

- The four largest refined indium (primary and new scrap) producing nations in 2015 were:
  - China (370 tonnes)
  - South Korea (150 tonnes)
  - Japan
  - Canada
- Gallium is produced in ~8 countries around the world; deposits are widespread (contained in bauxite and zinc ores), but concentrations vary and most gallium is produced from bauxite. Germanium is produced or refined in ~5 countries; deposits are fairly widespread (contained in zinc ores), but concentrations and recoverability varies. Indium is produced or refined in ~8 countries; deposits are fairly widespread (contained in zinc ores), but concentrations and recoverability varies.
- In the United States, germanium is mined as a byproduct in Alaska, Washington, and Tennessee.
- Gallium is not recovered from old scrap, but production facilities recycle new scrap created during the refining process. Germanium is recycled from the manufacture process (new scrap) and from old scrap (e.g., decommissioned military vehicles); worldwide, about 30 percent of total germanium consumption is from recycled materials. Indium is recovered from scrap in the U.S., Japan, and Korea, among other countries, but estimated quantities are not available.
- In the U.S. in 2015, 57 percent of gallium was used in integrated circuits for a large variety of devices, and 43 percent was used in optoelectronic devices (laser diodes, LEDs, photodetectors, and solar cells); 40 percent of germanium was used in fiber optics, 30 percent in infrared optics, 20 percent in electronics and solar applications, and 10 percent in other uses. Production of indium-tin-oxide (ITO; used in thin films for flat panel displays) accounts for 55-85 percent of indium consumption annually.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty affects demand for gallium-, germanium-, and indium-containing products.
  - Price of gallium, germanium, and indium (Figure 5-30)
  - Government spending budgets for defense applications
  - Amount of gallium, germanium, and indium from recycled sources
  - Use of substitutes
    - Gallium substitutes like silicon in semiconductors and solar cells may affect some demand, but many applications, especially defense, have no substitute.

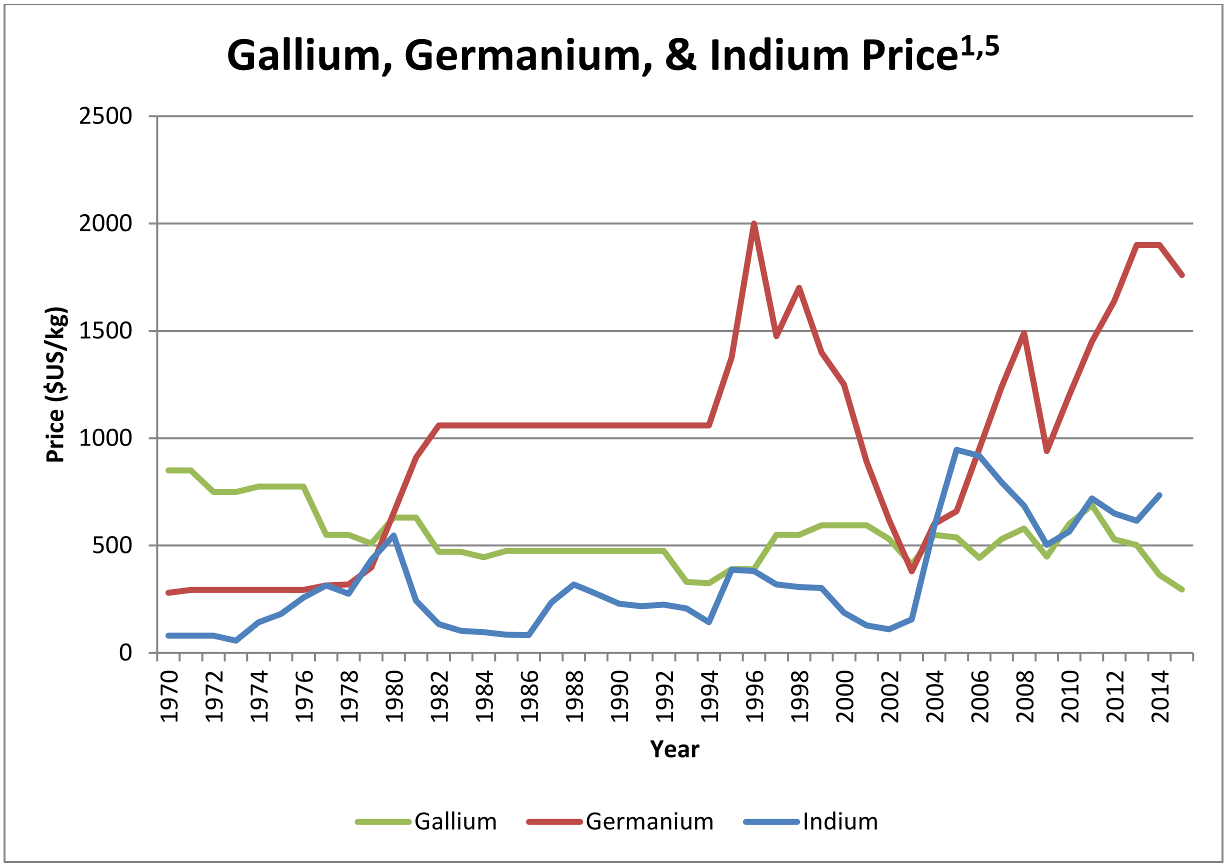


Figure 5-30. Annual average price of gallium, germanium, and indium from 1970 to 2015.

- Germanium substitutes, like silicon in electronic applications and antimony in polymerization catalysts, may affect some demand, but other applications, especially infrared optics, have no equal substitute.
- Several viable substitutes for ITO have been found for use in touch screens, solar cells, and LCDs. These could lower the demand for indium.

- Reasons for market fluctuations[1,2,6,7]
  - Economic uncertainty affects the growth or decline of the industries that use gallium, germanium, and indium.
  - Concentrations and recovery of gallium, germanium, and indium can vary, altering production amounts.
  - China began to focus on LED lighting in 2011 and increased primary gallium production significantly.
  - Germanium supply is heavily reliant on the zinc market, but several smelters have added the capacity to split base metals from minor metals in order to increase the amount of recoverable germanium even if mining rates remain constant.

- Lower zinc prices have reduced smelter throughput, thereby reducing the amount of germanium and indium obtained as byproducts.
- The Fanya Metal Exchange Co. Ltd. in China had been trading 14 minor metals, including gallium, germanium, and indium, at prices elevated compared to global markets. In mid-2015, all sales of its products were halted pending investigation into corruption and investor fraud; the fate of the company's stockpiles is uncertain and could have an unknown effect on the minor metals market.

- Current and projected trends for demand and why[1,2]
  - Demand for gallium-containing electronic devices and lighting is expected to continue to rise as the developing world adopts advanced smartphones and wireless technologies.
  - In certain applications, there are no appropriate gallium, germanium, or indium substitutes, meaning the demand in those cases will remain steady or increase.
  - Global demand for fiber optics is expected to increase, and new applications of infrared technology in smartphones means a general increase in germanium demand.
  - Demand for indium-containing electronic devices is expected to continue to rise as the developing world adopts advanced smartphones and large area tablets and TVs; however, several alternatives to indium-based thin films have been developed and may decrease demand if they can be produced cheaper.

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for gallium, germanium, and indium, high occurrence potential areas in the RGFO region could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Stanway, 2015
[7]Els, 2015

5.5.3 Rare Earth Elements

- The "usable" characteristics of the material[1,3]
  - Malleable
  - Ductile
  - Chemically reactive

- What technology/industrial practice it is used for currently[1,3,5]
    - Automotive propulsion batteries
    - Phosphors and lasers
    - Electric motors
    - High efficiency light bulbs
    - Generators in wind turbines
    - Defense technologies like radar, sonar, guidance systems
    - Computing components
    - Pollution abatement
    - Permanent magnets

- What technology/industrial practice it might be used for in the future[3,5]
    - High-temperature superconductors
    - Storage and transport of hydrogen for fuel cells
    - Magnetic refrigeration

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves were 130 million tonnes of rare earth oxide (REO) equivalent in 2015.
    - In 2015, the U.S. had reserves of 1.8 million tonnes of REO:
        - The Mountain Pass mine in California produced for part of 2015 before declaring bankruptcy, partially due to low prices. Reserves were reported at 17.8 million tonnes of material grading an average of 8.10 percent REO at year end 2014
        - The Bear Lodge deposit in Wyoming reported combined measured and indicated resources of 16.3 million tonnes of material with an average grade of 3.07 percent REO (using a 1.5 percent REO cutoff grade) in October 2014.
        - The Round Top deposit in Texas reported measured and indicated resources of ~307,000 tonnes REO (using 428 grams/metric ton yttrium equivalent as a cutoff grade) in early 2014.
    - There is no government stockpile of REEs, although they are listed as critical materials.
    - There are no primary producing REE mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
    - World REO production is depicted in Figure 5-31. The four largest REE primary producing nations in 2015 were:
        - China (105,000 tonnes)
        - Australia (10,000 tonnes)

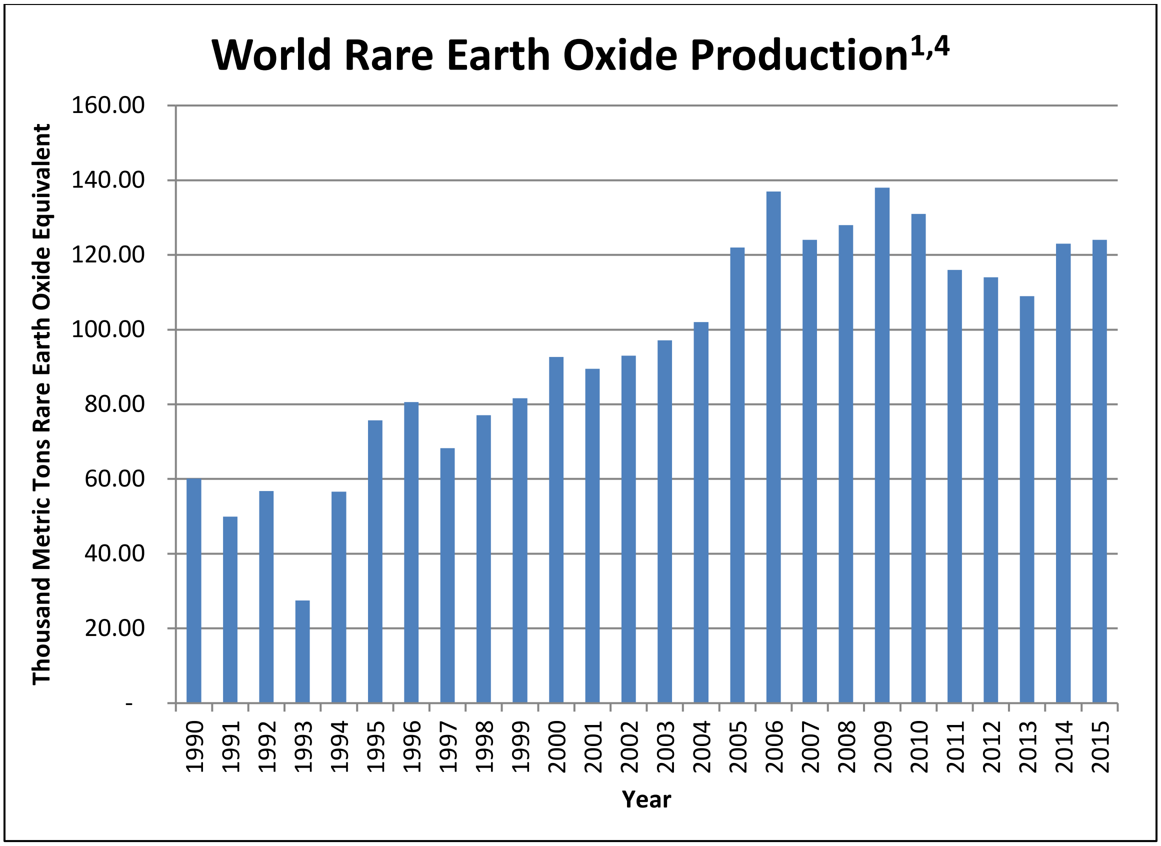


Figure 5-31. Annual world rare earth oxide production from 1990 to 2015.

- United States (4,100 tonnes from Mountain Pass, now closed)
- Russia (2,500 tonnes)

- o REEs are produced in ~9 countries around the world; deposits are unequally distributed, and laterite ion-adsorption clay deposits are easier and cheaper to process than intrusive deposits.
- o As of November 2016, there were no primary producing REE mines in the U.S.
- o REEs are recovered from recycling of batteries, polishing compounds, permanent magnets, and fluorescent lamps.
- o In the U.S. in 2015: 60 percent of REEs were used for catalysts, 10 percent for metallurgical applications and alloys, 10 percent for ceramics and glass, 10 percent for glass polishing, and 10 percent for other uses.

- Reasons for market fluctuations[1,2,5]
  - o Economic uncertainty affects the growth or decline of the industries that use REEs.
  - o Closure of Mountain Pass mine
  - o Price of REEs (Figure 5-32):

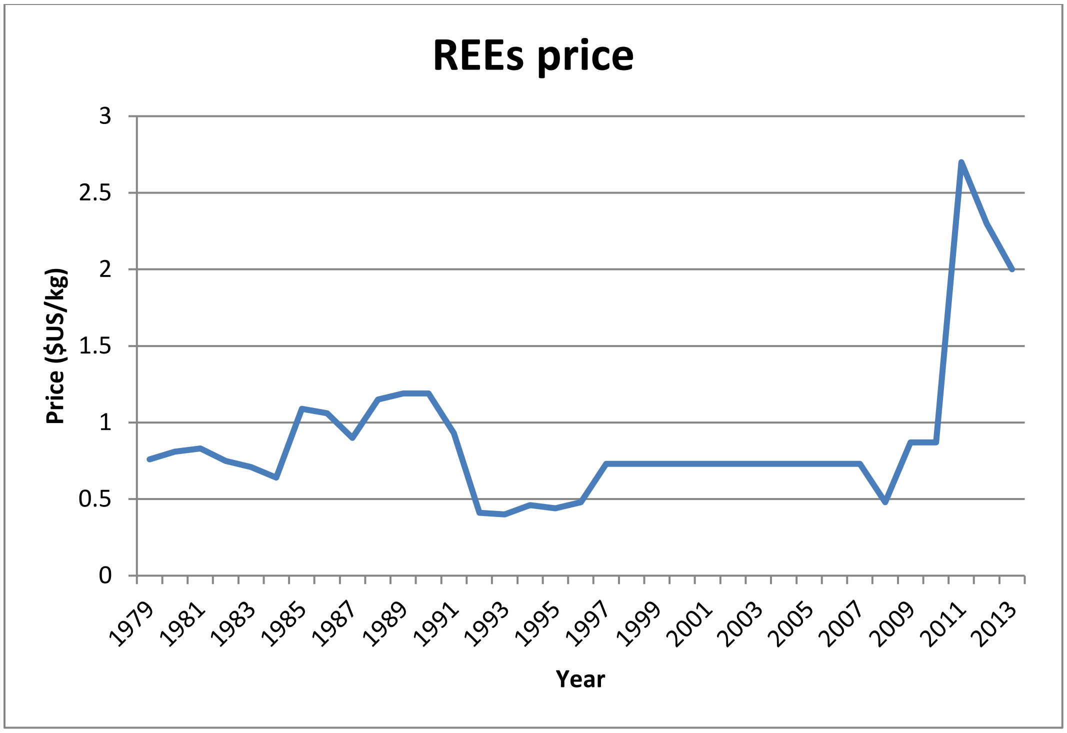


Figure 5-32. Annual average price of REEs from 1979 to 2013. Data from USGS Mineral Yearbooks, 1979-2014, Monazite concentrate, REO basis, $US/kg.

        - In 2010, China announced its intention to reduce REE exports, leading to higher prices and fears of limited supply for other nations. Export quotas were sufficient or even over-supplied world demand in 2015, but the continued reliance on China (>90 percent of world's supply) means that supply could be significantly impacted due to politics, continued production by China despite over-supply (causing price drops), or the decision to reduce export quotas.
        - A significant amount of REEs are produced illegally in China, possibly over 50,000 tons in 2013; curtailing of this practice is underway and could affect supply.
    - Despite the drop in price beginning in 2011, REE exploration has increased in Australia, Canada, South Africa, and the U.S. due to concerns about future supply.

- Current and projected trends for demand and why[1,2]
    - Demand for REE-containing electronic devices and lighting is expected to continue to rise in the developing world.
    - In certain applications, there are no appropriate REE substitutes meaning the demand in those cases will remain steady or increase.

    - Global demand for permanent magnets (used in wind turbines, electric vehicles, etc.) and REE-bearing batteries (used in electric cars) is expected to increase.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for REEs, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]Haxel et al., 2002

5.5.4 Niobium-Tantalum

- The "usable" characteristics of the material[1,3,7]
    - Niobium
        - Ductile
        - High melting point
        - Relatively low density
        - Superconducting
    - Tantalum
        - Very high melting point
        - Hard
        - Dense
        - Ductile
        - Conductive to heat and electricity
        - Resistant to acid corrosion

- What technology/industrial practice it is used for currently[1,3,7]
    - Niobium
        - High-strength steel alloys
        - Ni-Co-Fe alloys for jet engines, gas turbines, rocket subassemblies, turbocharger systems, and combustion equipment
        - Superconducting magnets for medical hardware such as MRIs and NMRs
        - Catalyst
    - Tantalum
        - Cell phones
        - Hearing aids
        - Hard drives

        - Medical applications like blood vessel support stents, plates, bone replacements, and suture clips
        - Corrosion-resistant lining for pipes, tanks and vessels
        - Glass and cutting tool manufacture

- What technology/industrial practice it might be used for in the future[1,7]
    - Niobium
        - Superconducting magnets for particle accelerators
        - Catalysts to convert palm oil into bio-diesel fuel
        - Aerospace
    - Tantalum
        - Tantalum polymer capacitors
        - Advanced medical implants
        - Aerospace

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
    - Worldwide, in the ground reserves of niobium were estimated to be at least 4.3 million tonnes in 2015.
    - Worldwide, in the ground reserves of tantalum were estimated to be at least 100,000 tonnes in 2015.
    - In 2015, the U.S. had no reserves of niobium or tantalum.
    - As of November 2016, there are no primary producing niobium or tantalum mines in the U.S.
        - One niobium-rich project, Elk Creek in Nebraska, held indicated resources of 572,000 tonnes of contained niobium pentoxide as of October 16, 2015 (NioCorp, 2015).
    - As of September 30, 2015, the National Defense Stockpile contained 10 tonnes of niobium and 1.71 tonnes of tantalum carbide powder.
    - There are no primary producing niobium or tantalum mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
    - World niobium and tantalum production is depicted in Figure 5-33.
    - The two largest niobium primary producing nations in 2015 were:
        - Brazil (50,000 tonnes)
        - Canada (5,000 tonnes)
    - The four largest tantalum primary producing nations in 2015 were:
        - Rwanda (600 tonnes)
        - Congo (Kinshasa) (200 tonnes)
        - Brazil (150 tonnes)
        - China (60 tonnes)

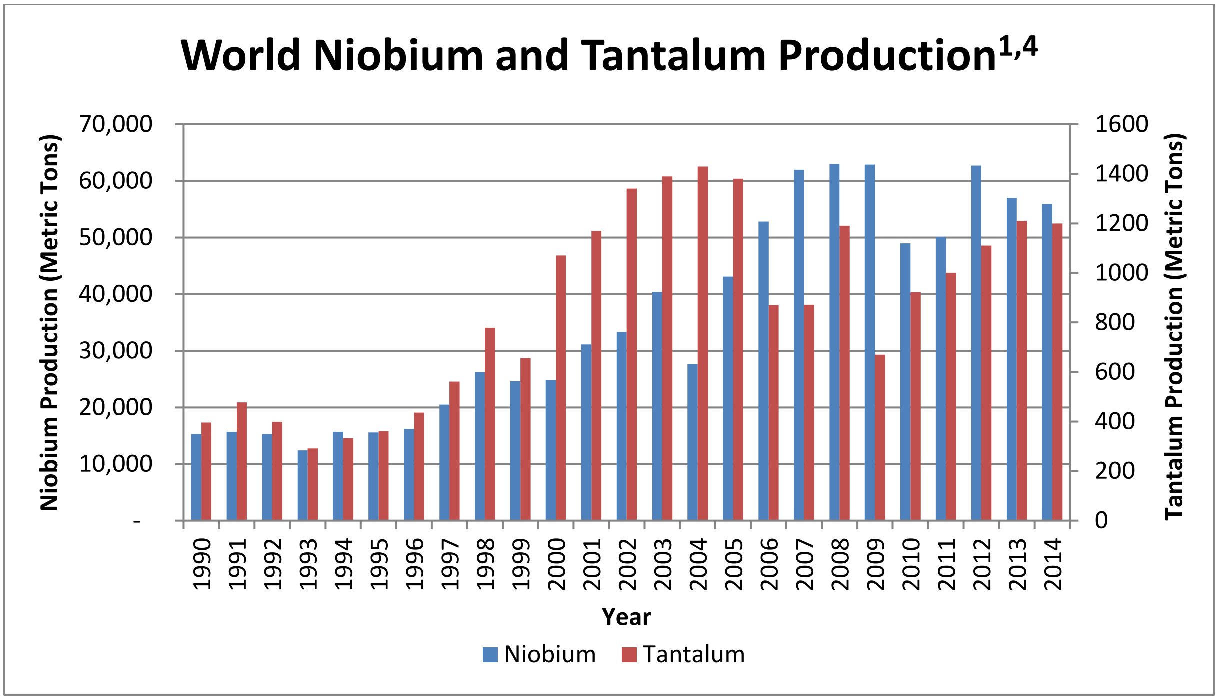


Figure 5-33. Annual world production of niobium and tantalum from 1990 to 2014.

- Niobium is produced in ~9 countries around the world; deposits are unequally distributed and concentration is generally low. Tantalum is produced in ~9 countries; deposits are unequally distributed and concentration is generally low.
- Niobium is recovered from recycled niobium-bearing steels and superalloys, but is not recycled specifically; as much as 20 percent of apparent consumption may be from recycled sources. Tantalum is recycled from the manufacturing of tantalum-containing electronics, carbide, and superalloy scrap.
- In the U.S. in 2015: 80 percent of niobium was used in steel alloys, and 20 percent was used in superalloys; major end uses for tantalum were tantalum capacitors (includes automotive electronics, mobile phones, and PCs), tantalum oxide glass lenses, and tantalum carbide cutting tools.

- Reasons for demand fluctuations[1,2]
    - Economic uncertainty affects demand for niobium- and tantalum-containing products.
    - Price of niobium and tantalum (Figures 5-34; 5-35)
    - Government spending budgets for aerospace/rocketry
    - Health of the mining and petroleum sectors, which use tantalum for cutting tools and pipeline coatings
    - Amount of niobium and tantalum from recycled sources

- o Use of substitutes
  - ▪ Niobium substitutes like ceramics, molybdenum, and tungsten in temperature applications may affect some demand, but many applications, have no equal substitute.
  - ▪ Tantalum substitutes may affect some demand, but they are generally less effective.

- Reasons for market fluctuations[1,2]
  - o Economic uncertainty affects the growth or decline of the industries that use niobium and tantalum.
  - o Passage of rules by SEC requiring publicly traded companies to ensure their tantalum is not sourced as a conflict mineral from Congo or surrounding areas (conflict minerals are those that may be funding armed groups)
  - o Tantalum is often associated with tin, and supply is reliant on the tin market.
  - o Niobium and tantalum experienced a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. .There was an 18 percent decrease in exploration budgets for niobium and tantalum from 2014 to 2015 (Wilburn and Karl, 2015).

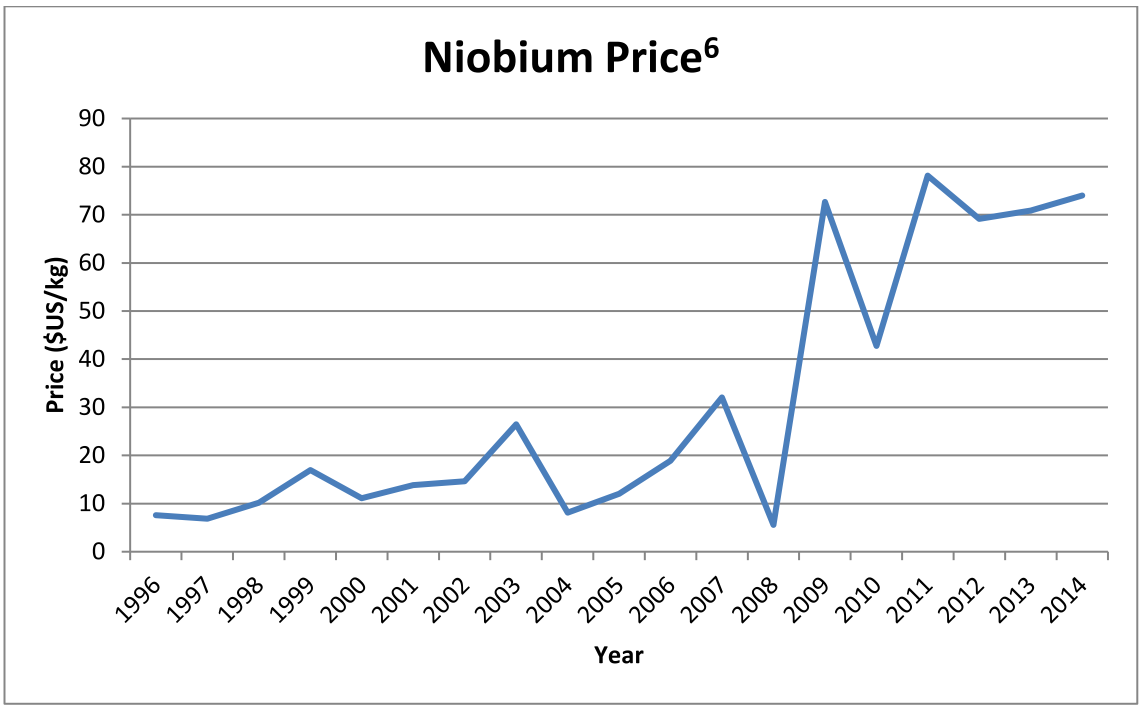


Figure 5-34. Annual average price of niobium from 1996 to 2014. Note: There is no official price for niobium, as it is not traded on any metal exchange; price is generally determined by negotiation between buyer and seller. These data are from the U.S. International Trade Commission: U.S. Imports for consumption, niobium ores and concentrates, customs value/first unit of quantity for all countries in actual dollars, annual data.

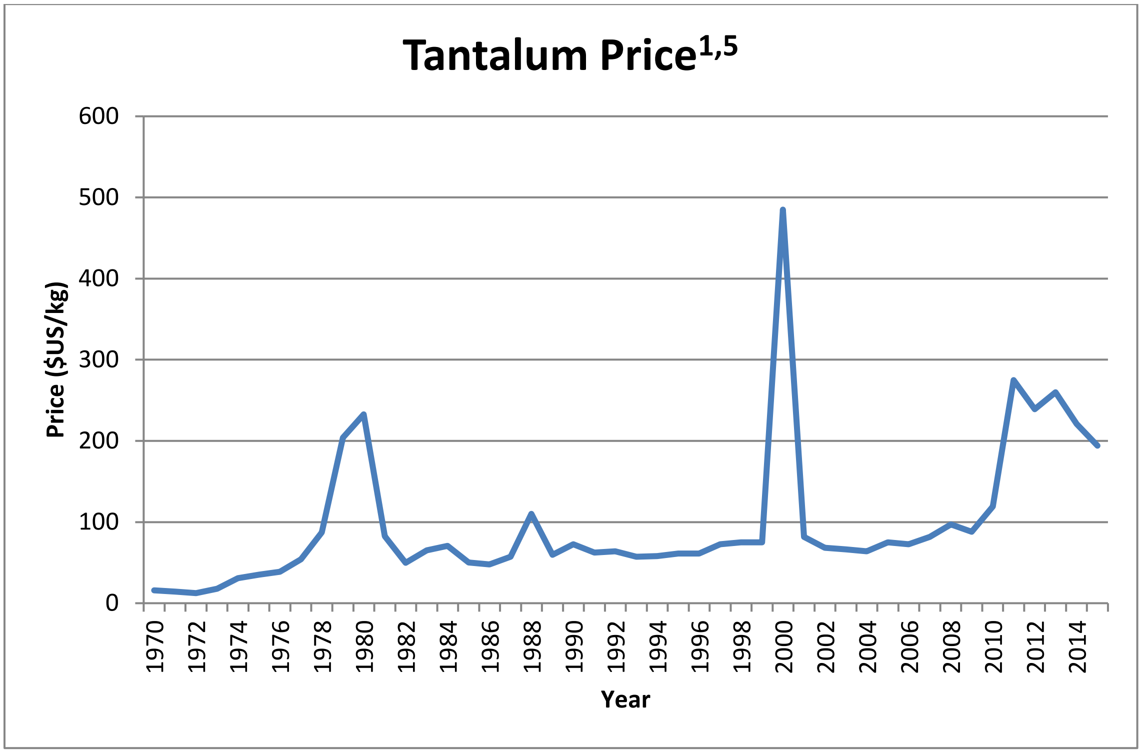


Figure 5-35. Annual average price of tantalum from 1970 to 2015.

- Current and projected trends for demand and why[1,2]
    - Demand for tantalum-containing electronic devices is expected to continue to rise as the developing world adopts advanced smartphones and other technologies.
    - In certain applications, there are no appropriate niobium or tantalum substitutes, meaning the demand in those cases will remain steady or increase.
    - Global demand for niobium-containing steel alloys is expected to increase.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for niobium or tantalum, high occurrence potential areas in the RGFO region could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]U.S. ITC
[7]Schulz and Papp, 2014

5.5.5 Tellurium

- The "usable" characteristics of the material[1,3]
    - Semiconductor properties
    - Non-reactive with water

- What technology/industrial practice it is used for currently[1,3]
    - Thermoelectric applications
    - Machine steel alloys
    - Cadmium-telluride (CdTe) solar cells
    - Semiconductors
    - Ceramics
    - Catalysts

- What technology/industrial practice it might be used for in the future[3,8]
    - Continued advancement of high-efficiency CdTe solar cells
    - Neutrino detectors

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves of tellurium were estimated to be 25,000 tonnes in 2015.
    - In 2015, the U.S. had reserves of 3,500 tonnes of tellurium.
    - As of November 2016, there is one primary producer of tellurium in the U.S.:
        - An ASARCO refinery in Texas produces tellurium as a byproduct of copper electrolytic refining of ore from several copper mines.
    - There is no government stockpile for tellurium.
    - There are no primary producing tellurium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
    - Annual world tellurium production is depicted Figure 5-36. The four largest refined tellurium producing nations in 2015 were (U.S. not included; data withheld):
        - Sweden (40 tonnes)
        - Russia (35 tonnes)
        - Japan (35 tonnes)
        - Canada (10 tonnes)

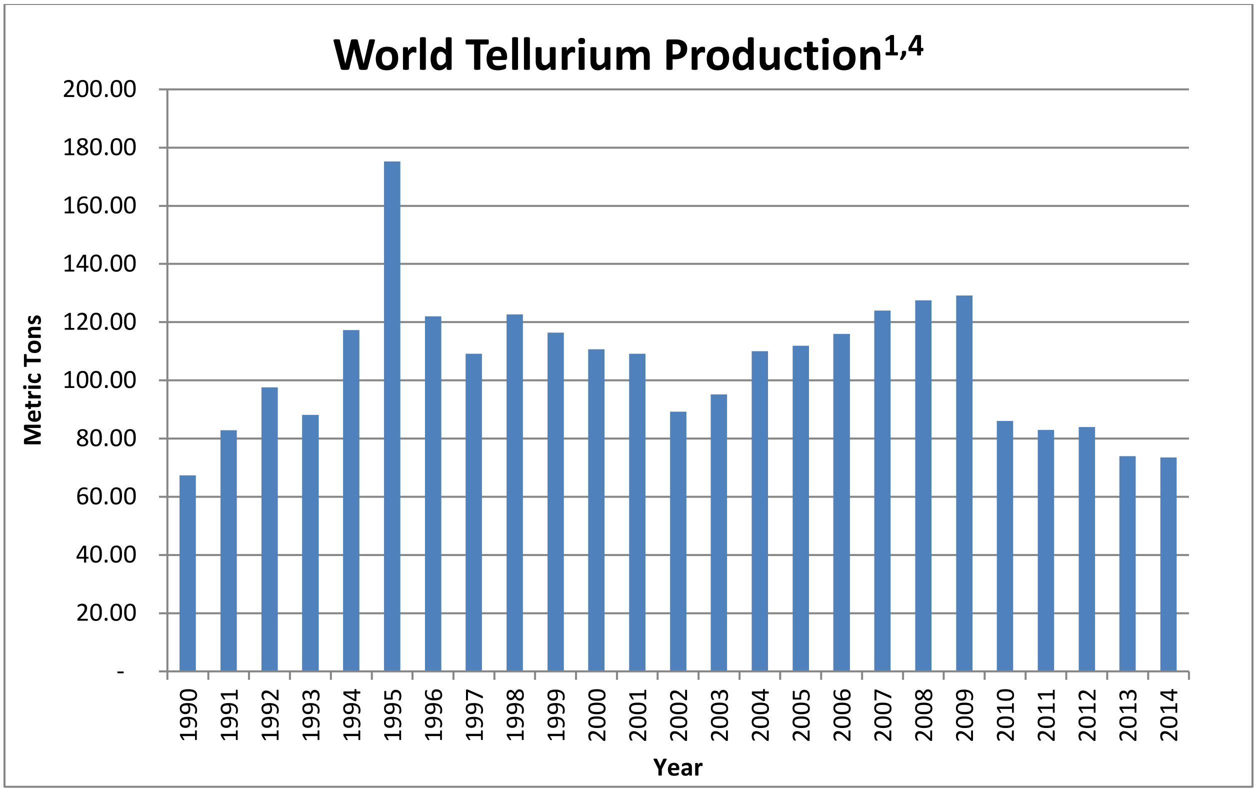


Figure 5-36. Annual world tellurium production from 1990 to 2014.

- Tellurium is produced and/or refined in ~15 countries around the world; tellurium is generally recovered as a byproduct of copper processing, and therefore is distributed with large copper deposits. It may also be recovered from processing volcanogenic massive sulfide deposits. There are two primary tellurium deposits: one in China and one in Sweden.
- A limited amount of tellurium was recycled from selenium-tellurium photoreceptors and CdTe solar cells in 2015; most solar cells were still in operation and had not reached the end of their life, so recycling of them would be expected to increase as their use increases and they wear out.
- Around the world in 2015: 40 percent of tellurium went to solar applications, 30 percent went to thermoelectric power generation, 15 percent went to metallurgy, 5 percent went to rubber applications and vulcanization, and 10 percent was for other uses.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty affects demand for tellurium-containing products.
  - Price of tellurium (Figure 5-37)
  - Decreasing demand for thermoelectrics in China

- Decreasing cost and increasing efficiency of silicon-based solar cells means less demand for more expensive CdTe types.
- Amount of tellurium from recycled sources
- Use of substitutes

- Reasons for market fluctuations[1,2,6,7,8]
  - Economic uncertainty affects the growth or decline of the industries that use tellurium.
  - The Fanya Metal Exchange Co. Ltd. in China had been trading 14 minor metals, including tellurium, at prices elevated compared to global markets. In mid-2015, all sales of its products were halted pending investigation into corruption and investor fraud; the fate of the company's stockpiles is uncertain and could have an unknown effect on the minor metals market.
  - Tellurium is recovered as a byproduct of electrolytic copper production, and the amount produced depends on copper production rates as well as varying concentrations in processed material.
    - Electrolytic refining works best on high-grade copper deposits; as fewer high-grade deposits are processed, there may be a shift in the mode of production of copper (to increase the recovery of copper) from electrolytic refining to solvent extraction (electrowinning (SX-EW)), which doesn't produce tellurium as a byproduct.

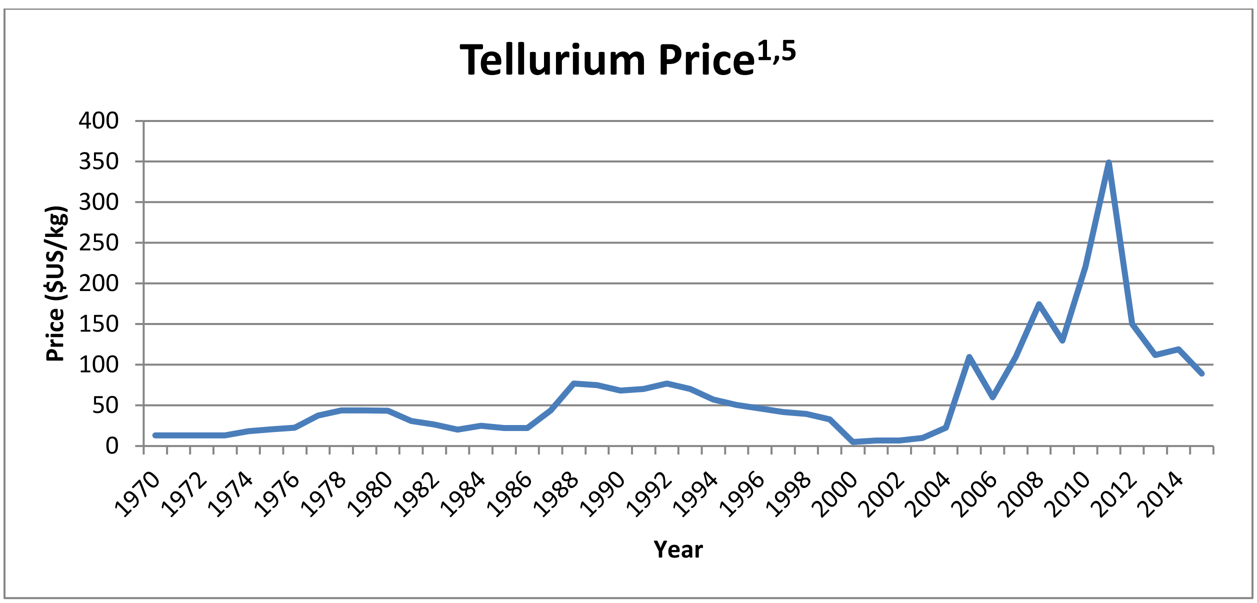


Figure 5-37. Annual average price of tellurium from 1970 to 2015.

- Current and projected trends for demand and why[1,2,8]
    - Demand for CdTe solar cells may rise as prices drop and efficiencies increase.
    - In certain applications, there are no appropriate tellurium substitutes, meaning the demand in those cases will remain steady or increase.
- Any influence of these trends that may directly affect the RGFO region[2,8,9]
    - The Cresson mine in Cripple Creek is a primary gold mine, with gold contained in telluride minerals (a mix of gold/silver and tellurium). At current market prices and with the bulk extraction available as a byproduct to copper mining, these minerals are not economic for tellurium extraction.
        - If demand for tellurium increases or the number of high-grade (electrolytically recoverable) copper deposits decreases, it may become economic to recover tellurium from telluride minerals such as those in Cripple Creek.
        - The Gold Hill and Jamestown districts in Boulder County are noted for their tellurium occurrences, which could become economically viable at higher prices.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Els, 2015
[7]Stanway, 2015
[8]Goldfarb, 2015
[9]USGS, 2016

5.5.6 Titanium

- The "usable" characteristics of the material[1,3]
    - Corrosion resistance
    - High strength-to-weight ratio
    - High melting point
    - High refractive index
- What technology/industrial practice it is used for currently[1,3,6]
    - Aerospace applications
    - Pigments
    - Armor
    - Chemical processing

    - Marine hardware applications
    - Medical implants
    - Power generation
    - Sporting goods
    - Sunscreen
- What technology/industrial practice it might be used for in the future[1,6]
    - Commercial aerospace (private space companies)
    - High efficiency aircraft
    - Titanium is abundant on the moon, and could be used as an in-place building material for future lunar development.

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
    - Worldwide, in the ground reserves of ilmenite and rutile (the minerals that provide most of the commercial feedstock) were estimated to be 790 million tonnes in 2015.
    - In 2015, the U.S. had reserves of 2 million tonnes of ilmenite and 22 million tonnes of rutile.
    - Iluka, a producer of heavy mineral concentrates on the eastern seaboard of the U.S., had proven and probable reserves of 850,000 tonnes of in situ heavy minerals grading 59 percent ilmenite (Iluka, 2015).
    - The estimated largest resource of titanium in the United States is Iron Hill near Gunnison, Colorado. It is estimated to have 350 million tonnes of material grading an average 11.5 percent titanium oxide (Van Gosen, 2009).
    - There is no government stockpile for titanium.
    - There are no primary producing titanium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
    - The four largest ilmenite producing nations in 2015 were:
        - China (900,000 tonnes)
        - Australia (720,000 tonnes)
        - Vietnam (540,000 tonnes)
        - South Africa (480,000 tonnes)
    - The four largest rutile producing nations in 2015 were (in descending order) (U.S. not included; data included w/ilmenite):
        - Australia (144,000 tonnes)
        - Sierra Leon (110,000 tonnes)
        - Kenya (65,000 tonnes)
        - Ukraine (63,000 tonnes)
    - World titanium sponge production is depicted in Figure 5-38. The four largest titanium sponge (the first refined titanium product) producing nations in 2015 were (in descending order) (U.S. not included; data withheld):

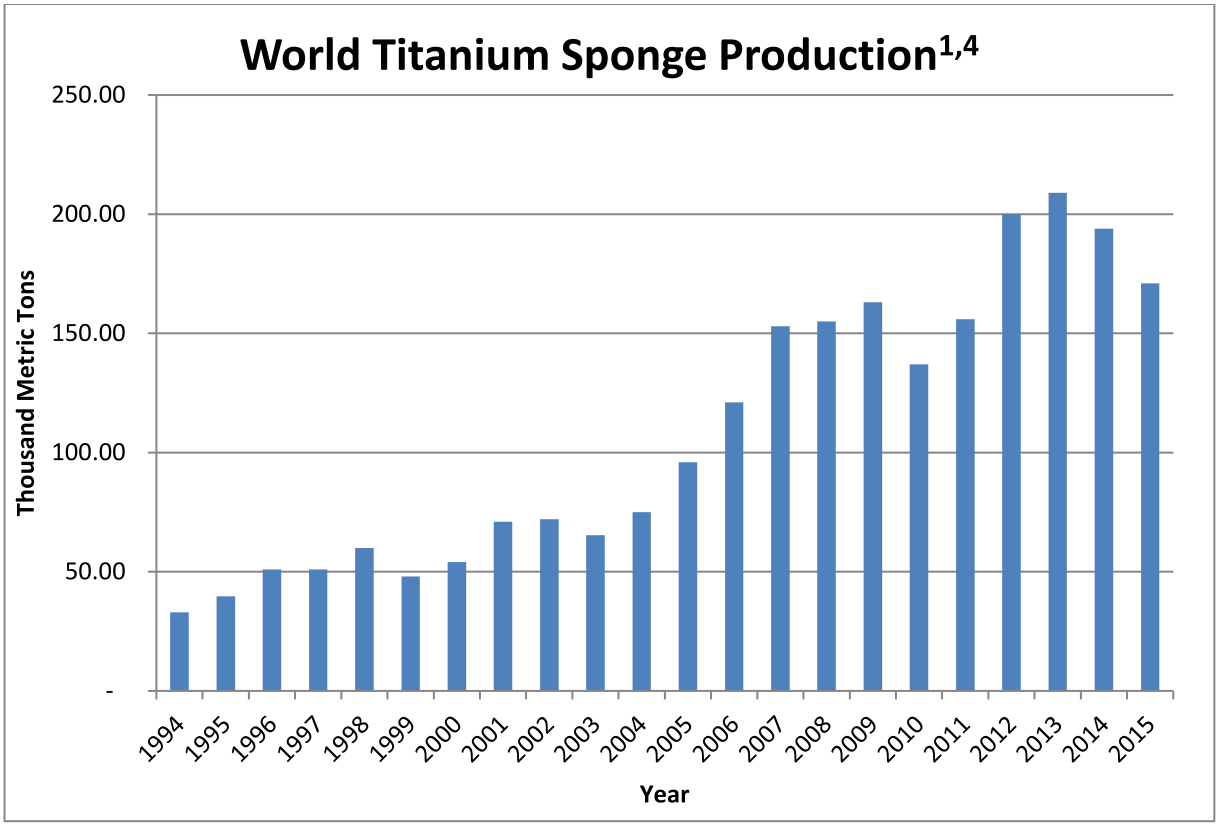


Figure 5-38. Annual world production of titanium sponge from 1994 to 2015.

  - China (80,000 tonnes)
  - Russia (42,000 tonnes)
  - Japan (30,000 tonnes)
  - Kazakhstan and Ukraine (9,000 tonnes each)
- The various titanium minerals and/or concentrates are produced in ~20 countries around the world; ilmenite is the most important mineral, with heavy mineral deposits producing more than magmatic ilmenite deposits. Deposits are unequally distributed and vary in titanium percentage and ease of use/recovery.
- In 2015, there were 4 producing titanium mines in the U.S., one in Florida, one in Georgia, and two in Virginia.
- About 51,000 tons of titanium scrap were recycled in the U.S. in 2015 mainly for use in the steel industry.
- In the U.S. in 2015, 95 percent of titanium mineral concentrates were consumed by pigment producers; of the remaining 5 percent, 77 percent went to the aerospace industry and the remainder was used for armor, chemical processing, marine hardware applications, medical implants, and other applications.

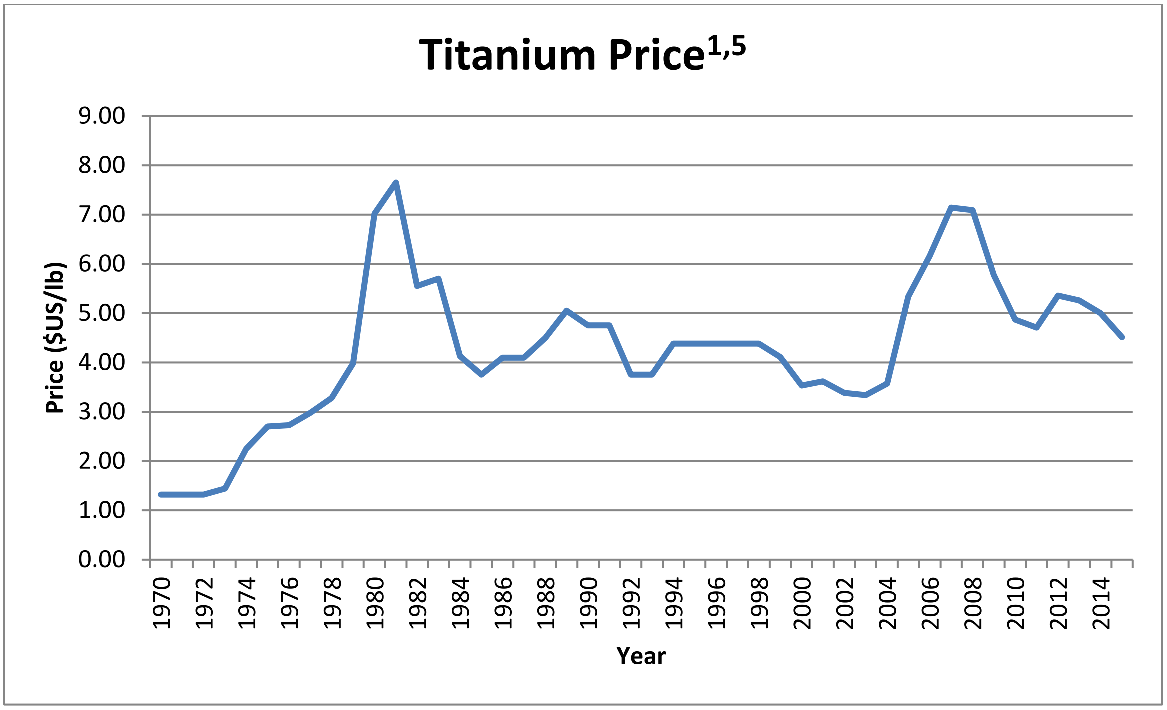


Figure 5-39. Annual average price of titanium from 1970 to 2015.

- Reasons for demand fluctuations[1,2,6]
    - Economic uncertainty affects demand for titanium-containing products.
    - Price of titanium (Figure 5-39)
    - Increasing demand for aircraft- and space-grade titanium and titanium alloys
    - Amount of titanium from recycled sources
    - Use of substitutes

- Reasons for market fluctuations[1,2]
    - Economic uncertainty affects the growth or decline of the industries that use titanium.
    - Titanium dioxide production was 32 percent greater than consumption in 2014, which has led to production plant closures or expansion curtailments; this could affect availability if demand rises in the future.
    - The two mines in Virginia were idled at the end of 2015, leading to reduced U.S. production.
    - A mineral sands wet concentration plant was under construction in New Jersey in 2016, set to reprocess tailings from former sand operation and produce an ilmenite concentrate.

- Current and projected trends for demand and why[1,2,6]
  - Demand for aerospace titanium airframes is expected to increase as older model planes retire, and as commercial space operations increase.
  - In certain applications, there is no appropriate titanium substitute, meaning the demand in those cases will remain steady or increase.

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for titanium, high titanium occurrence potential areas in the RGFO region could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013
[6]Woodruff and Bedinger, 2013

5.6 Uranium

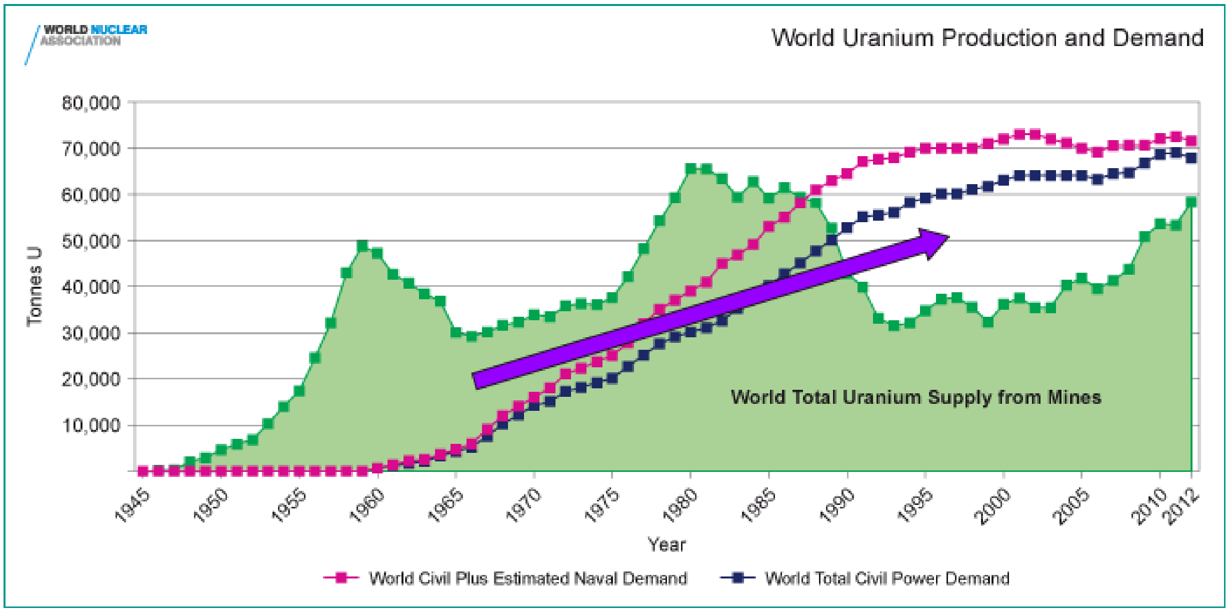
- The "usable" characteristics of the material[1,2]
  - Radioactive
  - Relatively abundant
  - Chemically active
  - Dense

- What technology/industrial practice it is used for currently[1,2]
  - Nuclear fuels
  - Creating actinides
  - X-ray source
  - Pigments
  - Military applications

- What technology/industrial practice it might be used for in the future[1,2]
  - High efficiency power plants
  - Computer hard drives (Henry, 2011)
  - Medical applications

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground Reasonably Assured Resources plus inferred Resources of uranium were estimated to be 5.9 million tonnes in 2013 (using US$ 130/kg U).
    - In 2015, the U.S. had reserves of ~30,000 tonnes uranium (using US$0-30/lb.).
    - Energy Fuels, operator of the only operating uranium mill in the U.S., had inferred resources of ~725 tonnes of uranium at its Canyon mine (slated to start production as early as 2017), along with more resources at several other conventional and in situ projects (Energy Fuels, 2016).
    - The Department of Energy has several sub-organizations that oversee the U.S.'s excess uranium stockpile, which is sourced from weapons disarmament and other sources.
        - Worldwide in 2014, it is estimated that highly enriched uranium from weapons stockpiles displaced ~8850 tonnes of uranium production from mines.
    - There are no primary producing uranium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2,3]
    - World uranium supply and demand is depicted in Figure 5-40.
    - The four largest uranium producing nations in 2014 were:
        - Kazakhstan (23,127 tonnes)
        - Canada (9,134 tonnes)
        - Australia (5,001 tonnes)
        - Niger (4,057 tonnes)
    - Uranium is produced in ~20 countries around the world; uranium occurs in a variety of deposits that occur globally in different geologic settings, although the grade of different deposit types can vary substantially.
    - In 2015, 1 underground mine and 7 in situ leach operations produced uranium in the U.S.
    - The majority of uranium worldwide goes towards nuclear fuel

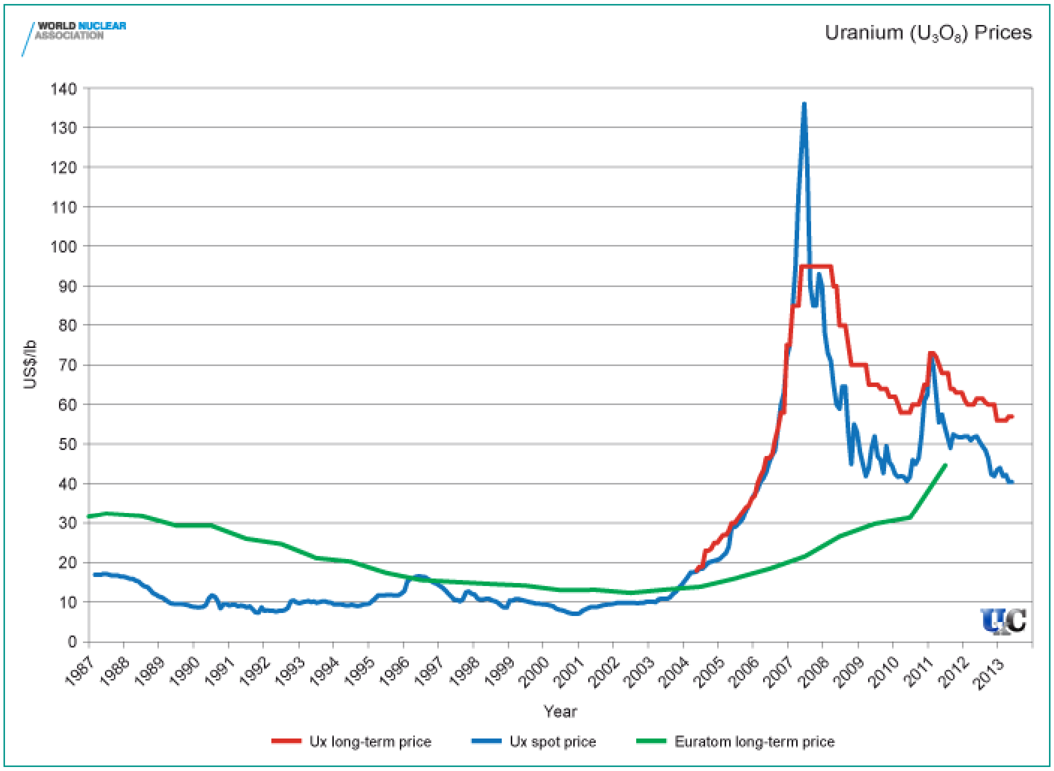


Source: World Nuclear Association

Figure 5-40. Annual world uranium production and demand from 1945 to 2012.

- Reasons for demand fluctuations[2,3]
  - Growing demand for non-fossil fuel options can increase demand, but the increased use of other renewable energies such as solar could decrease demand.
  - Increased efficiency of nuclear reactors means they require less fuel.
  - Accidents at nuclear reactors can cause fear of using nuclear energy sources and decrease demand.
  - Price of uranium (Figure 5-41)
  - Amount of uranium that can be obtained from secondary sources (ex-military and others)

- Reasons for market fluctuations[2,3]
  - Low uranium prices have driven almost all U.S. underground mines to close.
  - As secondary sources are depleted, there is a gap between demand and mine production output, which could increase the number of mines or in situ leach projects needed.



Graph courtesy of UxC

Figure 5-41. Annual average price of uranium from 1987 to 2013. Note that the Euratom long-term price is the average price of uranium delivered into the EU that year under long-term contracts. It is not the price at which long-term contracts are being written in that year.

- Utilities are vertically integrating and seeking equity in uranium mines, thereby partially bypassing the free market.
- Political instability in major uranium-producing nations could have an effect on worldwide supply.
- Drop in uranium price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was a 34 percent decrease in exploration budgets for manganese from 2014 to 2015.

- Current and projected trends for demand and why[2,3]
  - Demand for clean energy is likely to continue to increase, and at least some part of that will be provided by nuclear energy.
  - As nuclear weapons arsenals are reduced, more uranium will need to be from primary sources.

- Any influence of these trends that may directly affect the RGFO region
  - If there is sufficient demand for uranium, high uranium occurrence potential areas in the RGFO region could become economically viable.

Summarized from:
[1]MEC, 2016
[2]U.S. EIA, 2014a
[3]WNA, 2016

5.7 Thorium

- The "usable" characteristics of the material[1,3]
  - High melting temperature
  - Relatively abundant
  - Naturally radioactive

- What technology/industrial practice it is used for currently[1,3]
  - Incandescent gas mantles
  - Tungsten filament coatings
  - High temperature lab equipment
  - Alloys, especially with magnesium
  - Optical lenses
  - Catalysts
  - Ceramics

- What technology/industrial practice it might be used for in the future[2]
  - New reactor technologies that would allow thorium to be used as fuel
- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Worldwide, in the ground reserves were not available for thorium; it is recovered as a byproduct of rare earth element (monazite) ores, and because monazite would not be recovered for its thorium without the demand for rare earths, an estimate of reserves is not practicable.
  - There was no thorium produced in the U.S. in 2015; monazite is sometimes recovered as a byproduct of heavy minerals sands (like those processed for titanium) but was not produced as a saleable product.
  - There is no government stockpile for thorium.
  - There are no primary producing thorium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - World monazite production is depicted in Figure 5-42. The three largest monazite concentrate producing nations in 2014 were:
    - Thailand (2,000 tonnes)

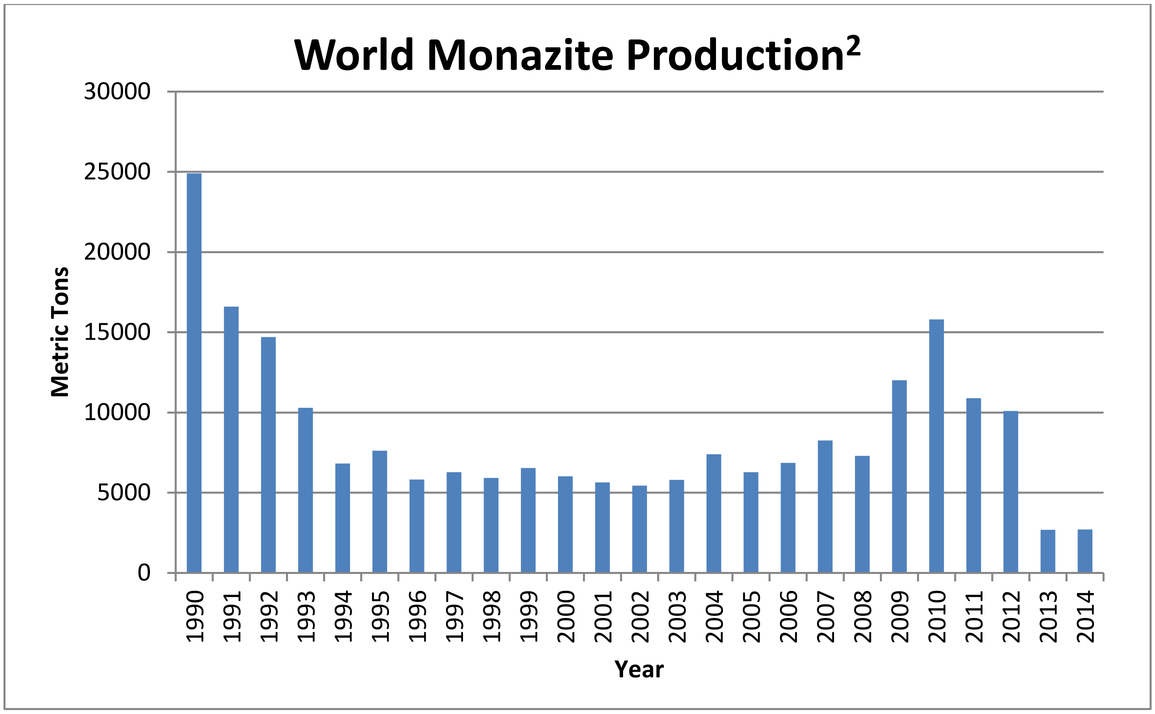


Figure 5-42. Annual world monazite production from 1990 to 2014. Data from USGS Mineral Yearbooks 1990-2014.

        - Malaysia (500 tonnes)
        - Vietnam (200 tonnes)
    - Monazite, the main source of thorium, is produced in ~5 countries around the world; deposits are unequally distributed
    - In 2015, there were no primary thorium mines in the U.S.
    - There was no reported thorium recycling in 2015

- Reasons for demand fluctuations[1,2]
    - Thorium is used in research, and demand may fluctuate with research budgets.
    - Price of thorium
    - Use of substitutes that are not naturally radioactive has decreased demand.
    - No consistent long-term price data are available for thorium.

- Reasons for market fluctuations[1,2]
    - Thorium is produced as a byproduct of rare earths and depends on rare earth supply and price.
    - China produces an unknown amount of thorium as a byproduct of rare earth processing.
  - As more countries explore for rare earths, more thorium deposits may be found.

- Current and projected trends for demand and why[1,2]
    - Non-energy uses for thorium will likely remain limited due to its natural radioactivity.
    - If thorium-fueled reactors become a viable technology, demand for thorium could increase dramatically.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for thorium, high thorium occurrence potential areas in the RGFO region (especially those that could also be mined for REEs) could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016

5.8 Vanadium

- The "usable" characteristics of the material[1,3]
    - Corrosion resistance
    - Gives strength and hardness in alloys

- What technology/industrial practice it is used for currently[1,3]
    - High strength alloys like automobile crankshafts, pistons, and axels
    - High-speed airframes and jet engines
    - Ceramics
    - Glass manufacturing
    - Chemical catalyst
- What technology/industrial practice it might be used for in the future[1,3]
    - Aerospace
    - Advanced building construction
    - Vanadium redox flow battery (VRB) energy storage systems

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide, in the ground reserves of vanadium were estimated to be 15 million tonnes in 2015.
    - In 2015, the U.S. had reserves of 45,000 tonnes of uranium.
    - Vanadium can be produced as a byproduct at the White Mesa uranium mill (Energy Fuels), though no production was reported in 2014 or 2015.

  - American Vanadium Corp.'s Gibellini Project in Nevada held measured and indicated resources of 59,500 tonnes of vanadium pentoxide in 2011; as of November 2016 the project is still not in production (American Vanadium, 2016).
  - There is no government stockpile for vanadium.
  - There are no primary producing vanadium mines in the RGFO region.

- Local, regional and worldwide markets and why[1,2]
  - World vanadium production is depicted in Figure 5-43. The four largest vanadium producing nations in 2015 were:
    - China (42,000 tonnes)
    - South Africa (19,000 tonnes)
    - Russia (15,000tonnes)
    - Brazil (2,800 tonnes)
  - Vanadium is produced in ~5 countries around the world; deposits are unequally distributed.
  - In 2015, there were no primary vanadium mines in the U.S.
  - About 40 percent of total vanadium catalysts were from recycled sources in the U.S. in 2015.
  - In the U.S. in 2015, 93 percent of vanadium was consumed in making alloys; the dominant non-metallurgical use was for catalysts.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty affects demand for vanadium-containing products.
  - Price of vanadium (Figure 5-44)
  - Increasing demand for aircraft- and space-grade vanadium alloys
  - Amount of vanadium from recycled sources
  - Use of substitutes

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects the growth or decline of the industries that use vanadium, especially the steel industry.
  - In 2015, a vanadium producer in South Africa filed for bankruptcy; this will affect primary and feedstock supplies to vanadium-containing merchandise producers.
  - Low prices and permitting delays have slowed the opening of the Nevada Gibellini project.
  - On May 1, 2015, China removed export duties on vanadium pentoxide, hoping to promote exports and reduce domestic oversupply.

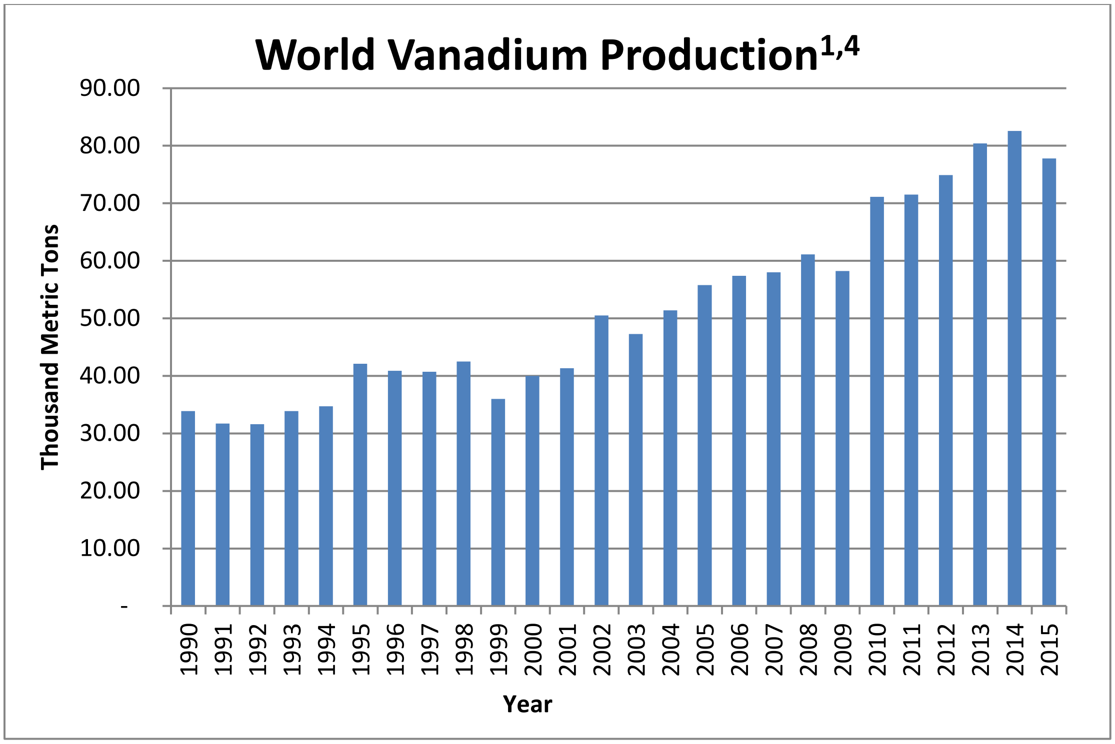


Figure 5-43. Annual world vanadium production from 1990 to 2015.

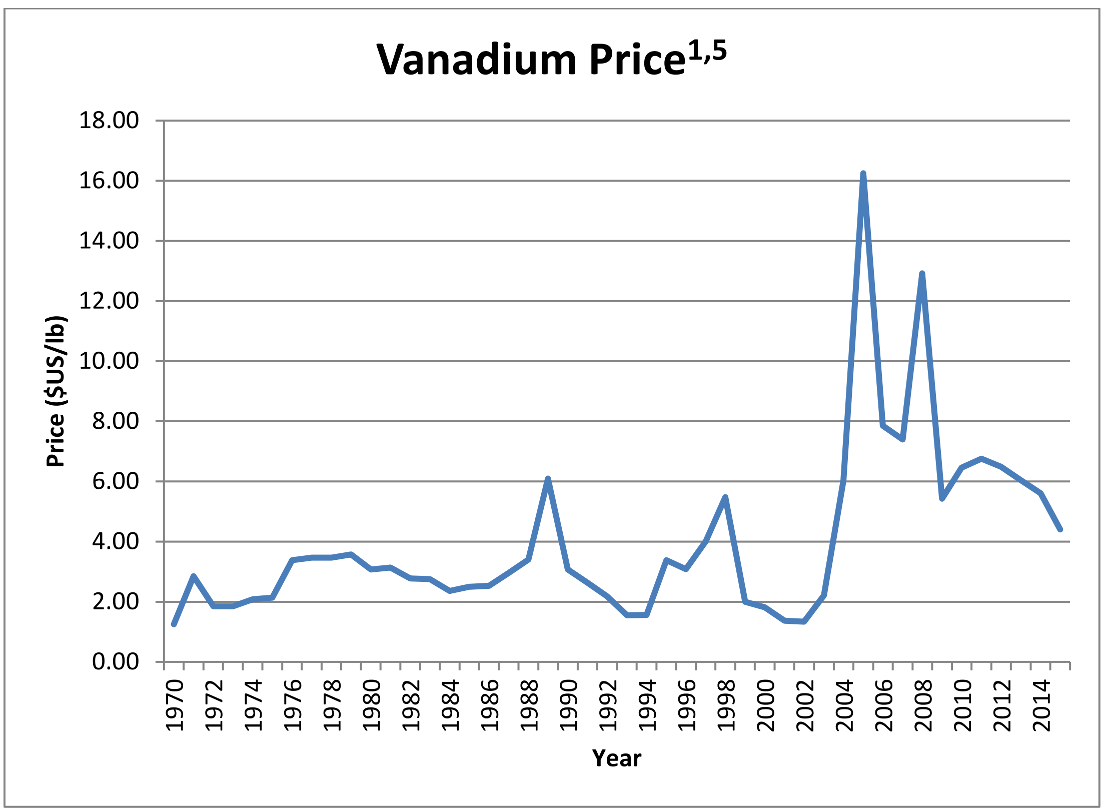


Figure 5-44. Annual average price of vanadium from 1970 to 2015.

- Current and projected trends for demand and why[1,2]
    - Demand for aerospace airframes is expected to increase as older model planes retire, and as commercial space operations increase.
    - In certain applications, there is no appropriate vanadium substitute, meaning the demand in those cases will remain steady or increase.
    - VRB technology could become a large market as power grids look for ways to store renewable energy, if the efficiency increases and prices decrease.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for vanadium, high vanadium occurrence potential areas in the RGFO region (especially those that could also be mined for uranium) could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2015
[3]MEC, 2016
[4]Barry et al., 2013
[5]USGS, 2013

5.9 Nonmetallic Minerals / Industrial Minerals

5.9.1 Fluorspar

- The "usable" characteristics of the material[1,3]
    - Contains easily accessible fluorine

- What technology/industrial practice it is used for currently[1,3]
    - Used in production of hydrofluoric acid, which is used in
        - Metal pickling
        - Petroleum alkylation
        - Uranium processing
        - Aerosols
        - Insulating foams
        - Plastics
        - Refrigerants
        - Aerospace applications
        - Nonstick coatings
    - Flux for steelmaking
    - Used in production of aluminum fluoride

- What technology/industrial practice it might be used for in the future[1,3]
    - Polytetrafluoroethylene (PTFE) used in spacecraft wiring and shielding
    - Refrigerants and propellants that are environmentally safe and meet ozone and greenhouse gas standards

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
    - Worldwide, in the ground reserves of fluorspar were estimated to be 250 million tonnes in 2015.
    - In 2015, the U.S. had reserves of 4 million tonnes of fluorspar.
    - There is no government stockpile for fluorspar; there were 313,000 tonnes of fluorspar in consumer and distributor stocks at the end of 2013.

- Local, regional and worldwide markets and why[1,2]
    - Annual world fluorspar production is depicted in Figure 5-45. The four largest fluorspar producing nations in 2015 were:
        - China (3.8 million tonnes)
        - Mexico (1.1 million tonnes)
        - Mongolia (375,000 tonnes)
        - South Africa (200,000 tonnes)
    - Fluorspar is produced in ~25 countries around the world; deposits are unequally distributed and vary in quality and concentration.
    - As of 2015, there were no reported primary fluorspar mines in the U.S. Some fluorspar was sold from stockpiles produced as a byproduct of limestone quarrying.
    - There were no primary producing fluorspar mines in the RGFO area in 2016.
    - Hydrofluoric acid was recycled by primary aluminum producers, and fluorides were recycled from smelting operations; synthetic fluorspar is produced as a byproduct of petroleum alkylation, stainless steel pickling, and uranium processing; fluorosilicic acid is produced as a byproduct of phosphoric acid production; 70,100 tonnes were produced in 2014.
        - In the U.S. in 2014, acid grade fluorspar was mostly used to produce hydrofluoric acid, which was mostly used to produce a wide range of fluorocarbon chemicals.

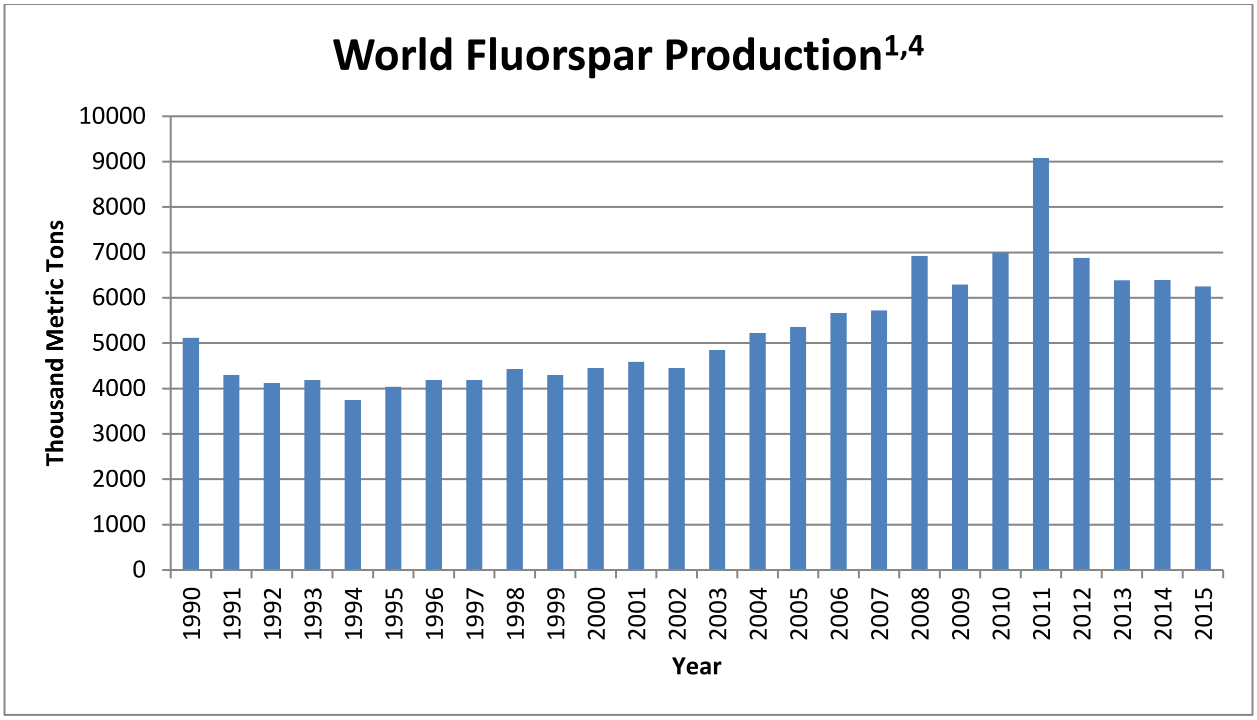


Figure 5-45. Annual world fluorspar production from 1990 to 2015.

- Reasons for demand fluctuations[1,2]
  - Economic uncertainty affects demand for fluorine-containing products.
  - Price of fluorspar (Figure 5-46)
  - A weak market and oversupply that began in 2011 continued in 2015
  - Amount of fluorspar from recycled, reused, or synthetic sources
  - Use of non-fluorine substitutes for refrigerants and metallurgical fluxes

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects the growth or decline of the industries that use fluorine.
  - Mines in India, Namibia, Russia, and South Africa were put on care-and-maintenance due to low demand and/or prices.
  - A polymetallic project in Vietnam that is producing fluorspar ramped up production in 2015.
  - U.S. Government stocks of fluorspar were maintained until 2006, but the reliance has been on imports since that time.

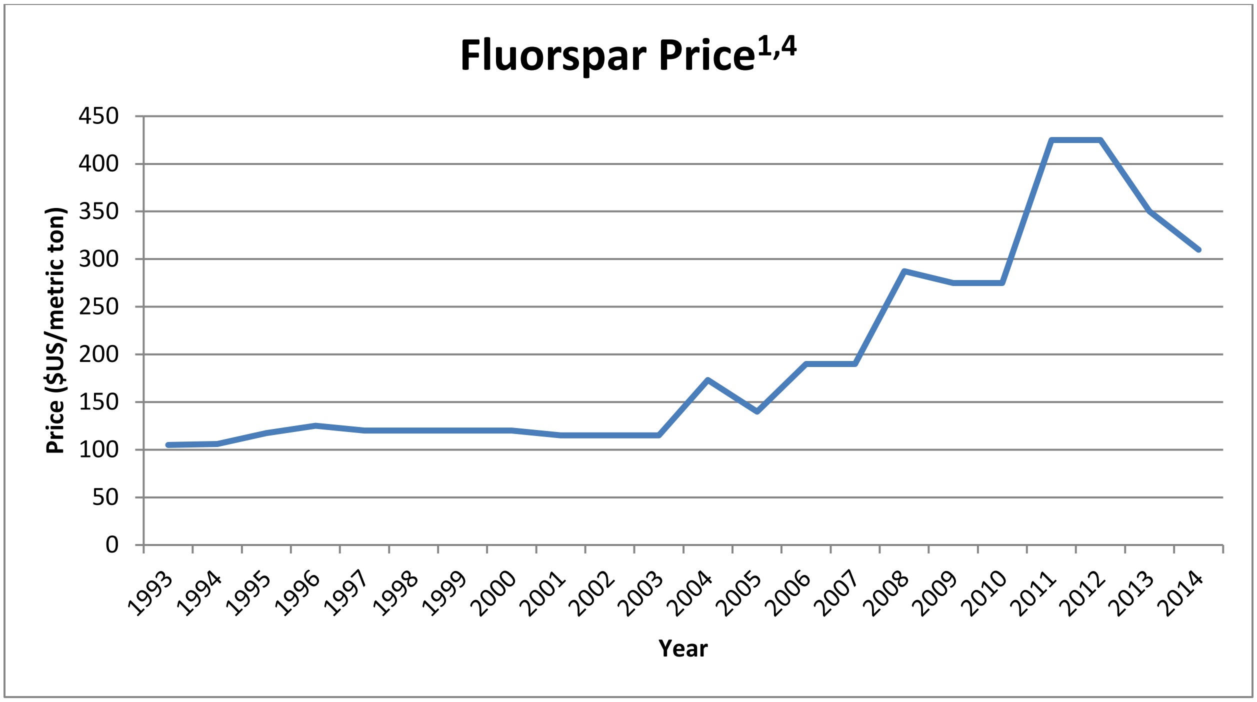


Figure 5-46. Annual average price of fluorspar from 1993 to 2015.

- Current and projected trends for demand and why[1,2]
    - Demand for certain fluorocarbons as nonstick coatings in cookware, as well as more high tech applications like spacecraft wiring insulation, is expected to increase.
    - Increased regulation of fluorinated gases for use as refrigerants, aerosols, etc. has led to a ban on ozone-harming chlorofluorocarbons, but newer hydrofluorocarbons are under scrutiny as greenhouse gases as well. .Newer replacement substances often contain more fluorine than previous generations, which could increase demand; however, the regulations have also introduced many non-fluorinated options, decreasing demand.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for fluorspar, high occurrence potential areas in the RGFO area could become economically viable.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014

5.9.2 Diamond and Gemstones

- The "usable" characteristics of the material[1,2]
  - Rarity
  - Beauty
  - Durability
  - Can be faceted

- What technology/industrial practice it is used for currently[1,3]
  - Fine jewelry
  - Gem carvings
  - Gem and mineral collections

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Worldwide, in the ground reserves of diamond were estimated to be “substantial” by the USGS in 2015; no reserve data were available for other gemstones.
  - As of the end of 2015, Rio Tinto reported global recoverable reserves of 114.8 million carats (Rio Tinto, 2015).
  - The only active diamond operation in the United States, Crater of Diamonds State Park in Arkansas, had an estimated 78.5 million tonnes of diamond-bearing rock (although this deposit is not open to commercial mining).
  - The State Line Diamond district on the Wyoming-Colorado border is a past producer of diamonds. The Kelsey Lake area has an estimated 16.9 million tonnes of diamond-bearing rock; the Sloan 1 kimberlite to the south has an estimated resource of 15.3 million tonnes of ore averaging 6.1 carats/100 tonnes and the Sloan 2 kimberlite has an estimated resource of 8.4 million tonnes averaging 17.1 carats/100 tonnes (Hausel, 1998).
  - There is no government stockpile for gemstones.

- Local, regional and worldwide markets and why[1,2]
  - Annual world production of diamonds is depicted in Figure 5-47. The four largest diamond-value producing nations in 2015 were:
    - Russia ($21.5 billion)
    - Botswana ($17.3 billion)
    - Canada ($12 billion)
    - Angola ($7.1 billion)

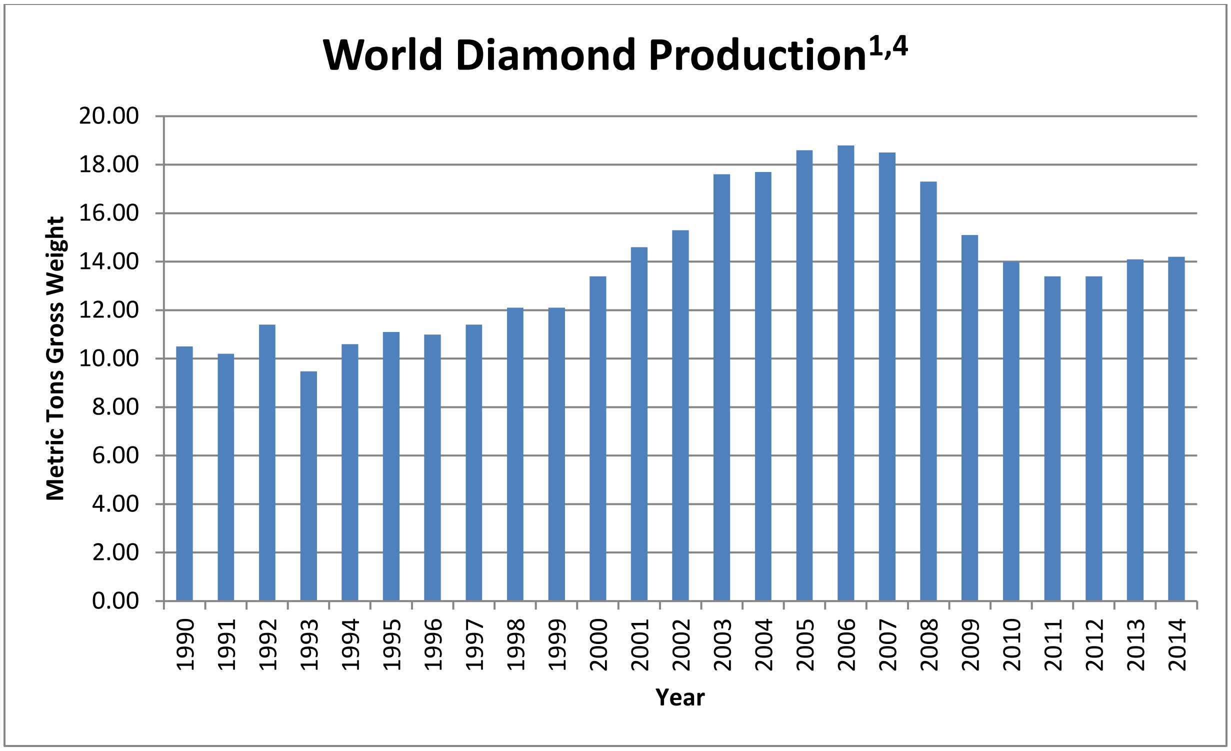


Figure 5-47. Annual world production of diamonds from 1990 to 2014.

- Diamonds are produced in ~25 countries around the world; deposits are unequally distributed (occurring mainly in kimberlites) and vary in quality and concentration.
- As of 2015, there were no reported primary commercial diamond mines in the U.S. Visitors to the Crater of Diamonds State Park in Arkansas can pay a fee to search for diamonds.
- In 2013, the value of non-diamond, natural gemstones produced in the U.S. was $9.57 million, including:
  - Turquoise—$1.31 million
  - Gem Feldspar—$698,000
  - Shell—$695,000
  - Quartz—$583,000
  - Sapphire/ruby—$266,000
- There were no primary producing diamond mines in the RGFO area in 2016; there were 7 active CDRMS permits for gemstone mines in Park and Teller counties in December 2016 (CDRMS, 2016).
- An unknown amount of gemstones may be recycled by being resold as estate jewelry, resetting, or recutting.

- Reasons for demand fluctuations[1,2,5]

  - Economic uncertainty affects demand for luxury items like jewelry.
  - Price of gemstones (Figure 5-48)
  - Production of synthetic gemstones is replacing the need for naturally mined gemstones; the value of synthetic gemstones sold in the U.S. in 2015 was 5.5 times that of natural gemstones.
  - Amount of gemstones from estate/resold jewelry
  - Increasing awareness of conflict diamonds and their consequences led the diamond industry to adopt the Kimberley Process Certification Scheme (KPCS) in 2003; this had led to increased consumer demand for conflict free diamonds and 99 percent of the diamond market being certified conflict free.

- Reasons for market fluctuations[1,2]
  - Economic uncertainty affects the growth or decline of the industries that use gemstones.
  - De Beers restructured its operations in 2000, leading to a shift in the diamond market. Between 2003 and 2012, market share controlled by De Beers decreased from 65 percent to 40 percent, by value. This opened opportunities for competitors to enter the market and also changed the way diamonds were produced and valued (previously managed by De Beers to control quality and quantity of diamond availability).
  - Drop in diamond price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was an 18 percent decrease in exploration budgets for diamonds from 2014 to 2015.
  - Four new diamond projects started production in 2013: the Grib Pipe (Russia), Merlin (Australia), Mobilong Diamond (Cameroon), and Saxendrift (South Africa) mines.
  - The USGS estimates that by 2020, about 25 percent of diamond production will come from projects that are currently being developed.

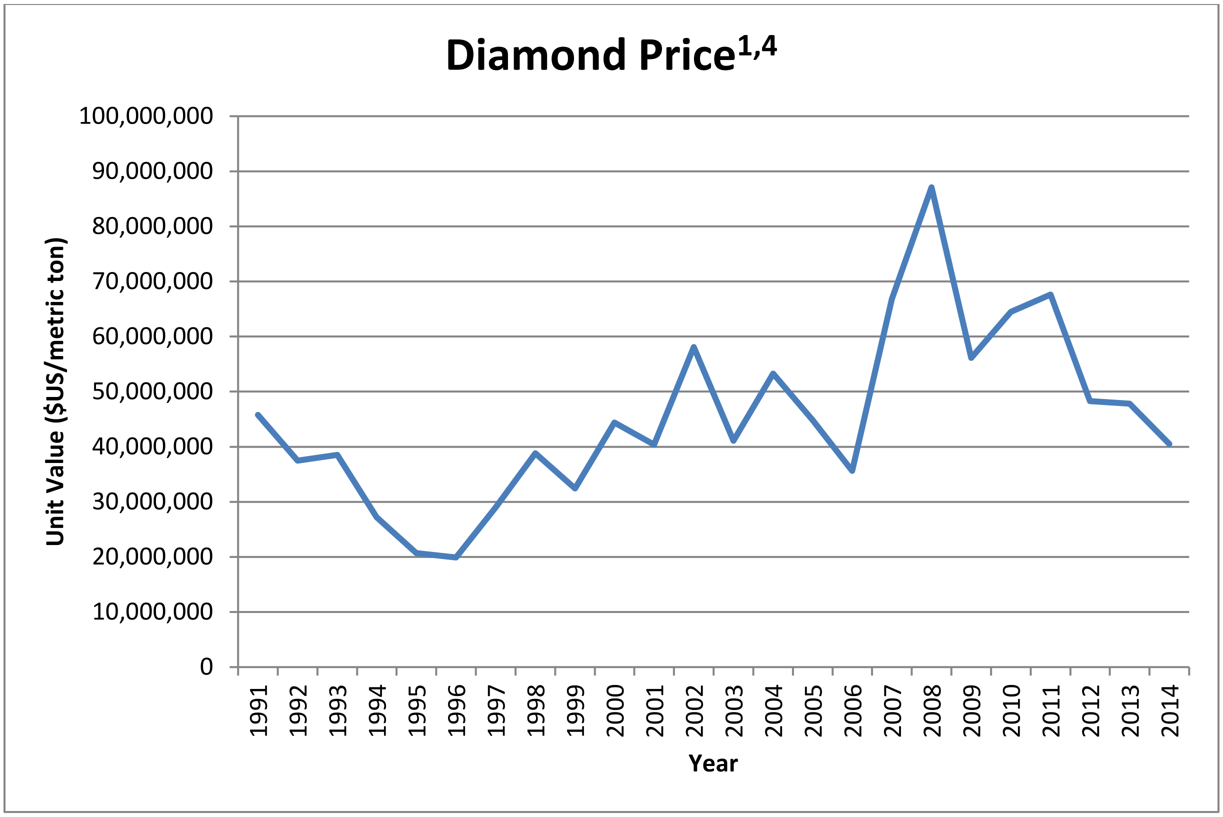


Figure 5-48. Annual average price of diamonds from 1991 to 2014.

- Current and projected trends for demand and why[1,2]
    - E-commerce and internet sales of gemstones are expected to increase in popularity, adding to and perhaps partially replacing store sales; this will increase demand.
    - Synthetic gemstones may continue to become more popular, replacing natural gemstone demand.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for diamonds, the previously producing State Line Diamond district in Larimer County may become economically viable.
    - There are smaller gemstone operations in the RGFO area that operate as a niche market, but those could expand if demand for natural gemstones increases.

Summarized from:

[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]DiamondFacts, 2016

5.9.3 Pegmatite Minerals

- This section will cover feldspar and mica, two common pegmatite commodities; other commodities associated with pegmatites (e.g., REEs and beryllium) have been addressed in other sections.

- The "usable" characteristics of the material[1,3]
  - Feldspar
    - Hard
    - Alumina content
  - Mica
    - Fissile (flakes into sheets)
    - Heat resistant
    - Not electrically conductive

- What technology/industrial practice it is used for currently[1,3]
  - Feldspar
    - Glassmaking
    - Ceramics
  - Mica
    - Filler and extender for wallboard joint compound
    - Oil and gas drilling
    - Paint pigment/filler
    - Rubber molding
    - Electrical insulators

- What technology/industrial practice it might be used for in the future[1,3]
  - Feldspar
    - Thinner, stronger ceramic sheets that can be laid over existing tile surfaces
  - Mica
    - Engineered mica composites

- Local, regional and worldwide reserves—both in the ground and stockpiled[1]
  - Reserves are generally not estimated for industrial materials like feldspar and mica. These materials are generally plentiful and are sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances.
  - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized there is less land available for resource exploitation. Also, urban areas often do not want quarry operations nearby; this forces operations

further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

- Local and regional markets and why[1,2]
    - The four largest feldspar producing countries in 2015 were:
        - Turkey (5 million tonnes)
        - Italy (4.7 million tonnes)
        - China (2.5 million tonnes)
        - India and Thailand (1.5 million tonnes each)

    - The four largest mica (scrap and flake) producing countries in 2015were:
        - China (780,000 tonnes)
        - Russia (100,000 tonnes)
        - Finland (54,000 tonnes)
        - United States (41,500 tonnes)
    - Annual U.S. feldspar and mica production is depicted in Figures 5-49 and 5-50, respectively. Feldspar was produced in 6 States in 2015; mica was produced in 4 States.
    - There was recycling of an unknown amount of feldspar contained in glass scrap in 2015; glass is not recycled specifically for feldspar.
    - In the U.S. in 2015, 60 percent of feldspar was used in glass, and 40 percent in ceramic tile, pottery, and other uses; 54 percent of mica went to joint compound, 21 percent to paint, 3 percent to plastics, and the rest to mostly well drilling mud (among other uses).

- Reasons for demand fluctuations[1,2]
    - Feldspar is consumed in the production of glass containers, demand for which has grown as consumers and governments push for more environmentally friendly, recyclable food containers.
    - As more glass is recycled, less feldspar raw materials are needed, decreasing demand.
    - Use of substitutes for feldspar such as nepheline syenite in ceramic tile
    - Mica is mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building and development.
    - Construction is the main driver for mica demand, although oil and gas drilling also has an effect.

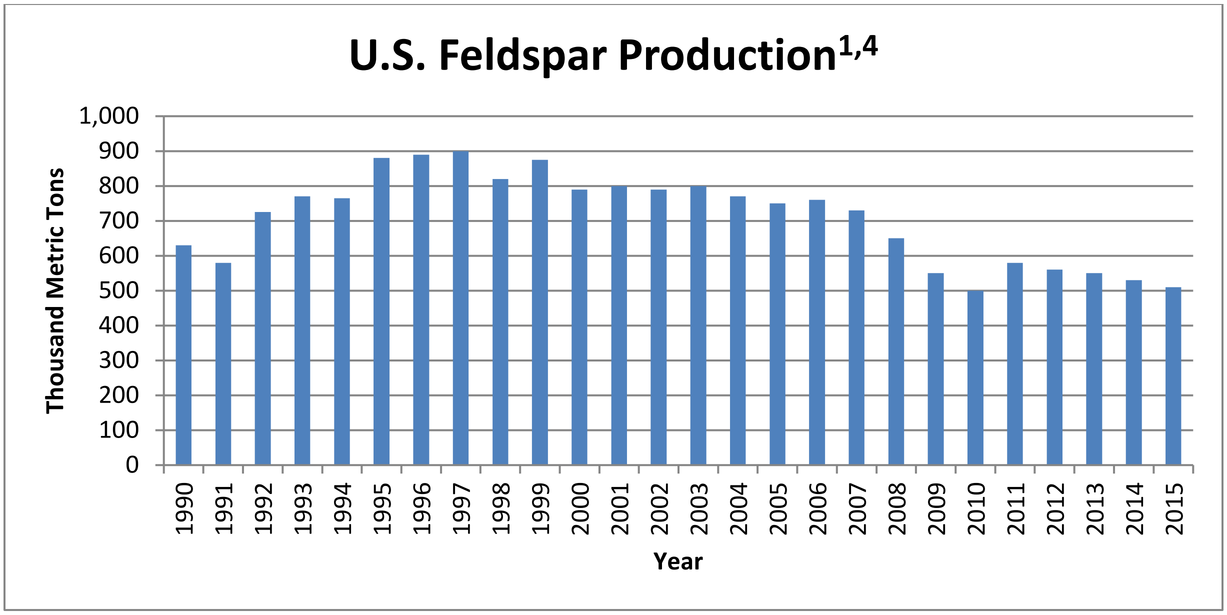


Figure 5-49. Annual U.S. production of feldspar from 1990 to 2015.

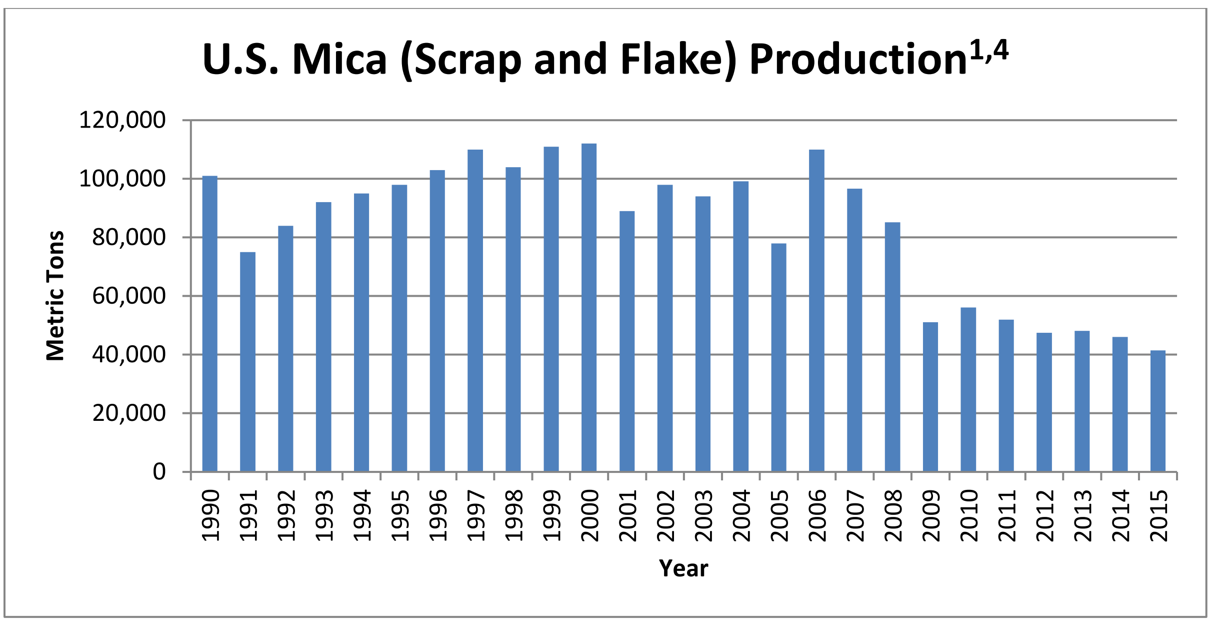


Figure 5-50. Annual U.S. production of mica (scrap and flake) from 1990 to 2015.

  - Use of substitutes for mica, such as lightweight aggregates for filler or plastics for insulators
  - Price of feldspar and mica, Figures 5-51 and 5-52, respectively

- Reasons for market fluctuations[1,2]
  - Sheet mica occurs sporadically and requires hand labor, reducing overall availability
  - In 2014, I-minerals started selling tailings from its Helmer-Bovill project as feldspar-quartz sands, providing new supply
  - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving operations farther from the point of sale, affecting price and availability
  - Excess supply has led to lower production of both feldspar and mica

- Current and projected trends for demand and why[1,2]
  - Mica demand relies heavily on the construction industry. As housing markets grow and building increases, demand will rise.
  - Feldspar for use in tile is tied to residential and commercial construction and refurbishment, and demand will increase as new buildings are constructed and as the economy prospers, allowing people to perform home renovations.
  - A shortage of high-quality block mica will continue, possibly leading to the increased use of substitutes and less demand, even if new deposits are found.

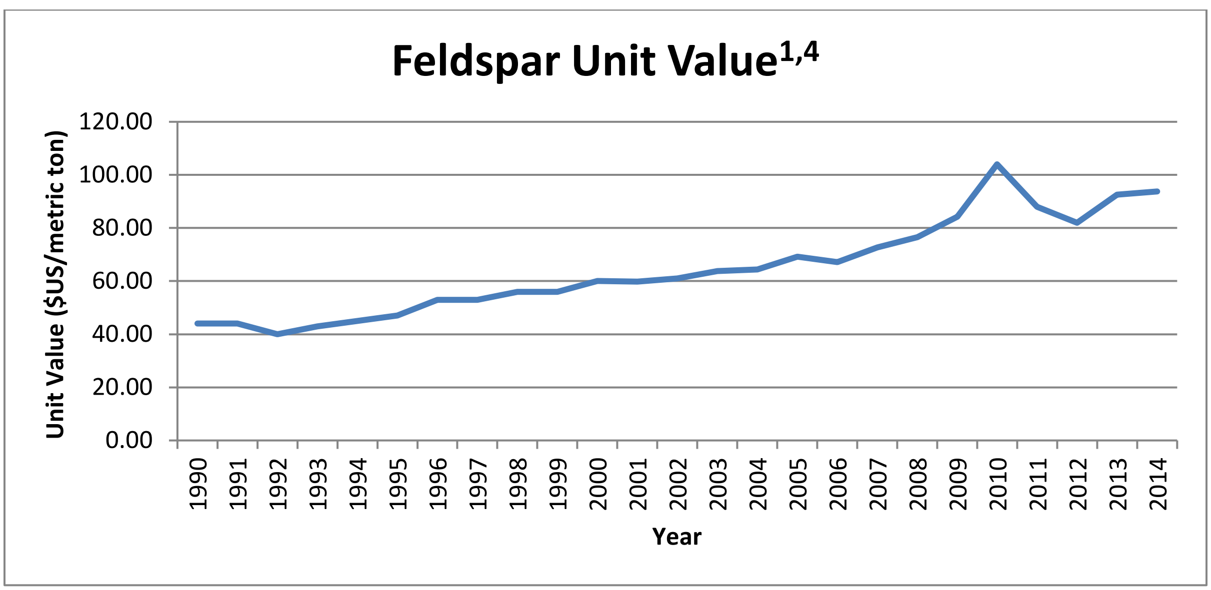


Figure 5-51. Annual average price of feldspar from 1990 to 2014.

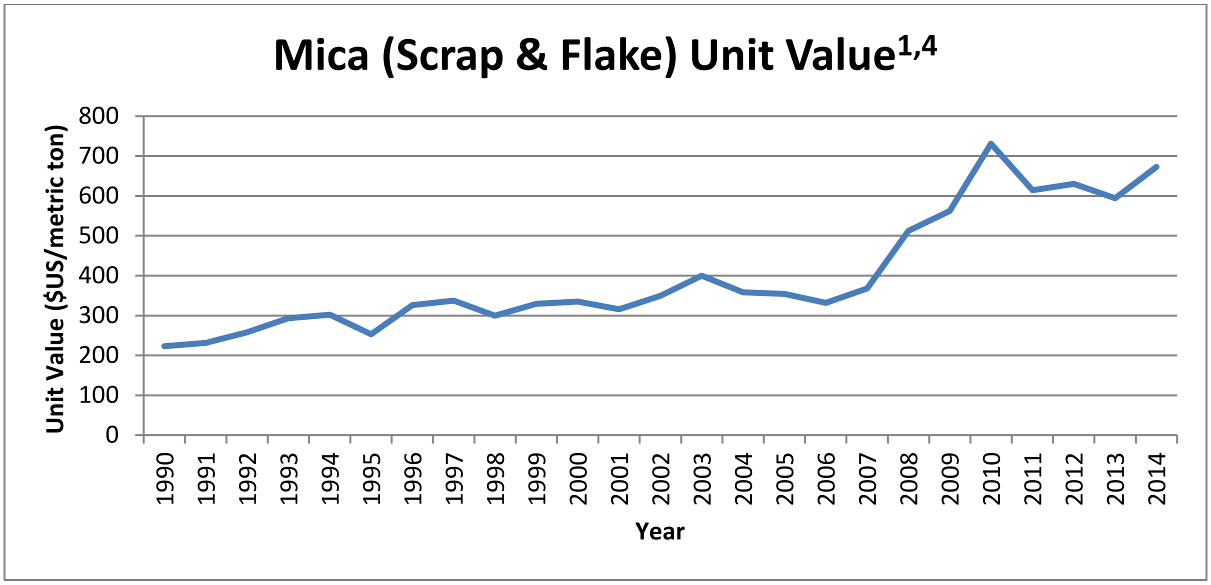


Figure 5-52. Annual average price of mica from 1990 to 2014.

- Any influence of these trends that may directly affect the RGFO region[5]
  - The RGFO region has several pegmatite districts, including some that have been mined for feldspar and sheet mica in the past (Sterrett, 1923). If there is sufficient local demand for feldspar or mica, these areas may become economically viable. Feldspar and mica may also be mined as byproducts if the pegmatites become economically viable due to their metal content.
  - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for feldspar and mica will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for construction use.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]U.S. CB, 2016

5.9.4 Industrial Abrasives

- The "usable" characteristics of the material[1,3]
  - Hard
  - Wear resistant

- What technology/industrial practice it is used for currently[1,2,3]

   - Drill bits for oil, gas, and other drilling operations
   - Cutting tools for metal machine parts
   - Sand paper
   - Polishing abrasives (such as for gem cutting or lens making)
   - Abrasive for use in water jet cutting
   - Water filtration (garnet only)
   - Heat sinks for electronic circuits (diamond only)

- What technology/industrial practice it might be used for in the future[2]
   - Wear-resistant diamond coatings
   - Increased use of garnet waterjet cutting and polishing, and close-tolerance machining of ceramic parts by diamond tools in aerospace applications

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
   - Worldwide, in the ground reserves of industrial diamond were estimated at 700 million carats in 2015. Reserves of industrial garnet are very large.
   - In 2015, the USGS had not calculated industrial diamond reserves and estimated there were 5 million tonnes of industrial garnet reserves.
   - The State Line Diamond district on the Wyoming-Colorado border is a past producer of diamonds. The Kelsey Lake area held an estimated 16.9 million tonnes of diamond-bearing rock; the Sloan 1 kimberlite to the south has an estimated resource of 15.3 million tonnes of ore averaging 6.1 carats/100 tonnes and the Sloan 2 kimberlite has an estimated resource of 8.4 million tonnes averaging 17.1 carats/100 tonnes (Hausel, 1998).
   - There is no government stockpile for industrial diamond or garnet.

- Local, regional and worldwide markets and why[1,2]
   - Annual world industrial abrasives production is depicted in Figure 5-53.
   - The four largest natural industrial diamond producing nations in 2015 were:
      - Russia (16 million carats)
      - Congo (13 million carats)
      - Australia (10 million carats)
      - Botswana (7 million carats)
   - The four largest industrial garnet producing nations in 2015 were:
      - India (800,000 tonnes)
      - China (520,000 tonnes)
      - Australia (260,000 tonnes)
      - United States (34,000 tonnes)
   - Industrial diamond is produced in ~15 countries around the world; deposits are unequally distributed. Industrial garnet is produced in ~14 countries; deposits are

unequally distributed, and the lower value for garnet means it is often produced by countries for domestic use only.

- As of 2015, there were no reported primary industrial diamond mines in the U.S. There were four industrial garnet producing firms in Idaho, Montana, and New York.
- There were no primary producing industrial diamond or garnet mines in the RGFO area in 2016.
- In the U.S. in 2015, 37.8 million carats of diamond bort, grit, and dust, as well as 477,000 carats of diamond stone (mostly from originally synthetic production), were recycled; very small quantities of industrial garnet were recycled.
- In the U.S. in 2015, computer chip production, construction, machinery manufacturing, mining services, stone cutting and polishing, and transportation industries were the major consumers of industrial diamond. Industrial garnet consumers in 2015 included: waterjet cutting (35 percent), abrasive blasting media (30 percent), water filtration (20 percent), abrasive powders (10 percent), and other uses (5 percent).

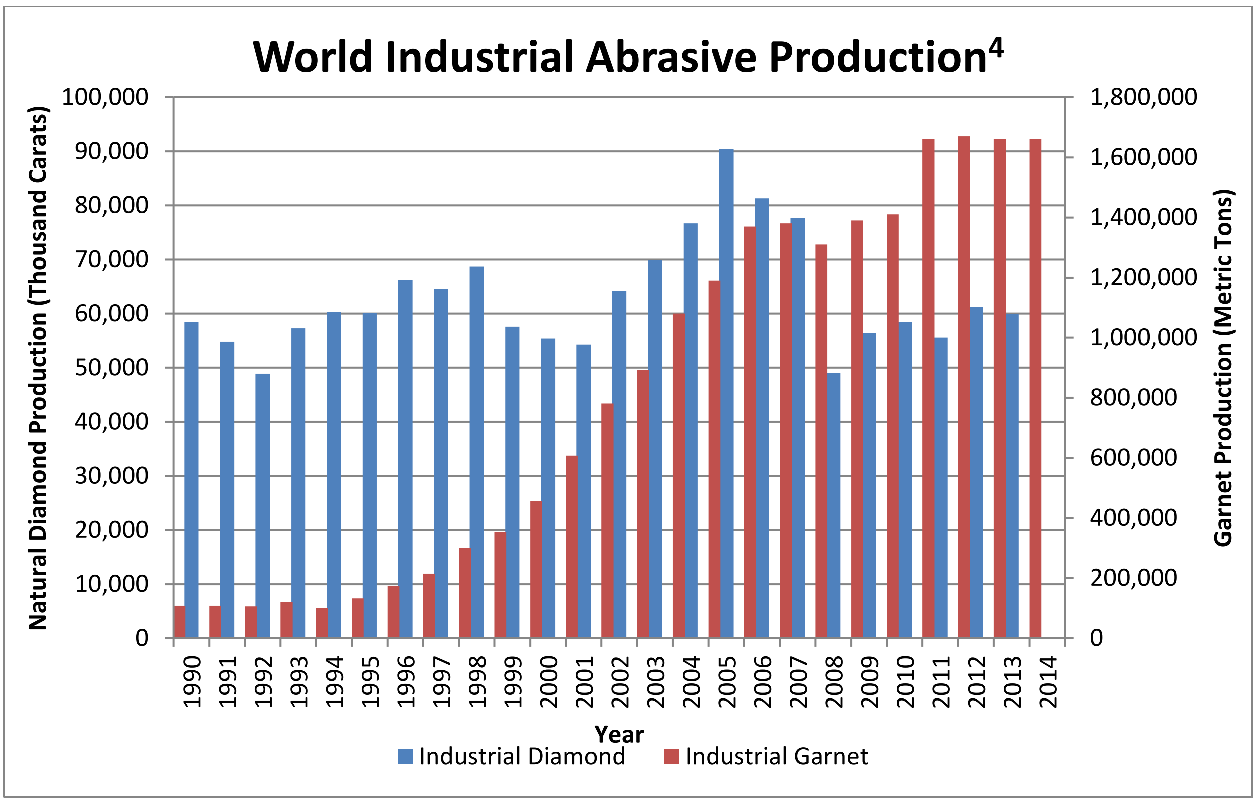


Figure 5-53. Annual world production of industrial abrasives from 1990 to 2014.

- Reasons for demand fluctuations[1,2]
    - Over 95 percent of the U.S. industrial diamond market in 2015 used synthetic industrial diamond, and the demand for synthetic rather than natural industrial diamond is expected to rise.
    - Price of industrial diamond and garnet (Figure 5-54)
    - Amount of industrial diamond from recycled sources
    - Use of substitutes for both diamond and garnet abrasives, including synthetic fused aluminum oxide, cubic boron nitride, and silicon carbide
    - Increased use of diamond as a wear-resistant coating: industrial diamond extends tool life justifying the initial higher cost
    - Garnet is replacing silica sand as a blasting media due to adverse health effects associated with silica.

- Reasons for market fluctuations[1,2]
    - Economic uncertainty affects the growth or decline of the industries that use industrial abrasives.
      De Beers restructured its operations in 2000, leading to a shift in the diamond market. Between 2003 and 2012, market share controlled by De Beers decreased from 65 percent to 40 percent, by value. This opened opportunities for competitors to enter the market and also changed the way diamonds were produced and valued (previously managed by De Beers to control quality and quantity of diamond availability).
    - A drop in diamond price led to a reduction in exploration budgets, meaning the number of prospects being discovered is decreasing. There was an 18 percent decrease in exploration budgets for diamonds from 2014 to 2015 (Wilburn and Karl, 2015).
    - Four new diamond projects started production in 2013: The Grib Pipe (Russia), Merlin (Australia), Mobilong Diamond (Cameroon), and Saxendrift (South Africa) mines.
    - U.S. garnet producers have seen increasing costs and rising competition from foreign imports, forcing noncompetitive producers out of the market.

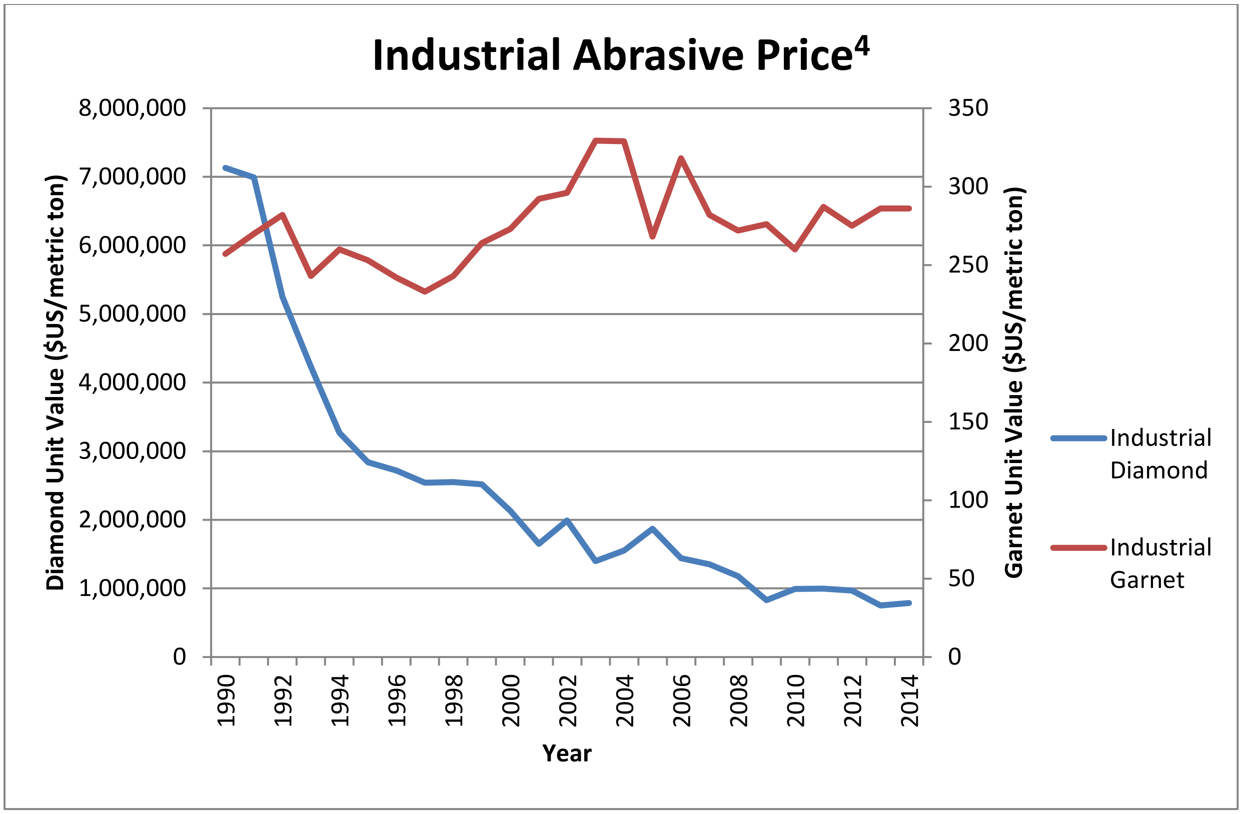


Figure 5-54. Annual average price of industrial abrasives from 1990 to 2014.

- Current and projected trends for demand and why[1,2]
    - Demand for industrial garnet as a blasting media and for use in waterjet technology is projected to increase.
    - High-technology uses for industrial diamond in the computer, manufacturing, and laser industries will increase demand, but mainly for synthetic industrial diamond. The manufacturing process can be precisely controlled, and technology allows synthetic diamond coatings to be applied directly to tools or other substrates, options that are not available with natural diamond.
        - However, natural industrial diamond is produced mainly as a byproduct of gemstone mining, and demand for gem-quality diamonds is projected to increase; this will leave non-gem-quality diamonds available for industrial use.

- Any influence of these trends that may directly affect the RGFO region
    - If there is sufficient demand for industrial abrasives, high occurrence potential areas in the RGFO region could become economically viable; the RGFO region is also unique in being home to only one of two known commercially mineable diamond deposits.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Kelly and Matos, 2014

5.9.5 Limestone and Dolomite

- This section covers limestone and dolomite not used for crushed stone or dimension stone; for use as crushed stone, see section 5.10.2; for use as dimension stone, see section 5.10.5. Cement and lime are two industrial products of limestone and/or dolomite with enough economic data to analyze.

- The "usable" characteristics of the material[1,3,5]
  - Abundant
  - Cohesive properties
  - Can be calcined to lime

- What technology/industrial practice it is used for currently[1,3,5]
  - Cement manufacture
  - Steelmaking
  - Glass manufacture
  - Nonferrous metal refining and recovery
  - Flue gas desulfurization
  - Construction
  - Water treatment
  - Mining (used mainly as dust to coat coal mines)
  - Paper production
  - Precipitated calcium

- What technology/industrial practice it might be used for in the future[2,3]
  - Emerging technologies for sulfur dioxide scrubbing of power plant emissions
  - Rebuilding of aging public infrastructure

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Reserves are generally not estimated for industrial materials such as limestone and dolomite. These materials are generally plentiful and sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances (unless they are of a specialized type).
  - Reserves are influenced by land use, environmental concerns, and price. As more construction occurs, more limestone is needed to produce lime, but there is less land available for resource exploitation. Also, urban areas often do not want

quarry or plant operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions

- Local and regional markets and why[1,2]
    - The four largest lime (calcined from limestone and/or dolomite) producing countries in 2014 were:
        - China (230 million tonnes)
        - United States (19.5 million tonnes) (Figure 5-55)
        - India (16 million tonnes)
        - Russia (11 million tonnes)
    - The four largest cement producing countries in 2014 were:
        - China (2.48 billion tonnes)
        - India (260 million tonnes)
        - United States (83.2 million tonnes) (Figure 5-55)
        - Turkey (75 million tonnes)
    - In 2015, there were 31 companies producing lime and 99 plants producing cement in the U.S.
    - The top producing States for lime in 2014 were Missouri, Alabama, Kentucky, Ohio, and Texas; Texas, California, Missouri, and Florida were the top cement producing States.
    - The west region, including Colorado, produced 3.13 million tonnes of lime in 2014. Colorado and Wyoming produced 3.187 million tonnes of Portland cement in 2014.
    - Lime is regenerated by paper mills and some municipal water-treatment plants.
    - Cement kiln dust is recycled back to cement kilns. Finely ground limestone can be used as an SCM added to Portland cement in blended hydraulic cements.
    - U.S. consumption of lime in 2014 included: metallurgical uses (37 percent), environmental uses (31 percent), chemical and industrial uses (22 percent), construction purposes (9 percent), and refractories (1 percent). U.S. consumption of cement in 2014 included: ready-mix concrete (70 percent), concrete product manufacturers (11 percent), contractors (8 percent), oil and gas well drillers (4 percent), building materials dealers (4 percent), and other uses (3 percent).

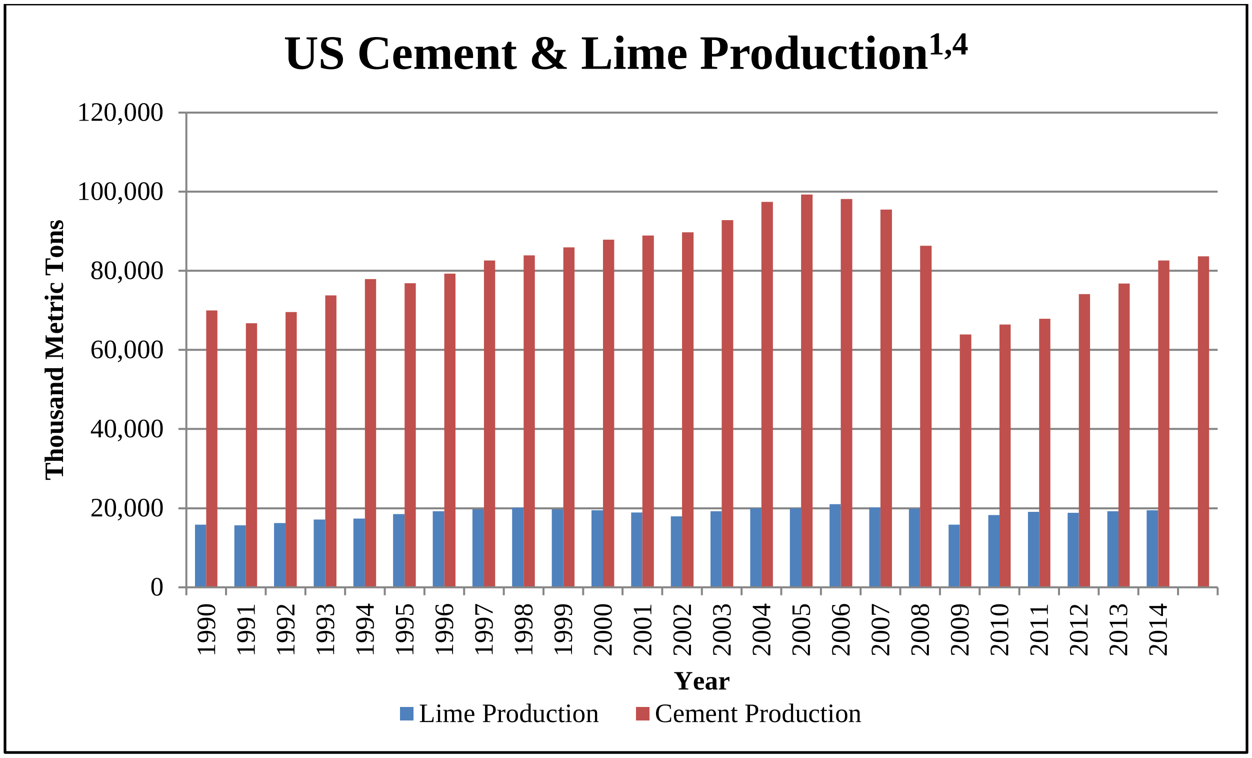


Figure 5-55. Annual U.S. production of cement and lime from 1990 to 2015.

- Reasons for demand fluctuations[1,2]
  - Lime is mainly consumed by the steel industry, and demand relies on economic conditions that promote steel-consuming activities like construction and manufacturing.
  - Cement is used mainly for concrete production, which relies on the building and construction industries.
  - Price of lime and cement (Figure 5-56)

- Constraint of budgets to repair aging infrastructure
  - Use of lime substitutes such crushed limestone, calcined gypsum, or fly ash; expanded use and allowance of secondary cementitious materials in finished cement

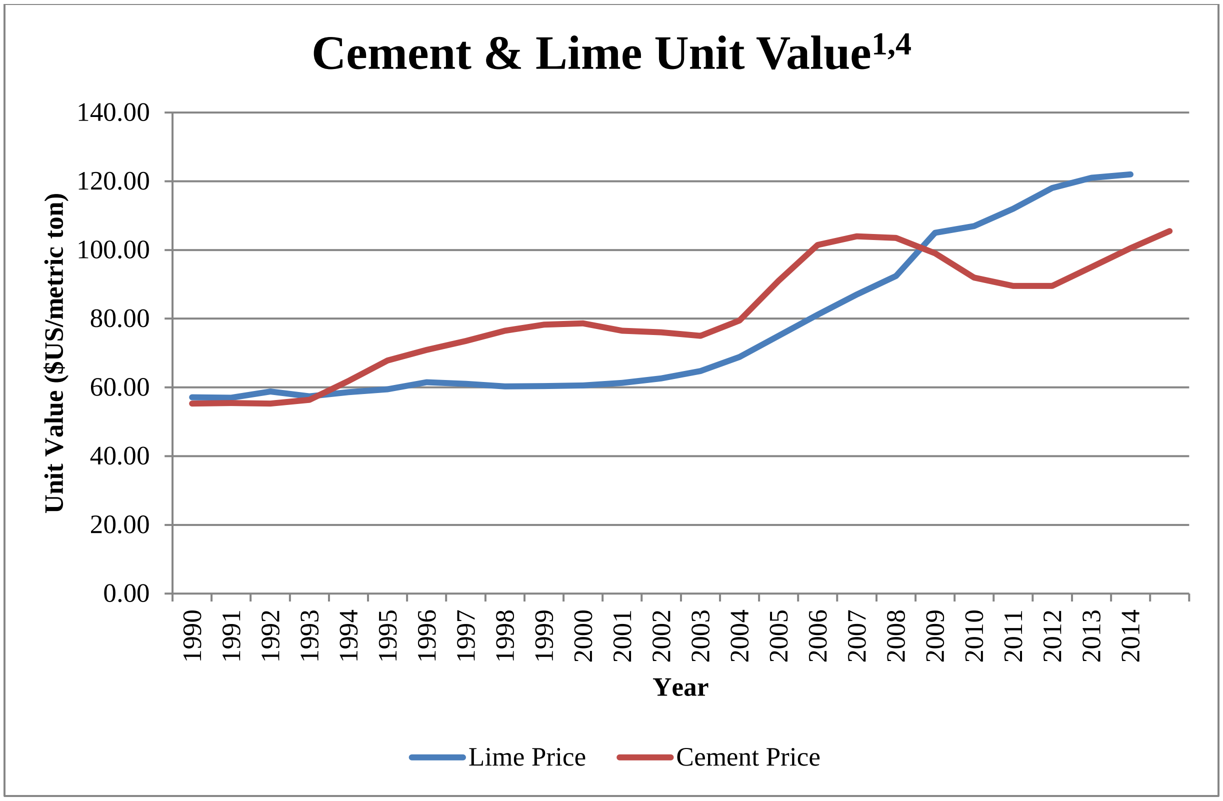


Figure 5-56. Annual average price of cement and lime from 1990 to 2015.

- Reasons for market fluctuations[1,2]
  - Availability of limestone and dolomite that meets project-specific needs
  - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving quarries farther from the point of sale, affecting price and availability.
  - In February 2016, Carmeuse (the largest lime producer in the U.S. at yearend 2014) opened two new vertical kilns at its Winchester, Virginia plant, bringing production to 400 tonnes per day (Carmeuse, 2016).
  - In April of 2016, Graymont (the third largest lime producer in the U.S. at yearend 2014) restructured its Tacoma, WA, plant by shutting down precipitated calcium carbonate and quicklime production and permanently idled a lime plant in British Columbia due to soft regional market conditions (Graymont, 2016a and 2016b).
  - There have been several large mergers and purchases within the cement industry that have shifted assets and consolidated operations; Holcim and Lafarge, two of the largest producers in the industry, merged in 2015.

- Current and projected trends for demand and why[1,2]
    - Limestone and dolomite demand rely heavily on the steel and construction industries, which is tied to overall economic growth. With ongoing manufacturing construction, demand is expected to increase.
    - Even as power plants transition to natural gas from coal, lime is an important part of sulfur dioxide scrubbing and will continue to be in demand.
    - The ASCE (2017) rates America's roads as D and bridges as C+. There is an estimated US$123 billion backlog in bridge rehabilitation, and one out of every 5 miles of highway pavement is in poor condition. If these conditions are addressed by government or private industry, they would require a large amount of cement.

- Any influence of these trends that may directly affect the RGFO region
    - The RGFO region hosts numerous limestone quarries used for the production of lime and/or cement. These quarries may expand or contract with market fluctuations.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]Freas et al., 2006

5.9.6 Industrial Sand

- The "usable" characteristics of the material[1,3]
    - Abundant
    - High silica content

- What technology/industrial practice it is used for currently[1,3]
    - Glassmaking
    - Foundry applications
    - Abrasive applications
    - Hydraulic fracturing
    - Landscaping
    - Filtration

- What technology/industrial practice it might be used for in the future[1,3]
    - Advanced oil recovery technologies

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Reserves are generally not estimated for construction materials like industrial sand. These materials are generally plentiful and sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances.
    - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized there is less land available for resource exploitation. Also, urban areas often do not want aggregate operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions

- Local and regional markets and why[1,2]
    - Recently, production of industrial sand in the U.S. has sharply risen (Figure 5-57).
    - The four largest industrial sand- and gravel-selling States in 2014 were:
        - Wisconsin (38.3 million tonnes)
        - Texas (16.5 million tonnes)
        - Illinois (13.5 million tonnes)
        - Minnesota (7.22 million tonnes)
    - Industrial sand was produced in 35 States in 2015.
    - In 2015, there were 335 sand operations from 230 companies known in the U.S.
    - There was recycling of an unknown amount of foundry sand in 2015.
    - In the U.S. in 2015, 71 percent of industrial sand was used as hydraulic-fracturing sand and well-packing and cementing sand, 8 percent as other whole-grain silica, 7 percent as glassmaking sand, 6 percent as foundry sand, 2 percent as whole-grain fillers, 2 percent as building products, 2 percent as other ground silica, 1 percent as ground and unground sand for chemicals, and 3 percent for other uses.

- Reasons for demand fluctuations[1,2]
    - Industrial sand is mainly consumed by the hydraulic fracturing/drilling industry, and demand relies on economic conditions that promote development of oil and gas wells. Oil and gas drilling is the main driver for sand demand.
    - Price of project-appropriate sand (Figure 5-58)
    - Use of substitutes such as recycled material (particularly recycled glass containers and cullet glass) for glassmaking and alternate well proppants for hydraulic fracturing

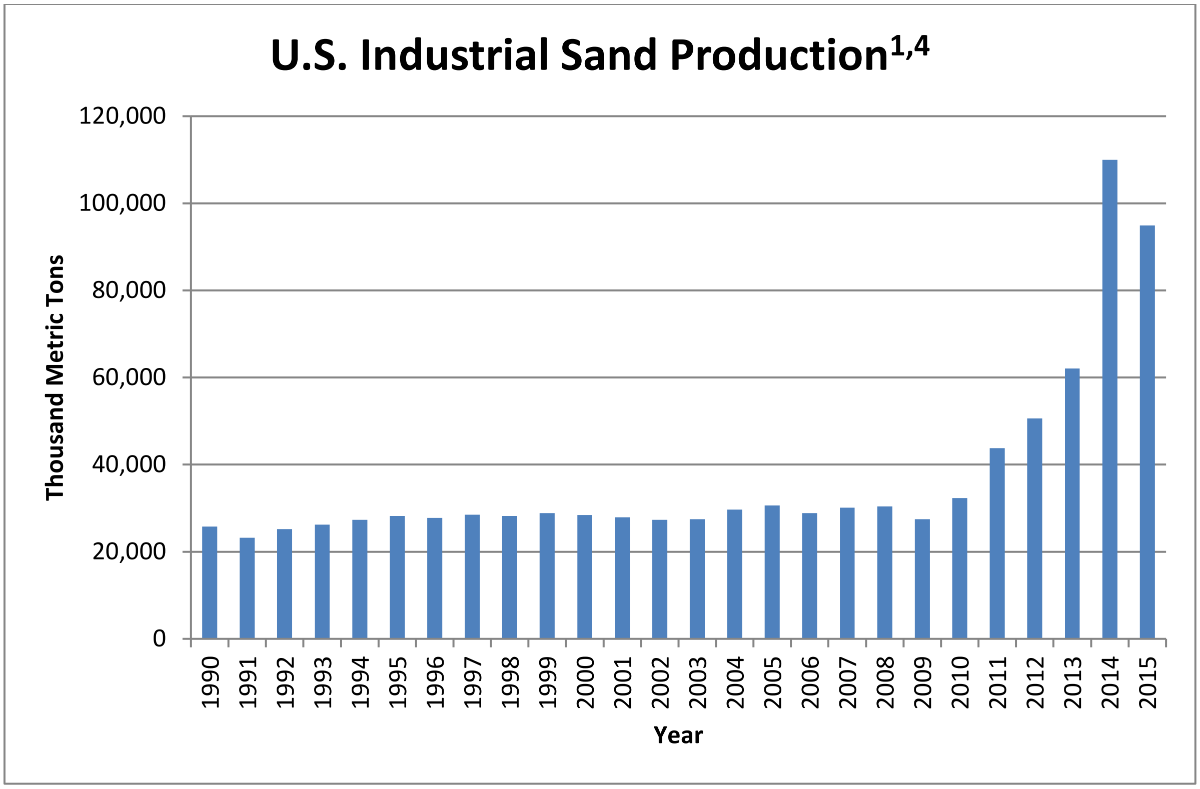


Figure 5-57. Annual U.S. production of industrial sand from 1990 to 2015.

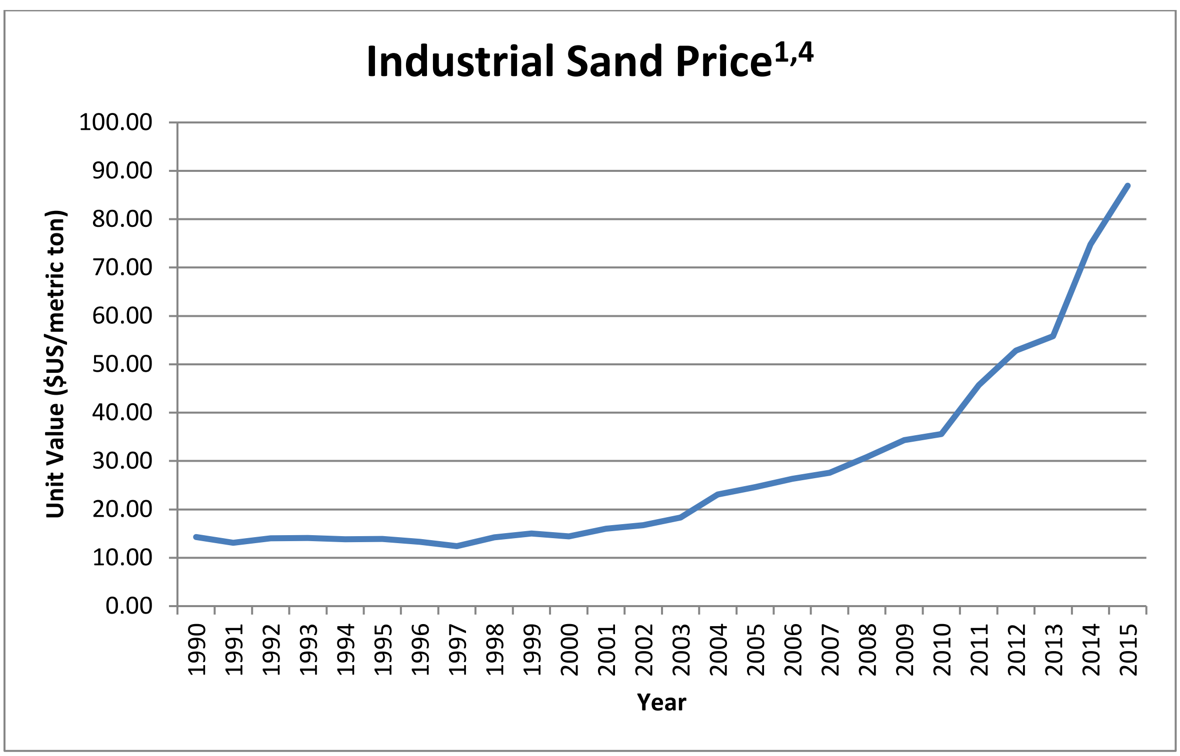


Figure 5-58. Annual average price of industrial sand from 1990 to 2015.

- Reasons for market fluctuations[1,2]
  - Availability of sand that meets project-specific needs
  - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving sand operations farther from the point of sale, affecting price and availability.
  - Drop in oil and gas prices in 2014 led to reduced fracking and reduced prices and production of industrial sand.

- Current and projected trends for demand and why[1,2]
  - Industrial sand demand relies heavily on the oil and gas industry. The use of alternate recovery techniques, increasing scrutiny of fracking, and continued reduced oil and gas prices could all decrease demand; alternatively, increased drilling of fracking wells would increase demand.
  - Increased use of recycled glass containers and glass pieces in glassmaking could reduce demand for glassmaking silica.

- Any influence of these trends that may directly affect the RGFO region
  - The eastern plains of the RGFO region contain eolian sand that meets industrial sand requirements and could become an area of interest if demand for fracking sand rises.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014

5.9.7 Gypsum

- The "usable" characteristics of the material[1,3]
  - Abundant
  - Variety of hydration states

- What technology/industrial practice it is used for currently[1,3]
  - Drywall (wallboard)
  - Concrete
  - Soil conditioner
  - Plaster
  - Glassmaking

- What technology/industrial practice it might be used for in the future[1,3]
  - Used as part of green building initiatives
  - Engineered gypsum panels with high wear and tear resistance and seismic rating

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Reserves are generally not estimated for construction materials like gypsum. These materials are generally plentiful and sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances.
    - The USGS estimated U.S. reserves of gypsum at ~700 million tonnes in 2015.
  - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized there is less land available for resource utilization and more demand for building materials. Also, urban areas often do not want quarry operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

- Local and regional markets and why[1,2]
  - World gypsum production (Figure 5-59) increased, and U.S. gypsum production (Figure 5-60) fluctuated, between 1990 and 2015.
  - The four largest gypsum producing countries in 2015 were:
    - China (132 million tonnes)
    - Iran (22 million tonnes)
    - Thailand (12.5 million tonnes)
    - United States (11.5 million tonnes)
  - The four largest gypsum producing States in 2014 were:
    - Oklahoma
    - Texas
    - Nevada
    - Kansas
  - Gypsum was produced in 16 States in 2015.
  - In 2015, there were 50 mines from 47 companies known in the U.S.
  - There was recycling of an unknown amount of gypsum in 2015. Scraps from wallboard installation may be recycled into new board or used in cement, stucco, water treatment, or other uses.
    - Ten to twelve percent of wallboard used in construction was discarded as scrap in 2014.

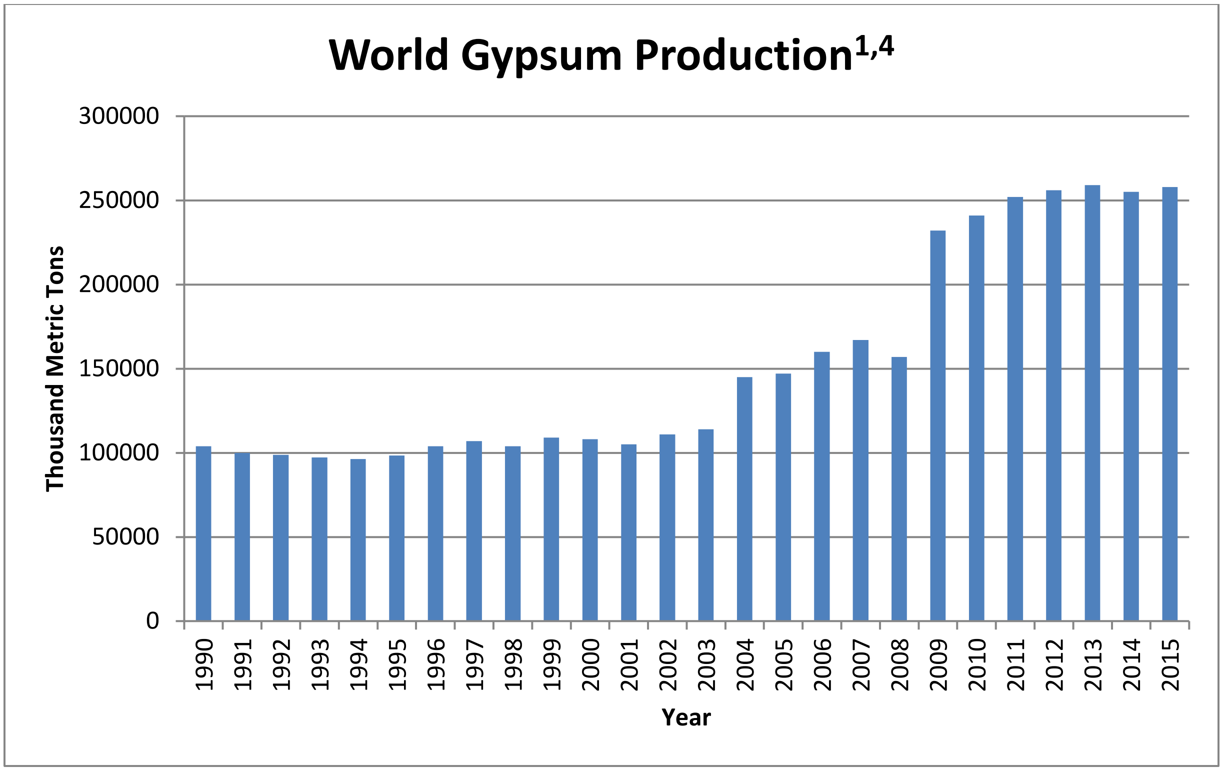


Figure 5-59. Annual world production of gypsum from 1990 to 2015.

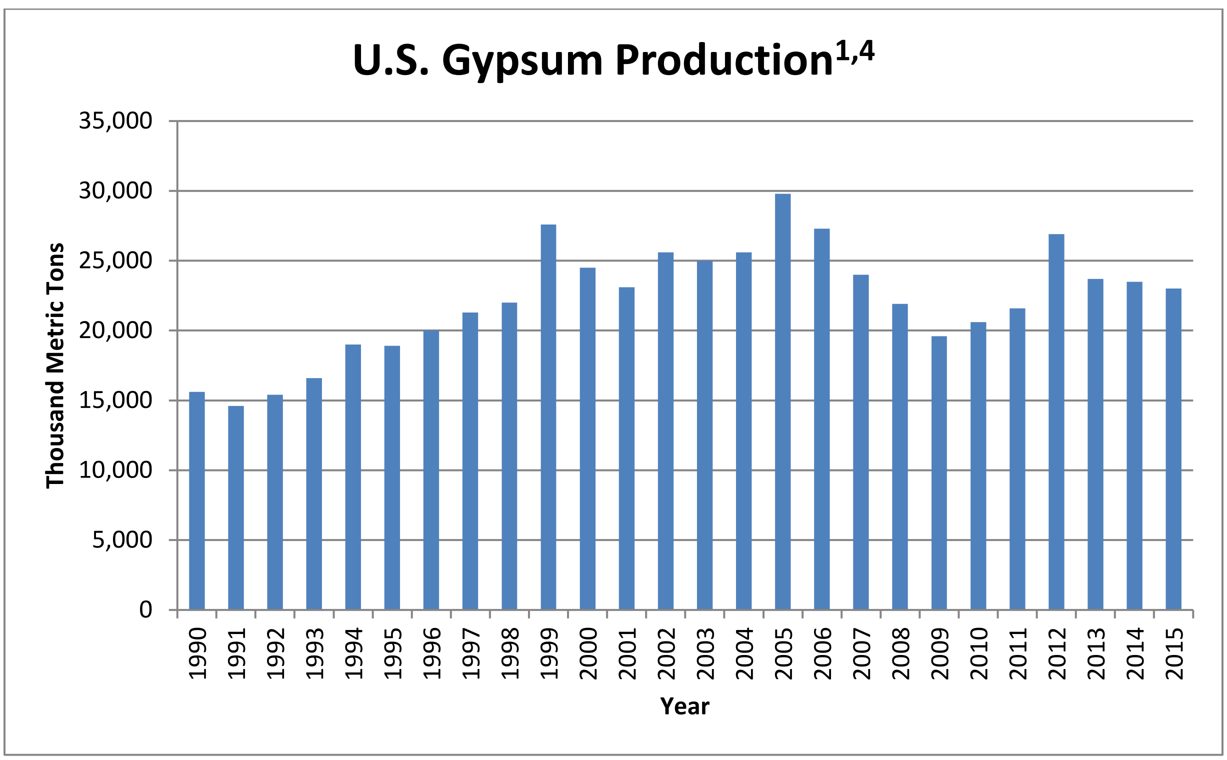


Figure 5-60. Annual U.S. production of gypsum from 1990 to 2015.

  - Synthetic gypsum is produced as a byproduct of Flue Gas Desulfurization (FGD). In 2015, 11.5 million tonnes of synthetic gypsum was used in the U.S. for mainly wallboard manufacture.
  - In the U.S. in 2015, 90 percent of gypsum went to wallboard and plaster products and most of the rest went to cement production and agricultural applications.

- Reasons for demand fluctuations[1,2]
  - Gypsum is mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building and development. Construction is the main driver for gypsum demand.
  - Price of gypsum (Figure 5-61)
  - Use of substitutes such as recycled material (a significant portion of wallboard is discarded as scrap, and the construction industry has come under scrutiny for such waste; credits in the LEED system can be earned by diverting waste and may contribute to more intense recycling efforts) and synthetic gypsum produced from coal or gas fired power plants

- Reasons for market fluctuations[1,2]
  - Availability of synthetic gypsum—as more power plants convert to natural gas, there is less synthetic gypsum produced to make up for domestic production shortfalls. However, only 49 percent of synthetic gypsum produced in 2014 was sold or used, leaving a significant untapped resource.
  - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving gypsum operations farther from the point of sale, affecting price and availability.
  - Decline of the housing market through ~2010 lead to reduced gypsum prices and the idling of several wallboard production plants

- Current and projected trends for demand and why[1,2]
  - Gypsum demand relies heavily on the construction industry. As housing markets prosper and building increases, demand will rise.
  - Increased use of synthetic gypsum could reduce demand for crude (mined) gypsum, although the amount of synthetic gypsum will decrease as coal-powered power plants are converted to natural gas.

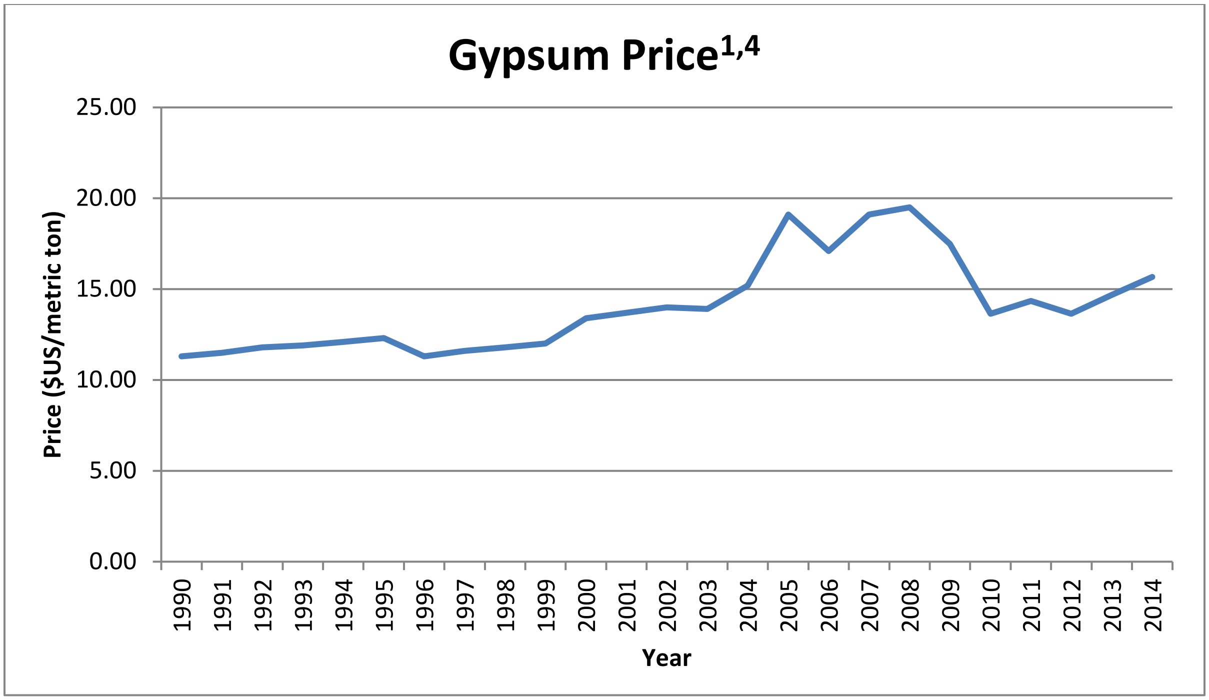


Figure 5-61. Annual average price of gypsum from 1990 to 2014.

- Any influence of these trends that may directly affect the RGFO region[1,2,5,6]
  - There were 6 active gypsum mines in the RGFO region in 2016; these operations could expand if gypsum demand increases.
  - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for gypsum will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for construction use.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]CDRMS, 2016
[6]U.S. CB, 2016

5.9.8 Helium

- The "usable" characteristics of the material[1,5]
  - Non-reactive
  - Liquid at extremely cold temperatures

- What technology/industrial practice it is used for currently[1,5]
    - Magnetic Resonance Imagers
    - Helium-neon laser for eye surgery
    - Rocket engine testing
    - Weather balloons
    - Cooling for thermographic cameras and other specialized equipment
    - Leak detection
    - Welding
    - Breathing mixtures (such as for SCUBA)
    - Cooling medium for nuclear reactors
    - Cryogenics

- What technology/industrial practice it might be used for in the future[4,5]
    - Aerospace
    - Brain cell research
    - Next-generation nuclear reactors

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,5]
    - Worldwide, in the ground reserves of helium (exclusive of the U.S.) were estimated at 31.3 billion cubic meters in 2006 (the last time a complete estimate was done).
    - The U.S. had an estimated 20.6 billion cubic meters of total resources and reserves as of December 31, 2006, including ~670 million cubic meters of total helium in the Federal Helium Reserve and ~3.9 billion cubic meters in known depleting fields.
    - The Rocky Mountain region had an estimated 9.1 billion cubic meters of total helium resources and reserves as of December 31, 2006 (BLM, 2008).
    - As of August, 2016, there were ~152 million cubic meters of government and ~80 million cubic meters of private helium in storage at the Cliffside Field Federal Reserve; helium in storage plus native gas totaled ~298 million cubic meters (BLM, 2016).

- Local, regional and worldwide markets and why[1,2,5]
    - World and U.S. helium production is depicted in Figure 5-62.
    - The four largest helium producing nations in 2015 were:
        - United States (extracted from natural gas) (76 million cubic meters)
        - Qatar (40 million cubic meters)
        - United States (from Cliffside Field) (24 million cubic meters)
        - Algeria (16 million cubic meters)

        - Australia (5 million cubic meters)
    - Helium is produced in ~8 countries around the world; deposits are unequally distributed, rely on a combination of helium source and trap, and are generally found with natural gas.
    - States containing gas fields that produce helium include Kansas, Texas, Oklahoma, Colorado, Utah, and Wyoming.
    - In the U.S. in 2015, 9 plants extracted crude helium from natural gas, 2 plants extracted Grade-A helium (99.997 percent or better) from natural gas, and 4 plants accepted crude helium from other producers and the BLM to produce Grade-A helium.
    - As of 2015, there was one Grade-A helium extraction plant in the RGFO region at Cheyenne Wells, CO.
    - In 2015, helium applications included: cryogenic applications (32 percent), pressurizing and purging (18 percent), controlled atmospheres (18 percent), welding cover gas (13 percent), leak detection (4 percent), breathing mixtures (2 percent), and other uses (3 percent).
    - Helium is seldom recycled in the U.S., although recent price increases have encouraged more re-use. Helium recycling is more prevalent in the rest of the world.

- Reasons for demand fluctuations[1,2,5]
    - Changes in policy regarding the Cliffside Federal Reserve have led to stockpile supply uncertainty, the use of substitutes, reduction in use of helium by certain parties, and/or increased demand of privately supplied helium.
        - If private entities sell refined helium to Federal agencies or their contractors, they must buy an equivalent amount of in-kind crude helium from the Federal Reserve, partially offsetting decreased demand.
    - Price of helium (Figure 5-63)
    - Increased use of helium-utilizing technologies

- Reasons for market fluctuations[1,2,5]
    - The U.S. Congress passed the Helium Privatization Act in 1996 in order to remove government controls on the helium industry and switch over to private industry (Cima, 2015).
        - Initially, the helium reserve was to be sold at a formula-driven price (not auctioned at market value) starting in 2005 and be shut down by 2015.
        - This led to an oversupplied market, reduced prices, higher consumption and waste, and reduced private investment due to low profits.

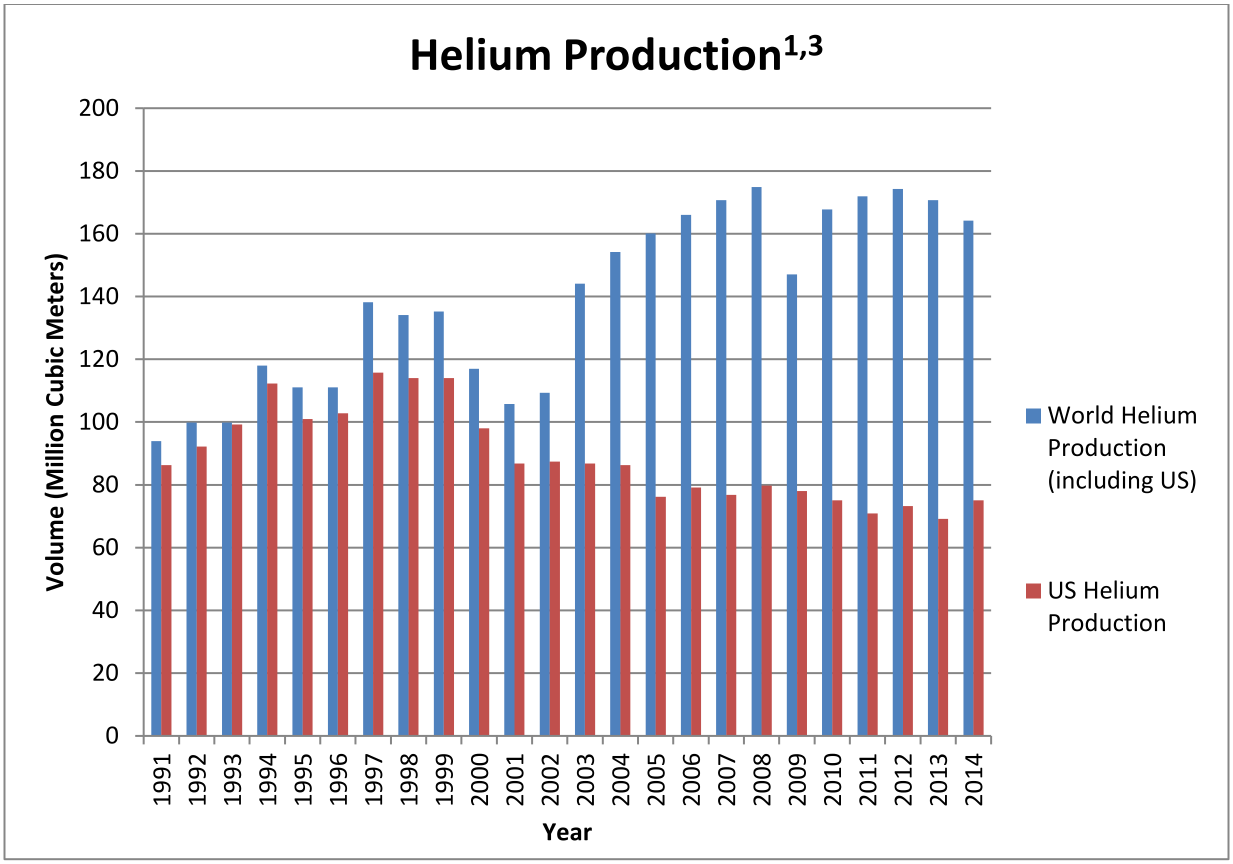


Figure 5-62. Annual world and U.S. production of helium from 1991 to 2014. Note: U.S. production is helium extracted from natural gas; world production is U.S. production plus world production from 1991-2004 and U.S. Grade-A helium sales plus world production from 2005-2014.

- Fears of the Helium Reserve shutdown with no substitute leading to a major shortage prompted the passage of the Helium Stewardship Act (HSA) in 2013 (Cima, 2015).
  - The Federal Helium Reserve started holding auctions for a portion of helium sold in 2014. The portion of helium sold at auction is to increase every year until the reserve is depleted to 3 billion cubic feet. The HSA allowed for sales to be equal to the volume available for production from the reserve, an increase over the equal annual volumes mandated in the 1996 legislation.
  - Once the Reserve reaches 3 billion cubic feet, reserve helium will only be sold to qualified Federal users. No sales to private entities will occur, although helium previously stored by private entities in the reserve may be delivered. The estimated date for reaching 3 billion cubic feet is October 2018.

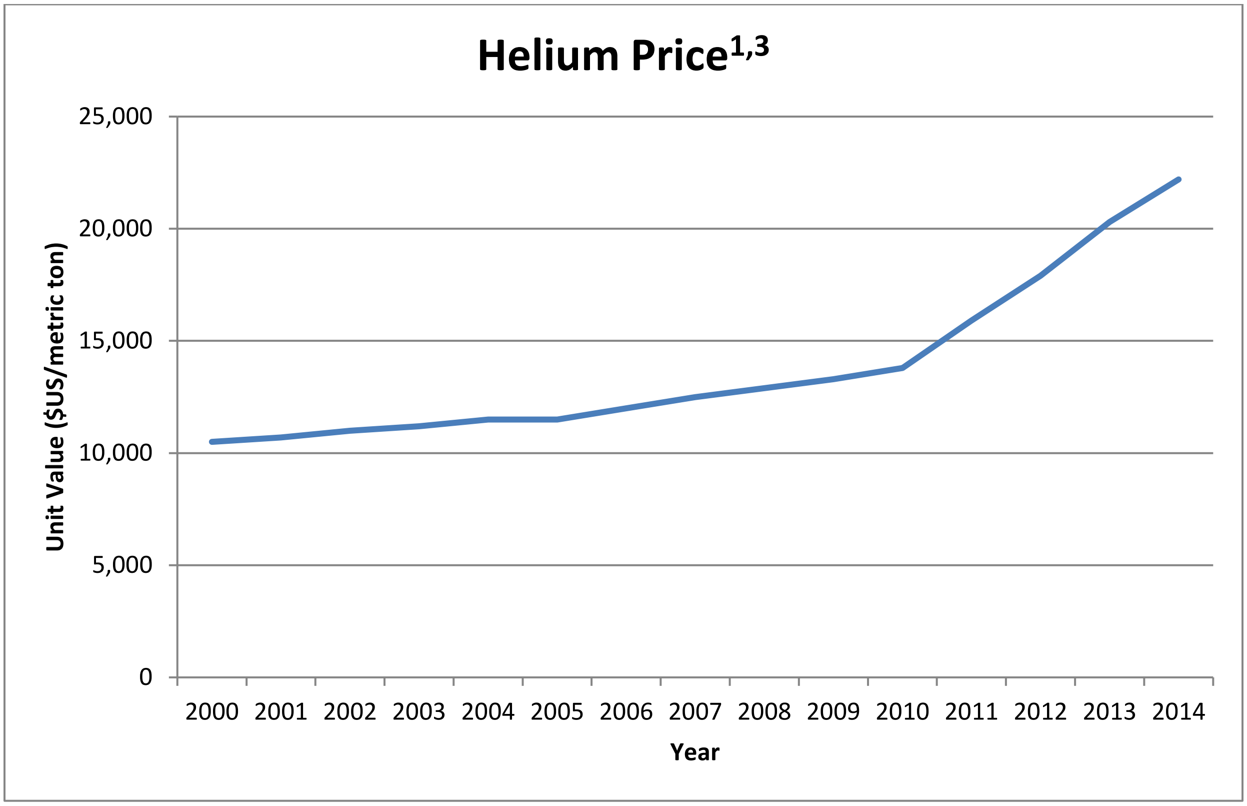


Figure 5-63. Annual average price of helium from 2000 to 2014. Unit value is the average fiscal year price per metric ton of crude helium sold by the U.S. Government.

    - The HSA mandates that all Federal Helium Reserve assets be disposed of no later than September 30, 2021. This includes all underground natural resources, the rights to those resources, and all equipment associated with the Federal Helium Reserve.
  - The eventual shutdown of the Federal Helium Reserve means the market will shift to private enterprise.
    - Until the shutdown, companies with a direct link to the Federal helium pipeline are the only ones who can purchase helium directly from the reserve; other companies must work out a tolling agreement with a connected refiner, which may increase their cost of obtaining helium and discourage increased competition (Cho, 2015).
  - Qatar and Algeria completed expansion of their facilities in 2015.
  - One new helium recovery plant opened in southwest Colorado in 2015.
  - The rise of natural gas production from shale gas (which is low in helium) has undercut production costs for more traditional gas reservoirs (Swearingen, 2013).
  - A large helium discovery in Tanzania is being developed by Helium One and contains a helium resource of 54.2 billion cubic feet. This is the first,

intentionally located helium deposit, and the new exploration technique could lead to further future discoveries (University of Oxford, 2016).

- Current and projected trends for demand and why[1,2,5]
  - Helium is used in a variety of high-tech applications and research; demand is expected to continue to rise.
  - As the Federal Helium Reserve is phased out, demand for imported helium may increase unless domestic companies can increase production.
  - There is uncertainty if the HSA will be the final legislation regarding the Federal Helium Reserve.

- Any influence of these trends that may directly affect the RGFO region[2]
  - There was one producing refined helium plant in the RGFO area as of December, 2016; if the demand for domestic helium increases, it may become profitable for companies to explore that gas field further.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]Kelly and Matos, 2014
[4]Diep, 2012
[5]U.S. BLM Helium Program, 2016

5.10 Construction Materials

The minerals addressed in the following section are largely considered common variety minerals and have local applications and markets. The cost associated with them is primarily related to transport.

5.10.1 Sand and Gravel

- The "usable" characteristics of the material[1,3]
  - Abundant
  - Wide variety of natural shapes and sizes

- What technology/industrial practice it is used for currently[1,3]
  - Concrete aggregates
  - Road base, coverings, and stabilization
  - Asphalt aggregates
  - Construction fill
  - Molded concrete products

    - Filtration
    - Railroad ballast
    - Oil well operations

- What technology/industrial practice it might be used for in the future[1,3]
    - Advanced oil recovery technologies
    - Microbial coated sands for filtering

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Reserves are generally not estimated for construction materials. These materials are generally plentiful and sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances. However, large companies may calculate reserves for their holdings:
        - Martin Marietta Aggregates held sand and gravel reserves of ~563 million tons as of December 31, 2015 (Martin Marietta, 2015).
    - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized, more construction aggregates are needed but there is less land available for resource exploitation. Also, urban areas often do not want aggregate operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

- Local and regional markets and why[1,2]
    - The four largest sand- and gravel-selling States in 2013 were:
        - California (87.9 million tonnes)
        - Texas (78.3 million tonnes)
        - Minnesota (43.6 million tonnes)
        - Colorado (34.5 million tonnes)
    - Sand and gravel are produced in all 50 States. (see Figure 5-64 for U.S. production between 2004 and 2015)
    - In 2013, there were 6,346 sand and gravel operations known in the U.S.
    - Colorado produced 34.5 million tonnes of sand and gravel valued at $US254 million from 260 operations in 2013.
    - There was reported recycling of 19.4 million tonnes of asphalt concrete and 21.2 million tonnes of Portland cement concrete in 2013.
    - U.S. sand and gravel applications in 2015 included: concrete aggregates (45 percent), road base and coverings (25 percent), asphaltic concrete aggregates (13 percent), construction fill (12 percent), 1 percent each to cast concrete products, plaster and gunite sands, and snow and ice control, and 2 percent to other.

- Reasons for demand fluctuations[1,2,6]
    - Sand and gravel are mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building and development. Construction is the main driver for sand and gravel demand.
        - Major construction projects in countries like China and India require importing sand from foreign markets, increasing demand.
    - Price of project-appropriate sand and gravel (Figure 5-65)
    - Use of substitutes such as recycled material or alternative size/composition mixtures if the ideal sand and gravel are not available or too expensive in the local market

- Reasons for market fluctuations[1,2]
    - Availability of sand and/or gravel that meets project-specific needs
    - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving sand and gravel operations farther from the point of sale, affecting price and availability.
    - In the U.S. in 2013, 1,079 operations were reported idle since 2012; despite this, production was up 4 percent.

- Current and projected trends for demand and why[1,2,6]
    - Sand and gravel demands rely heavily on the construction industry, which is tied to overall economic growth. With the ongoing construction, demand is expected to increase.
    - The Highway Trust Fund distributes funding for highway construction, and rulings by Congress may affect the amount of money going into the fund and the disbursements from it, thereby affecting the amount of road construction States may perform.
- Any influence of these trends that may directly affect the RGFO region[5]
    - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for sand and gravel will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand.

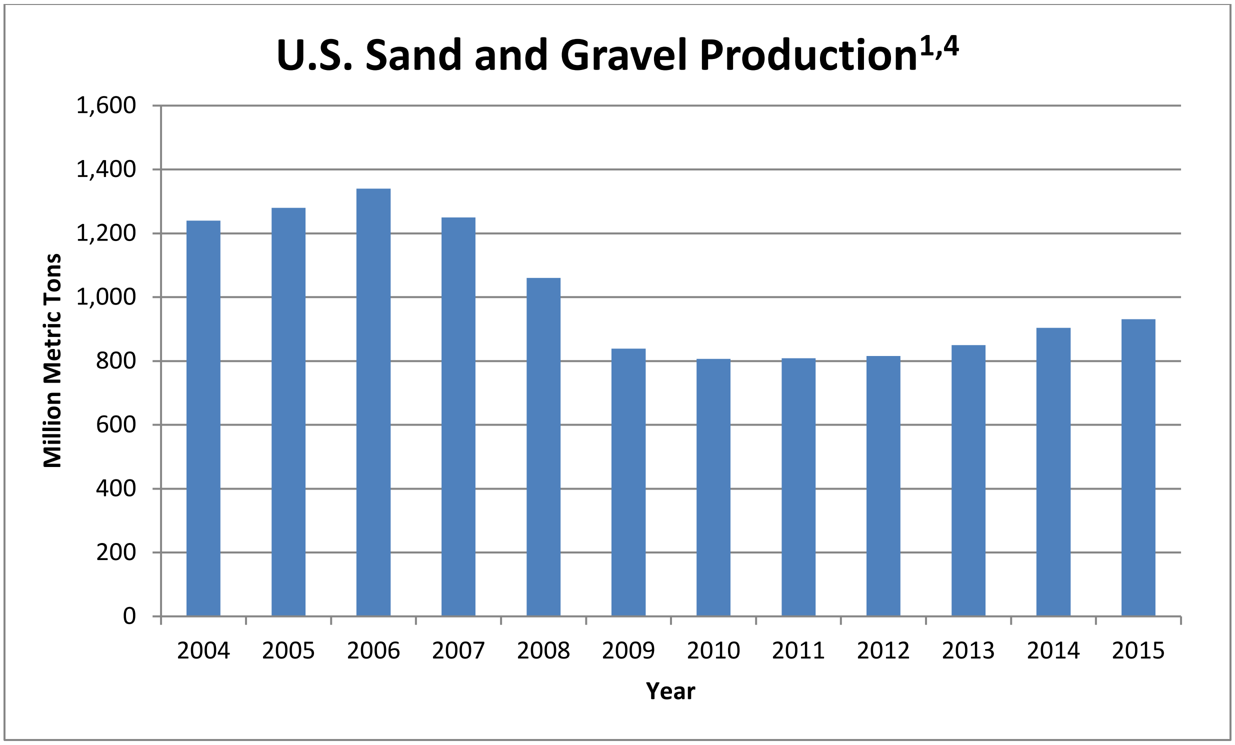


Figure 5-64. Annual U.S. sand and gravel production from 2004 to 2015.

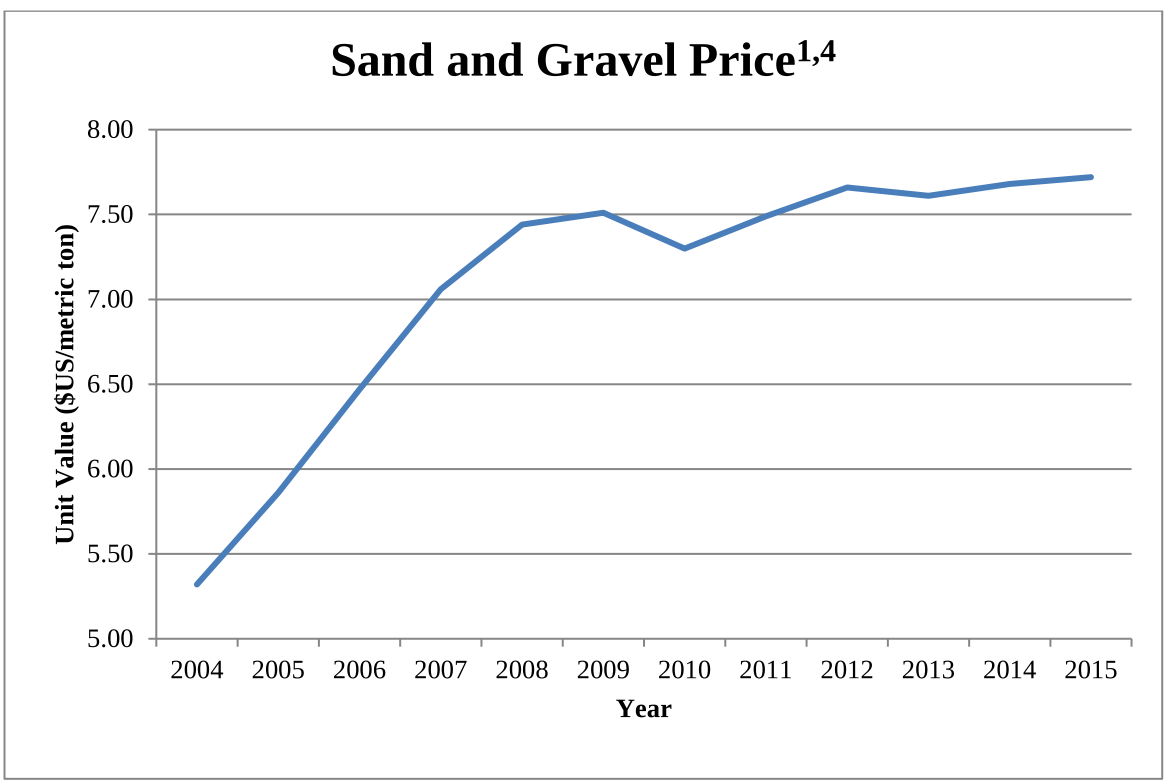


Figure 5-65. Annual average price of sand and gravel from 2004 to 2015.

    - As resources are depleted in the Front Range, sand and gravel from other areas of the RGFO region may become economically viable if demand remains high and prices increase.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]U.S. CB, 2016
[6]Rayasam, 2016

5.10.2 Crushed Stone Aggregate

- The "usable" characteristics of the material[1,3]
    - Abundant
    - Wide variety of natural shapes, colors and sizes

- What technology/industrial practice it is used for currently[1,3]
    - Road construction and maintenance
    - Cement manufacturing
    - Lime manufacturing
    - Chemical uses
    - Agricultural uses

- What technology/industrial practice it might be used for in the future[6,7]
    - High strength concrete
    - Shoreline erosion control
    - 3D concrete printing

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - National reserves are generally not estimated for construction materials. These materials are generally plentiful and sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances. However, large companies may calculate reserves for their holdings:
        - Martin Marietta Aggregates held hard rock reserves of ~15 billion tons as of December 31, 2015 (Martin Marietta, 2015).
        - Vulcan Materials reported 15.7 billion tons of permitted and proven or probable aggregates reserves in 2015 (Vulcan, 2015).
    - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized, more construction aggregates are needed but there is less land

available for resource exploitation. Also, urban areas often do not want aggregate operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

- Local and regional markets and why[1,2]
  - Annual U.S. crushed stone aggregate production is depicted in Figure 5-66.
  - The four largest aggregate selling States in 2014 were:
    - Texas (152 million tonnes)
    - Pennsylvania (81.1 million tonnes)
    - Missouri (68.8 million tonnes)
    - Florida (57.2 million tonnes)
  - Crushed stone was produced in all States except Delaware in 2014.
  - In 2014, there were 1,433 companies with 3,582 crushed stone operations known in the U.S.
  - Colorado produced 12.9 million tonnes of crushed stone aggregate from 44 operations and 239 quarries in 2014:

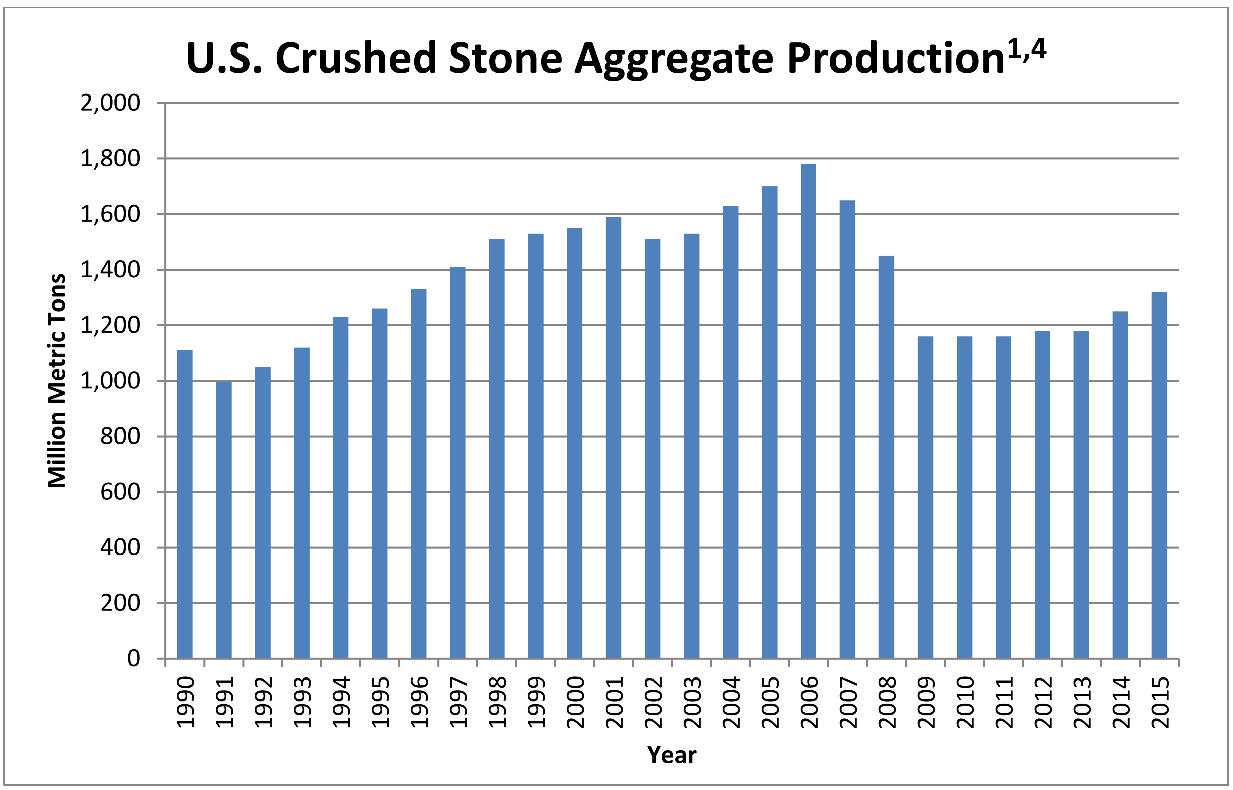


Figure 5-66. Annual U.S. production of crushed stone aggregate from 1990 to 2015.

        - Limestone: 805,000 tonnes
        - Dolomite: 31,000 tonnes
        - Marble: 45,000 tonnes
        - Granite: 5.7 million tonnes
        - Traprock: 1,000 tonnes
        - Sandstone and quartzite: (withheld)
        - Volcanic cinder and scoria: (withheld)
        - Miscellaneous stone: 6.26 million tonnes
    - There was reported recycling of 19.9 million tonnes of asphalt concrete and 21.8 million tonnes of Portland cement concrete in 2014.
    - U.S. crushed stone aggregate applications in 2015 included: construction material (76 percent), cement manufacturing (11 percent), lime manufacturing (7 percent), chemical and special uses (4 percent), and agricultural uses (2 percent).
    - In 2015, U.S. crushed stone aggregate source rocks included: limestone and dolomite (70 percent), granite (13 percent), traprock (6 percent), sandstone and quartzite (4 percent), volcanic cinder and scoria (0.3 percent), slate (0.15 percent), and miscellaneous stone.

- Reasons for demand fluctuations[1,2]
    - Crushed stone aggregates are mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building and road development. Construction and road building are the main drivers for crushed stone aggregate demand.
    - Price of project-appropriate crushed stone aggregate (Figure 5-67)
    - Use of substitutes such as recycled material or alternative size/composition mixtures if the ideal crushed stone is not available or too expensive in the local market

- Reasons for market fluctuations[1,2]
    - Availability of crushed stone aggregate that meets project-specific needs
    - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving quarry operations farther from the point of sale, affecting price and availability.
    - In the U.S. in 2014, 259 operations were reported idle, and 269 were reported closed since 2013; despite this, production was up 5 percent.

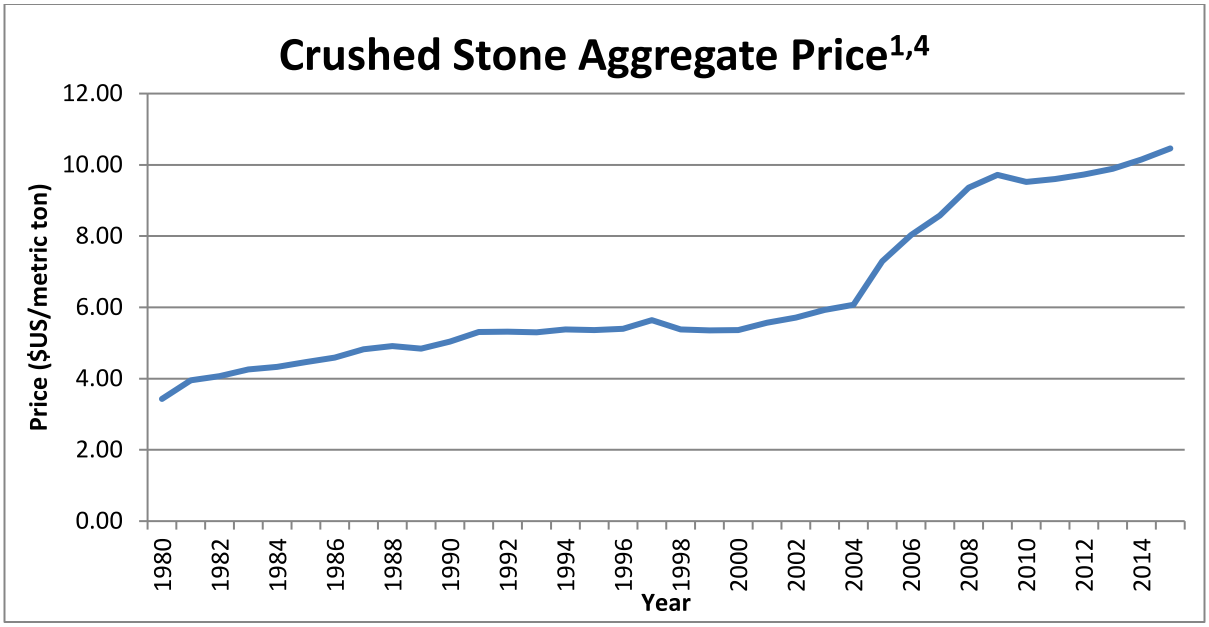


Figure 5-67. Annual average price of crushed stone aggregate from 1980 to 2015.

- Current and projected trends for demand and why[1,2]
  - Crushed stone aggregate demand relies heavily on the construction industry, which is tied to overall economic growth. With ongoing construction, demand is expected to increase.
  - The Highway Trust Fund distributes funding for highway construction, and rulings by Congress may affect the amount of money going into the fund and the disbursements from it, thereby affecting the amount of road construction States may perform.

- Any influence of these trends that may directly affect the RGFO region[5]
  - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for crushed stone aggregate will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for both construction and road building uses.
  - As resources are depleted in the Front Range, crushed stone aggregate from other areas of the RGFO may become economically viable if demand remains high and prices increase.
  - The RGFO region contains specialty aggregate for use in concrete railroad ties. There is also aggregate in the RGFO area that could be used as railroad ballast. Freight railroads invested about US$ 27 billion in 2015 for infrastructure improvement, and the railroad industry could be a large growth market for

specific types of crushed stone aggregate as both freight and passenger rail lines expand or are refurbished (ASCE, 2017).

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]U.S. CB, 2016
[6]LafargeHolcim, 2016
[7]CEMEX, 2016

5.10.3 Lightweight Aggregate

- Lightweight aggregates may be natural or manufactured. Natural varieties include perlite, pumice (pumicite), and vermiculite (scoria is also natural, but is included in the Crushed Stone Aggregate section (5.10.2)). Manufactured varieties include ceramics created by kiln heating shale, slate, and clay (these products are not tallied separately by the USGS, and production may be counted as crushed stone aggregate or clay).

- The "usable" characteristics of the material[1,3]
    - Relatively abundant
    - Wide variety of natural shapes, colors and sizes
    - Low density (large volume with low mass)

- What technology/industrial practice it is used for currently[1,3]
    - Lightweight concrete masonry and structural lightweight concrete
    - Agricultural uses
    - Horticultural uses (specialty soils)
    - Insulation
    - Construction fillers
    - Filter aids

- What technology/industrial practice it might be used for in the future[1,5,6]
    - High strength, lightweight concrete
    - Designer soils (e.g., for rooftop gardens)

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Worldwide reserves or resources of natural lightweight aggregates are estimated at 185 million tonnes of perlite, 25 million tons of pumice (few countries reported reserves), and 47 million tonnes of vermiculite in 2016.
    - U.S. reserves of natural lightweight aggregates included ~50 million tonnes of perlite, at least 25 million tons of pumice, and at least 25 million tonnes of vermiculite in 2016.

- Local and regional markets and why[1,2]
    - World production of natural lightweight aggregates is depicted in Figure 5-68
    - The four largest perlite-producing countries in 2015 were:
        - Turkey (1.1 million tonnes)
        - Greece (700,000 tonnes)
        - U.S. (483,000 tonnes)
        - Japan (200,000 tonnes)
    - The four largest pumice producing countries in 2015 were:
        - Turkey (5.5 million tonnes)
        - Italy (4 million tonnes)
        - Greece (1.2 million tonnes)
        - Ecuador (1.1 million tonnes)
    - The four largest vermiculite producing countries in 2015 were (in descending order, of those reported):
        - South Africa (160,000 tonnes)
        - U.S. (100,000 tonnes)
        - Brazil (70,000 tonnes)
        - Zimbabwe (40,000 tonnes)
    - North Carolina was the largest slate producer with 688 thousand tonnes; Wyoming was the largest volcanic cinder and scoria producer with 1.93 million tonnes.
    - Perlite was produced in ~14 countries, pumice was produced in ~28 countries, and vermiculite was produced in ~12 countries; deposits are unequally distributed with perlite and pumice being common in volcanic terrains and vermiculite occurring as an alteration product in intrusive rocks or other geologic settings.
    - In 2015, New Mexico was the top U.S. producer of perlite, Oregon was the top producer of pumice, and South Carolina and Virginia were the only producers of vermiculite.
    - There was no reported recycling of natural lightweight aggregates in 2015.

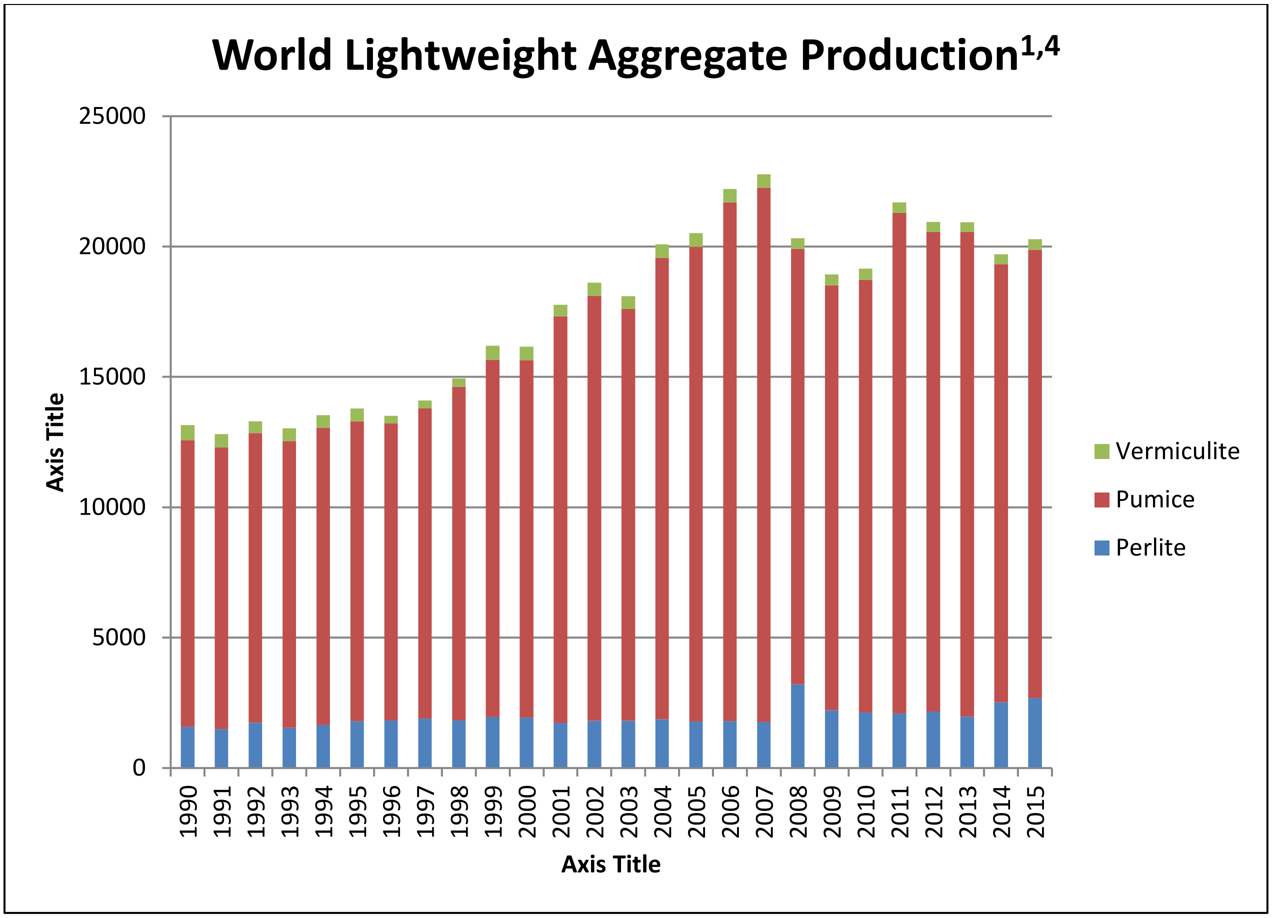


Figure 5-68. Annual world production of natural lightweight aggregate from 1990 to 2015.

- In the U.S. in 2015: 51 percent of perlite went to construction products, 19 percent to horticultural aggregates, 15 percent to fillers, 10 percent to filtering aids, and 5 percent to specialty insulation and miscellaneous uses. About 47 percent of pumice went to construction building block, 23 percent to horticultural purposes, and the rest to abrasives, concrete mixtures, and other miscellaneous uses. About 50 percent of vermiculite went to agriculture/horticulture, 10 percent to lightweight concrete aggregates, 5 percent to insulation, and 35 percent to other uses.

- Reasons for demand fluctuations[1,2]
  - Lightweight aggregates are mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building and road development. Construction and road building are the main drivers for lightweight aggregate demand.
  - Price of project-appropriate lightweight aggregates (Figure 5-69)
  - Use of substitutes, mostly manufactured varieties for natural aggregates

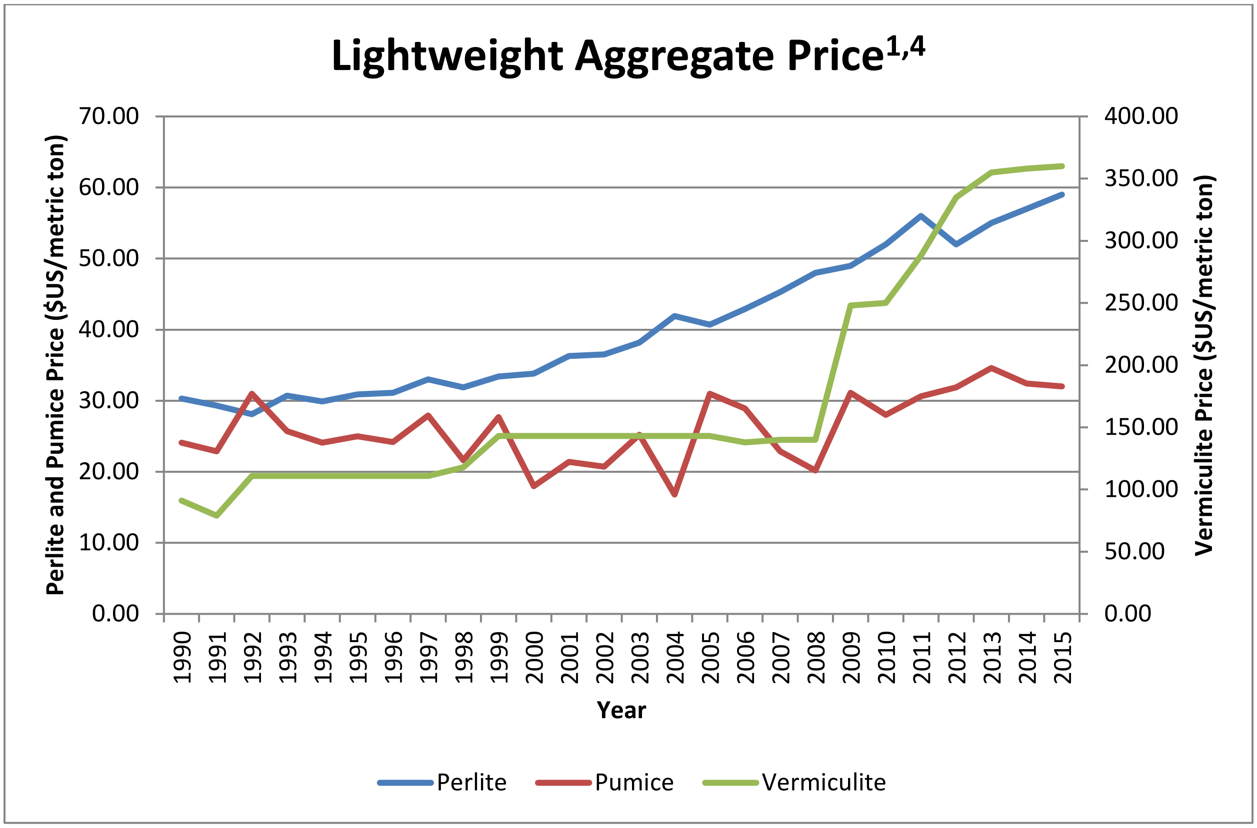


Figure 5-69. Annual average price of natural lightweight aggregate from 1990 to 2015.

- Reasons for market fluctuations[1,2]
  - Availability of lightweight aggregate that meets project-specific needs
  - Current vermiculite production is trending towards finer-grained products, but demand is for coarser, premium products.
    - South Africa has experienced grade constraints and lower recovery rates from its main vermiculite mine, leading to fine and superfine grading material.
    - The Namekara mine in Uganda had been on care-and-maintenance as part of a debt settlement. This mine, with significant resources of medium- and coarse-grained material, was purchased by Black Mountain Resources in February 2016 and is projected to return to 30,000 t/year production in the near future (Swanepoel, 2016).
  - China is a large exporter (and therefore producer) of perlite and vermiculite, but does not generally report production. This presents a large unknown factor in worldwide market share and supply.

  - Although there is domestic production of perlite and pumice, the U.S. imports about 20 percent of its consumption needs, mainly from Greece. Ongoing political instability could have an effect on import reliability.
  - The western U.S. has seen a number of legal challenges and public land designations that could reduce access to pumice deposits. If production becomes more expensive due to mining or transportation costs, domestic pumice could be replaced by imports or substitutes.

- Current and projected trends for demand and why[1,2,5]
  - Lightweight aggregate demand, both natural and manufactured, relies heavily on the construction industry, which is tied to overall economic growth. With ongoing construction, demand is expected to increase.
  - Natural lightweight aggregates are used in horticulture, and demand may increase as cities or individuals invest in rooftop gardens to reduce the heat island effect.

- Any influence of these trends that may directly affect the RGFO region[1,2,5,7]
  - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for lightweight aggregate will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for both construction and road building uses.
  - As resources are depleted in the Front Range, lightweight aggregate from other areas of the RGFO region may become economically viable if demand remains high and prices increase.
    - There was one manufactured lightweight aggregate mine and production facility in the RGFO area in December 2016, located on the Boulder-Jefferson county line on Hwy 93 (on private land). If demand increases, the company may need to find new source material.
    - There are resources of natural lightweight aggregates in association with volcanics in the RGFO region in Park, Chaffee, and Fremont Counties that could become economically viable if demand and prices increase.

Summarized from:

[1]USGS MCS, 2016
[2]USGS MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]ESCSI, 2016
[6]U.S. EPA, 2016b
[7]U.S. CB, 2016

5.10.4 Clay

- The USGS categorizes six types of clay: ball clay, bentonite, fire clay, kaolin, common clay, and fuller's earth. They are distinguished by composition, plasticity, color, adsorption qualities, firing characteristics, and clarification properties.

- The "usable" characteristics of the material[1,3]
    - Abundant
    - Wide variety of colors
    - Refractory (resistant to heat after firing)
    - Absorbent (particularly bentonite and Fuller's Earth)

- What technology/industrial practice it is used for currently[1,3]
    - Ceramic tiles, dishes, and other ceramic products
    - Sanitaryware
    - Absorbents
    - Drilling mud
    - Bricks and construction products
    - Iron pelletizing
    - Portland cement clinker
    - Paper making

- What technology/industrial practice it might be used for in the future[1,3,5]
    - Nanoclays
    - High-tech ceramics
    - Clay masonry products can contribute to "green" buildings and be used to earn LEED points on new construction

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
    - Reserves are generally not estimated for construction materials, including clay. These materials are generally plentiful and sourced as needed close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances.
    - Reserves are influenced by land use, environmental concerns, and price. As more land is urbanized, more construction aggregates like clay are needed, but there is less land available for resource exploitation. Also, urban areas often do not want aggregate operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

- Worldwide, Local and regional markets and why[1,2]
    - The four largest bentonite clay producing countries in 2015 were:
        - United States (4.32 million tonnes) (Figure 5-70)
        - China (3.5 million tonnes)
        - Greece (1.3 million tonnes)
        - India (1.08 million tonnes)
    - The four largest kaolin clay producing countries in 2015 were (in descending order):
        - United States (6.16 million tonnes) (Figure 5-70)
        - India (4.48 million tonnes)
        - China (3.3 million tonnes)
        - Czech Republic (3.3 million tonnes)
    - Bentonite is produced in ~45 countries, Fuller's earth was produced in ~10 countries, and kaolin was produced in ~50 countries; deposits are unequally distributed, as clays are generally the weathering product of feldspar and phyllosilicates.
    - In 2013, Georgia was the top total producer of clays followed by Wyoming.
    - There was no reported recycling of clays in 2015.
    - Colorado produced 234,000 tonnes of total clay in 2013, of which 228,000 tonnes were common clay.
    - In the U.S. in 2015, 41 percent of ball clay went to floor and wall tile and 18 percent to sanitaryware; 32 percent of bentonite went to drilling mud, 29 percent to pet waste absorbents, and 10 percent each to foundry sand and iron ore pelletizing; 42 percent of common clay went to brick, 28 percent to cement, and 20 percent to lightweight aggregate; 51 percent of fire clay went to refractory and miscellaneous products and 49 percent to heavy clay products; 69 percent of fuller's earth went to pet waste absorbent; 45 percent of kaolin went to paper coating and filling.

- Reasons for demand fluctuations[1,2]
    - Clays are consumed by the construction and building industry, and demand relies on economic conditions that promote residential and commercial building and road development. Construction is a major driver for clay demand.
    - Bentonite is used as drilling mud, usually in traditionally drilled holes; with the rise of hydraulic fracturing and horizontal drilling and the fluctuation in total drilling, bentonite demand has decreased slightly.

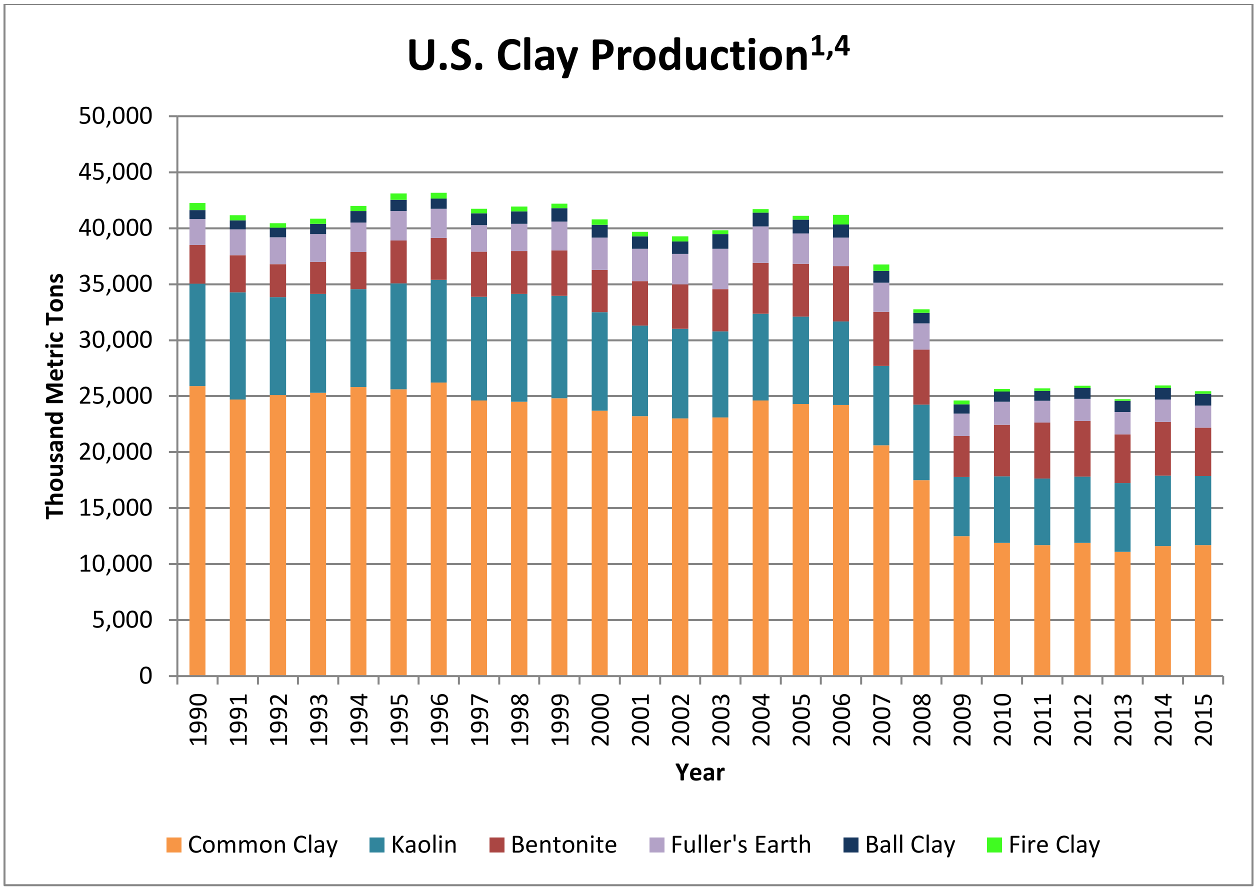


Figure 5-70. Annual U.S. production of clay from 1990 to 2015.

- o Bentonite is used to pelletize iron ore and as foundry sand. Both of these applications rely on the steel and automotive industries, and demand for bentonite will at least somewhat follow the trend for these industries.
- o The paper production industry is the lead consumer of kaolin, and as more information is exchanged electronically demand may decrease with decreased paper production.
- o Price of project-appropriate clay (Figure 5-71)
- o Use of substitutes such as brick siding alternatives, calcium carbonate fillers, and specialized polymers may decrease clay demand

- Reasons for market fluctuations[1,2]
  - o Availability of clay that meets project-specific needs
  - o Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving quarry operations farther from the point of sale, affecting price and availability.

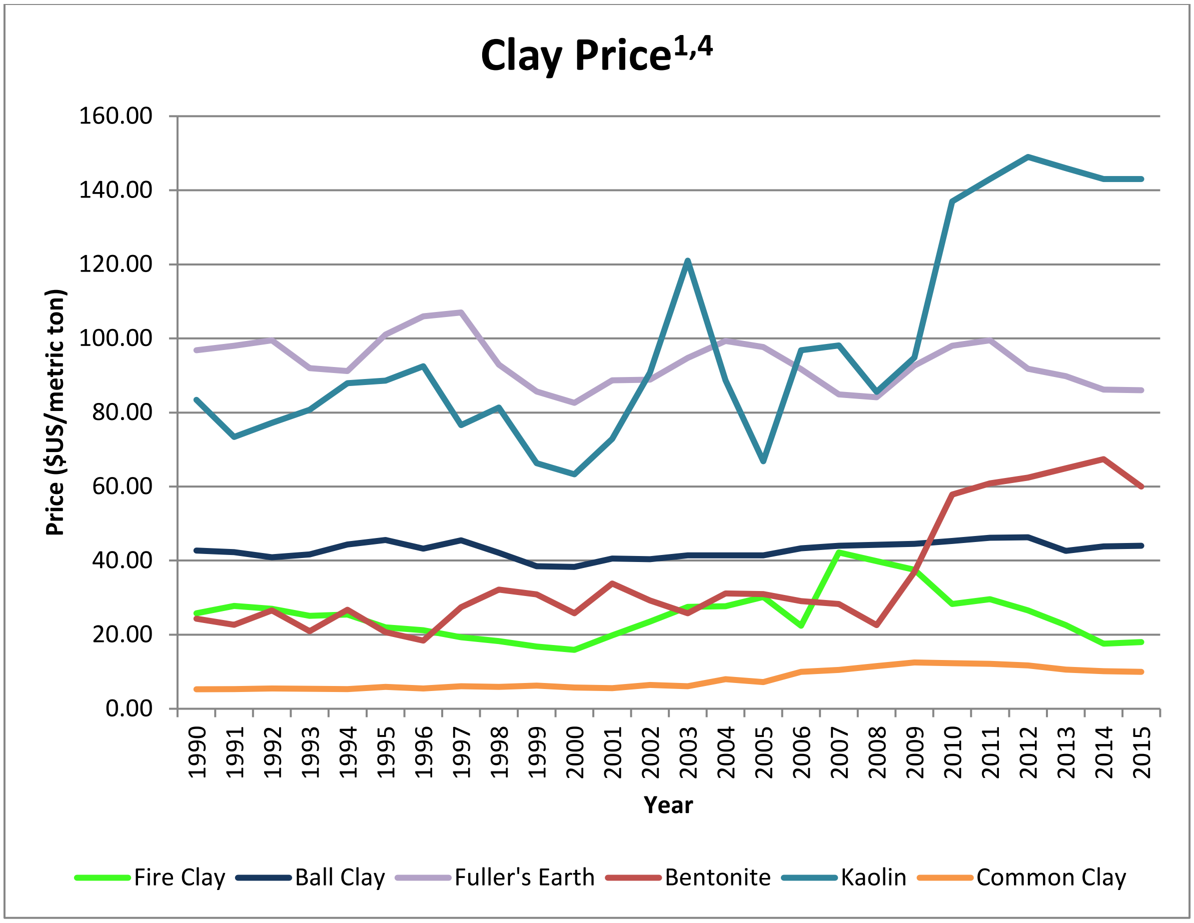


Figure 5-71. Annual average price of clay from 1990 to 2015.

- Current and projected trends for demand and why[1,2,5]
  - Clay demand relies heavily on the construction industry, which is tied to overall economic growth. With ongoing construction, demand is expected to increase.
  - Bentonite demand is tied to the drilling industry, and demand will fluctuate depending on government policy and public demand for oil and gas.
  - As buildings are designed to be more “green”, clay masonry products that contribute to environmentally friendly buildings may increase in demand.

- Any influence of these trends that may directly affect the RGFO region[5,6]
  - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for clay will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for construction use.

- As resources are depleted in the Front Range, clay from other areas of the RGFO region may become economically viable if demand remains high and prices increase.
- The RGFO contains specialty clays that can be used for custom masonry products. Products with specific colors, appearances, or environmental efficiency properties are likely to be in demand for new construction projects.

Summarized from:
[1]USGS MCS, 2016
[2]USGS MYB, 2013
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]Summit, 2016
[6]U.S. CB, 2016

5.10.5 Dimension and Building Stone

- The "usable" characteristics of the material[1,3]
  - Abundant
  - Wide variety of natural shapes, colors and sizes
  - Durability
  - Ability to be polished

- What technology/industrial practice it is used for currently[1,3]
  - Building and construction
  - Landscaping
  - Curbing
  - Flagging
  - Monuments or memorials

- What technology/industrial practice it might be used for in the future[5]
  - Used as part of green building initiatives

- Local, regional and worldwide reserves—both in the ground and stockpiled[1,2]
  - Reserves are generally not estimated for construction materials, such as dimension and building stone. These materials are generally plentiful and are sourced as needed, close to their destination, as they do not usually have a high enough unit value to warrant long shipping distances.
  - Reserves are influenced by land use, environmental concerns, and price. As more buildings are constructed or refurbished, more dimension stone is needed, but

there is less land available for resource exploitation. Also, urban areas often do not want quarry operations nearby; this forces operations further from the point of sale, increasing price. The market then achieves a balance between prices consumers are willing to pay and the material available at that price, creating reserves at those market conditions.

    - Certain dimension and building stone types are specialty products and can fetch a high enough price (or have low enough production costs) to warrant long shipping distances. The U.S. imports about 80 percent of consumed dimension stone, mostly from China and Brazil. These countries do not report reserves, but seem to have a steady supply of material at current production rates.

- Local and regional markets and why[1,2]
    - The four largest dimension stone-producing countries in 2013 were:
        - China
        - Turkey
        - India
        - Iran
    - U.S. production of dimension stone from 1990 to 2015 is depicted in Figure 5-72.
    - In 2014, there were 293 dimension stone operations known in the U.S.
    - The top producing States for dimension stone in 2014 were:
        - Granite: Massachusetts and Georgia
        - Limestone: Texas, Indiana, Wisconsin, Kansas, and Tennessee
        - Marble: Tennessee, Vermont, Georgia, and Colorado
        - Sandstone: Texas, Arizona, New York, Pennsylvania, and Oklahoma
        - Slate: Vermont, Idaho, and Pennsylvania
    - Colorado produced 17,300 tonnes of dimension stone in 2014, including 10,100 tonnes of sandstone.
    - There was a small amount of recycling of dimension stone, mostly in building restorations or refurbishments.
    - In the U.S. in 2015, 58 percent of dimension stone went to building and construction and 27 percent was used as irregularly shaped stone. About 44 percent of dressed (cut) stone was sold as partially squared pieces, 20 percent as curbing, and 11 percent as flagging.
    - Of the total domestic dimension and building stone produced in 2015, about 42 percent was limestone, 21 percent was granite, 17 percent was sandstone, 16 percent was miscellaneous stone, 2 percent was marble, and 2 percent was slate.

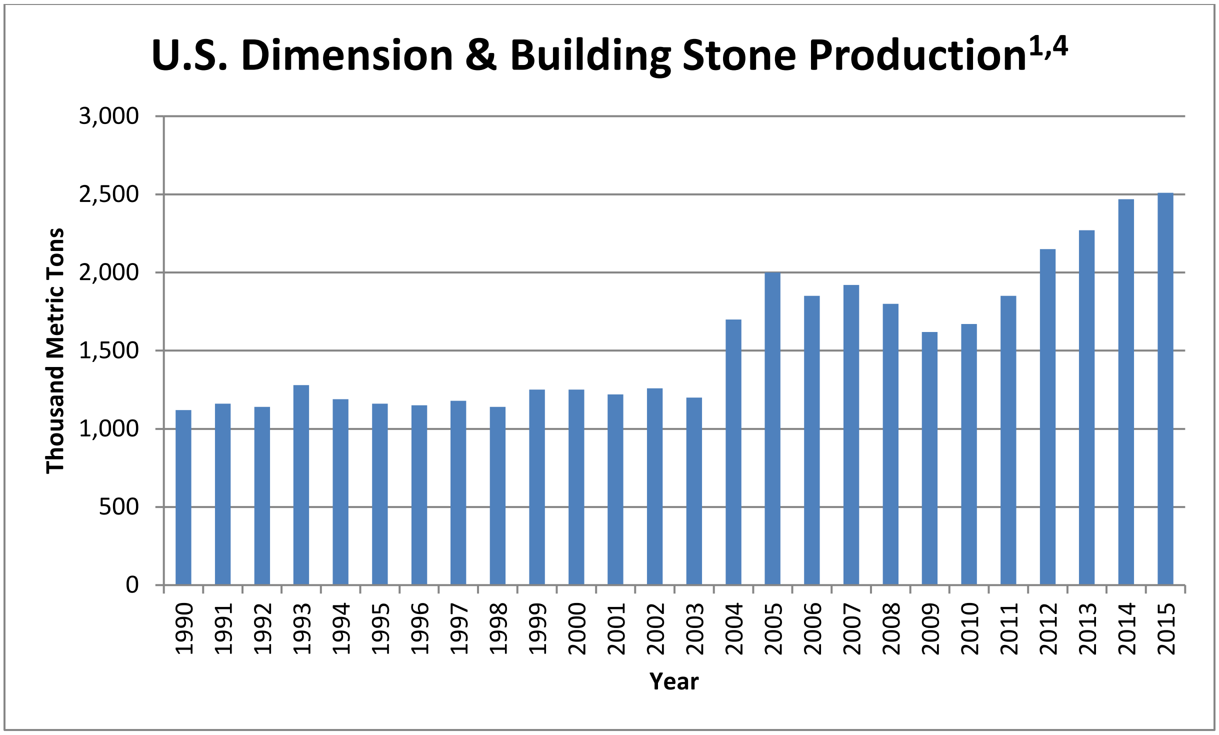


Figure 5-72. Annual U.S. production of dimension and building stone from 1990 to 2015.

- Reasons for demand fluctuations[1,2]
    - Dimension stone is mainly consumed by the construction industry, and demand relies on economic conditions that promote residential and commercial building development. Construction is the main driver for dimension and building stone demand.
    - Price of project-appropriate dimension stone (Figure 5-73)
    - Use of substitutes such as brick or manufactured stone

- Reasons for market fluctuations[1,2]
    - Availability of dimension stone that meets project-specific needs
    - Increasing concern about environmental and visual impacts are reducing the number of operations and/or driving quarries farther from the point of sale, affecting price and availability.
    - In February 2014, Indiana Limestone Company filed for bankruptcy. Production was interrupted during proceedings, but a year later the new owners had invested in new equipment, and production was up to double the 2013 pre-bankruptcy output (ILC, 2015).

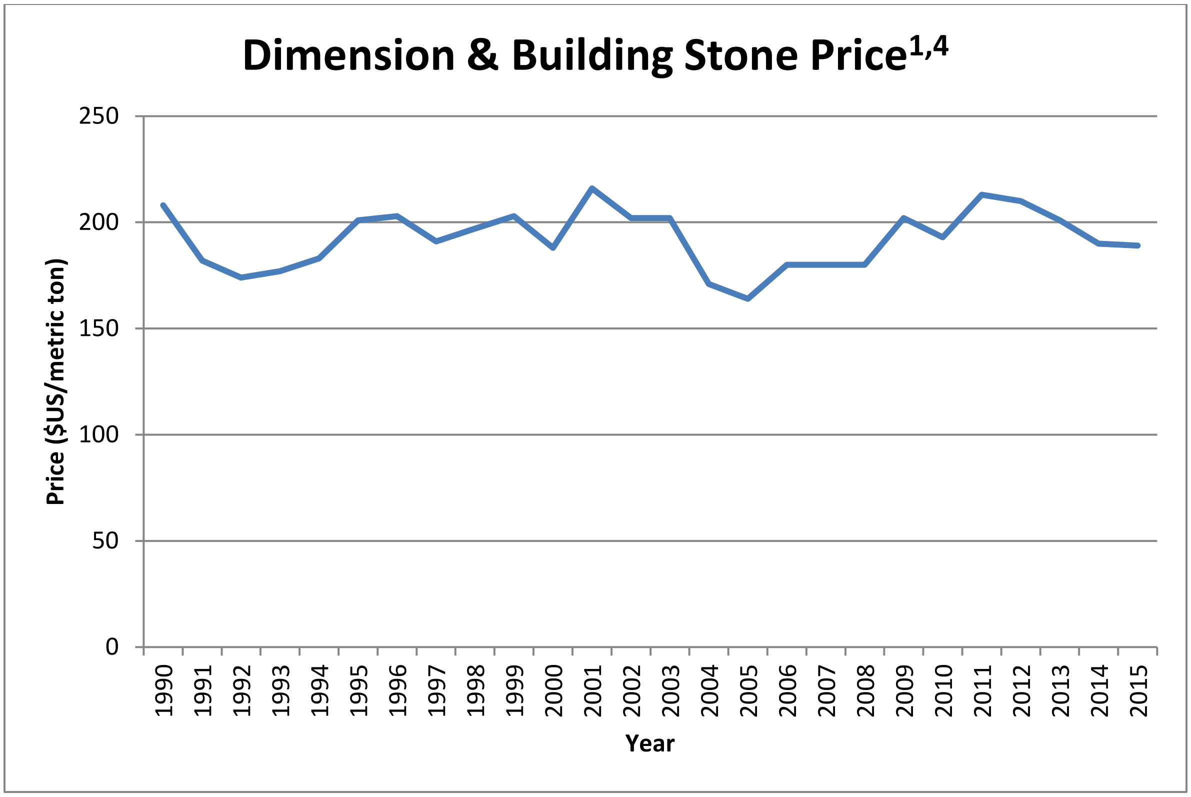


Figure 5-73. Annual average price of dimension and building stone from 1990 to 2015.

- Current and projected trends for demand and why[1,2,5]
    - Dimension and building stone demand relies heavily on the construction industry, which is tied to overall economic growth. With ongoing construction, demand is expected to increase.
    - There is a large focus to make new buildings more environmentally friendly, and dimension stone can be used as part of a plan to increase building sustainability through the LEED rating system. This may increase demand for certain dimension and building stone products.

- Any influence of these trends that may directly affect the RGFO region[1,2,6]
    - Colorado is one of the fastest growing States, with population increasing ~8.1 percent between 2010 and 2015. Demand for dimension and building stone will continue to increase, particularly in the Front Range: ~8100 housing units were constructed in the Denver Metro area between 2013 and 2014, and this number will likely continue or increase annually, leading to increased demand for both construction and road building uses.
    - Dimension and building stone quarries in the RGFO region in 2016 consisted mainly of sandstone, either the Lyons or Dakota Sandstones. These formations are likely to remain in demand for landscaping and flagging. There is also granite

in the RGFO region that has been quarried for monuments, and could become desirable for building purposes.

Summarized from:
[1]USGS MCS, 2016
[2]USGC MYB, 2014
[3]MEC, 2016
[4]Kelly and Matos, 2014
[5]NSC, 2016
[6]U.S. CB, 2016

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7. MAPS OF MINERAL OCCURRENCE POTENTIAL

The methodology for assigning the occurrence potential of each mineral, as well as the certainty level, is described in section 1.3, MPR Methodology, and section 3, Description of Energy and Mineral Resources. The mineral occurrence potential maps provide an intermediate level of detail for mineral resource occurrences in all lands within the RGFO management area regardless of the surface ownership. The assigned mineral occurrence potentials and the levels of certainty depicted on the maps are based on the *Mineral Potential Classification System* found in BLM Manual 3031, as described below.

I. Level of Potential

L. The geologic environment and the inferred geologic processes indicate low potential for accumulation of mineral resources.

M. The geologic environment, the inferred geologic processes, and the reported mineral occurrences or valid geochemical/geophysical anomaly indicate moderate potential for accumulation of mineral resources.

H. The geologic environment, the inferred geologic processes, the reported mineral occurrences and/or valid geochemical/geophysical anomaly, and the known mines or deposits indicate high potential for accumulation of mineral resources. The “known mines and deposits” do not have to be within the area that is being classified, but have to be within the same type of geologic environment.

II. Level of Certainty

A. The available data are insufficient and/or cannot be considered as direct or indirect evidence to support or refute the possible existence of mineral resources within the respective area.

B. The available data provide indirect evidence to support or refute the possible existence of mineral resources.

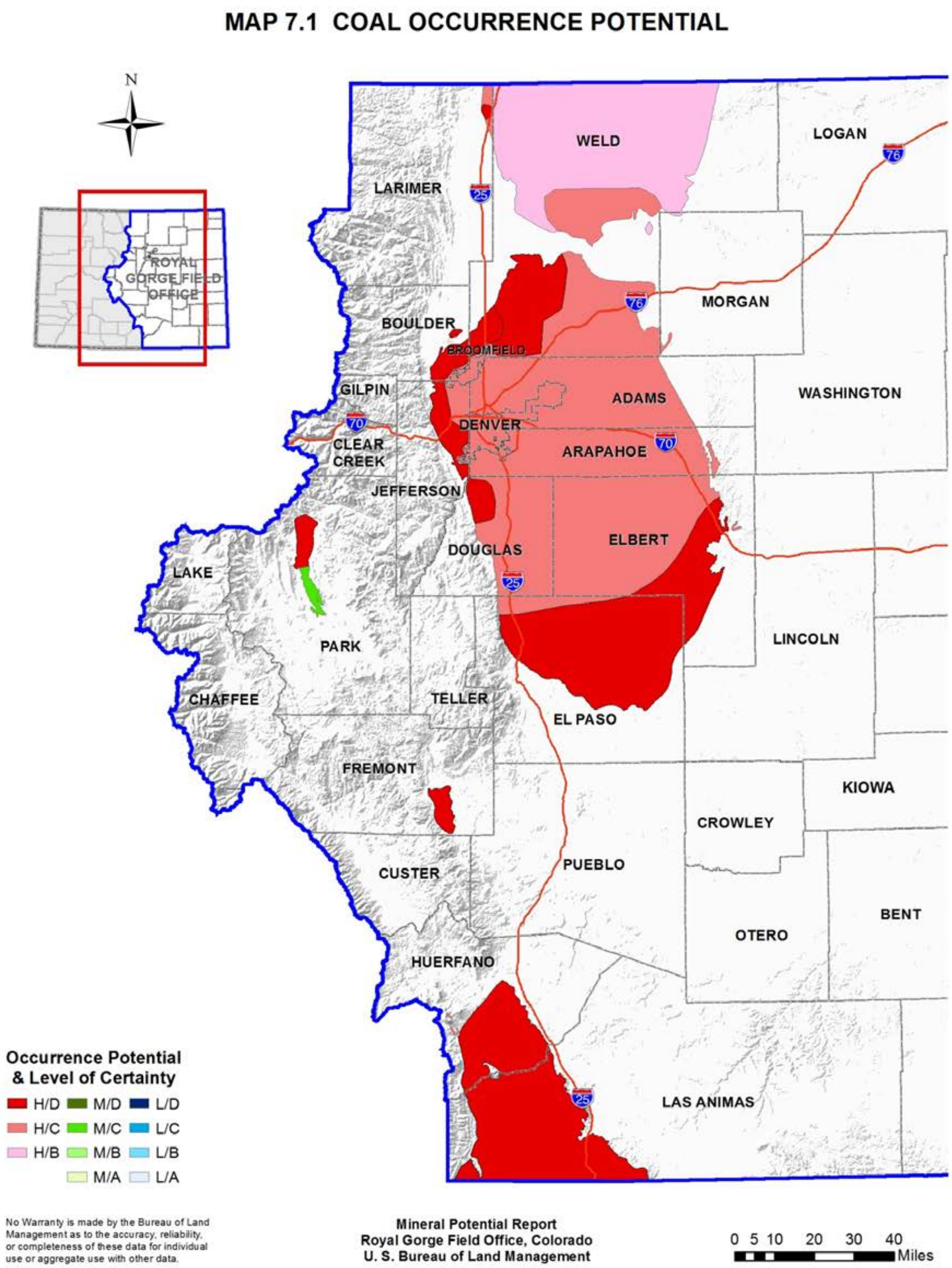
C. The available data provide direct evidence but are quantitatively minimal to support or refute the possible existence of mineral resources.

D. The available data provide abundant direct and indirect evidence to support or refute the possible existence of mineral resources.

As used in this classification, potential refers to potential for the presence (occurrence) of a *concentration* of one or more energy and/or mineral resources. It does not refer to or imply potential for development and/or extraction of the mineral resource(s). It does not imply that the potential concentration is or may be economic, that is, could be extracted profitably. These maps only depict color-coded areas with mineral potential ratings determined to be low (L), moderate

(M), or high (H). Areas of the RGFO region considered to have undetermined or no potential are not included in the color-coding scheme and are displayed only as white or shades of gray associated with topographic relief within the background on individual mineral commodity maps.

7.1 Coal


MAP 7.1 COAL OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
WELD
LOGAN
LARIMER
MORGAN
BOULDER
BROOMFIELD
GILPIN
ADAMS
WASHINGTON
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
ELBERT
DOUGLAS
LAKE
PARK
LINCOLN
CHAFFEE
TELLER
EL PASO
FREMONT
KIOWA
CROWLEY
CUSTER
PUEBLO
BENT
OTERO
HUERFANO
LAS ANIMAS
25
76
70
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
No Warranty is made by the Bureau of Land Management as to the accuracy, reliability, or completeness of these data for individual use or aggregate use with other data.
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U. S. Bureau of Land Management
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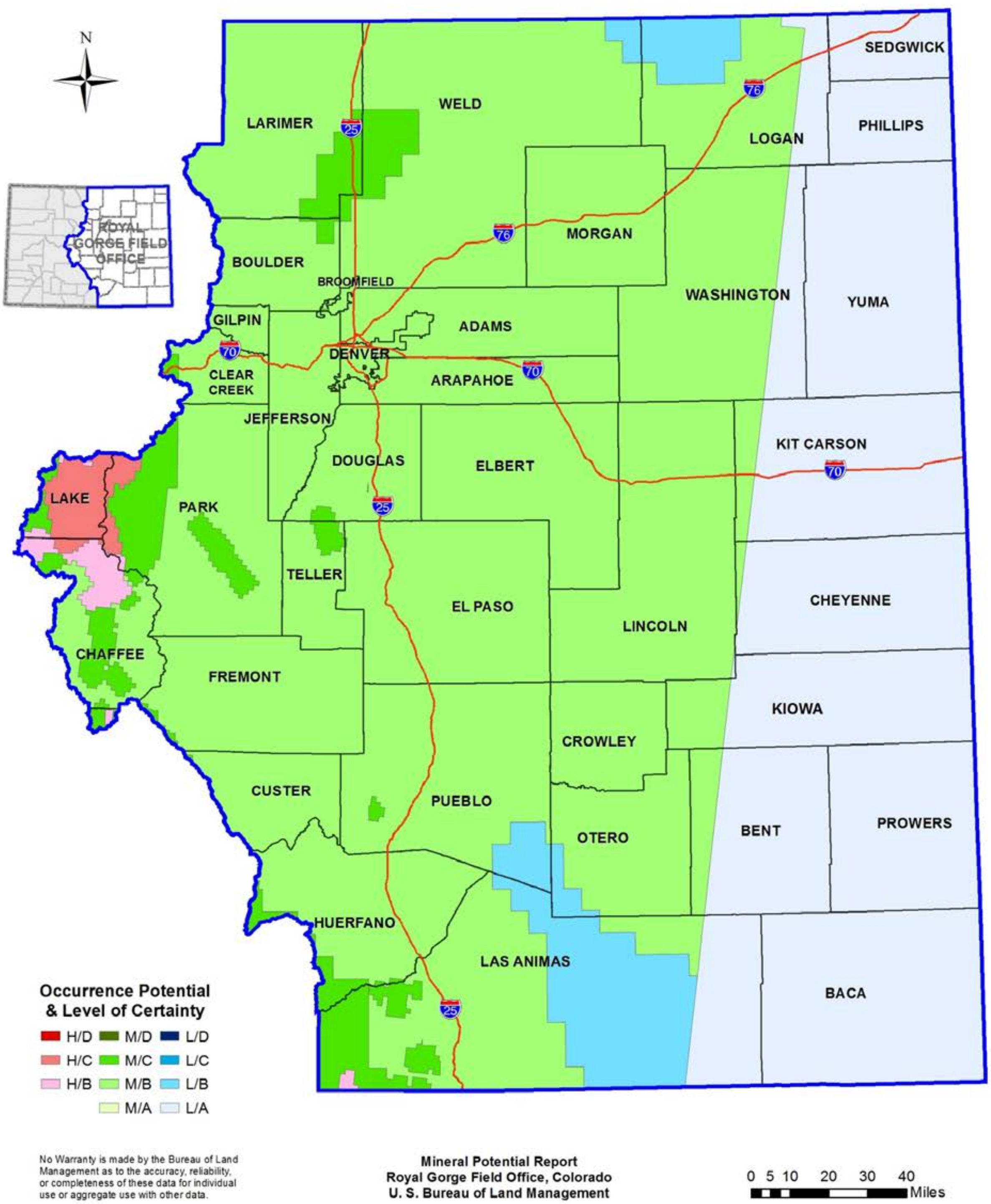
Miles

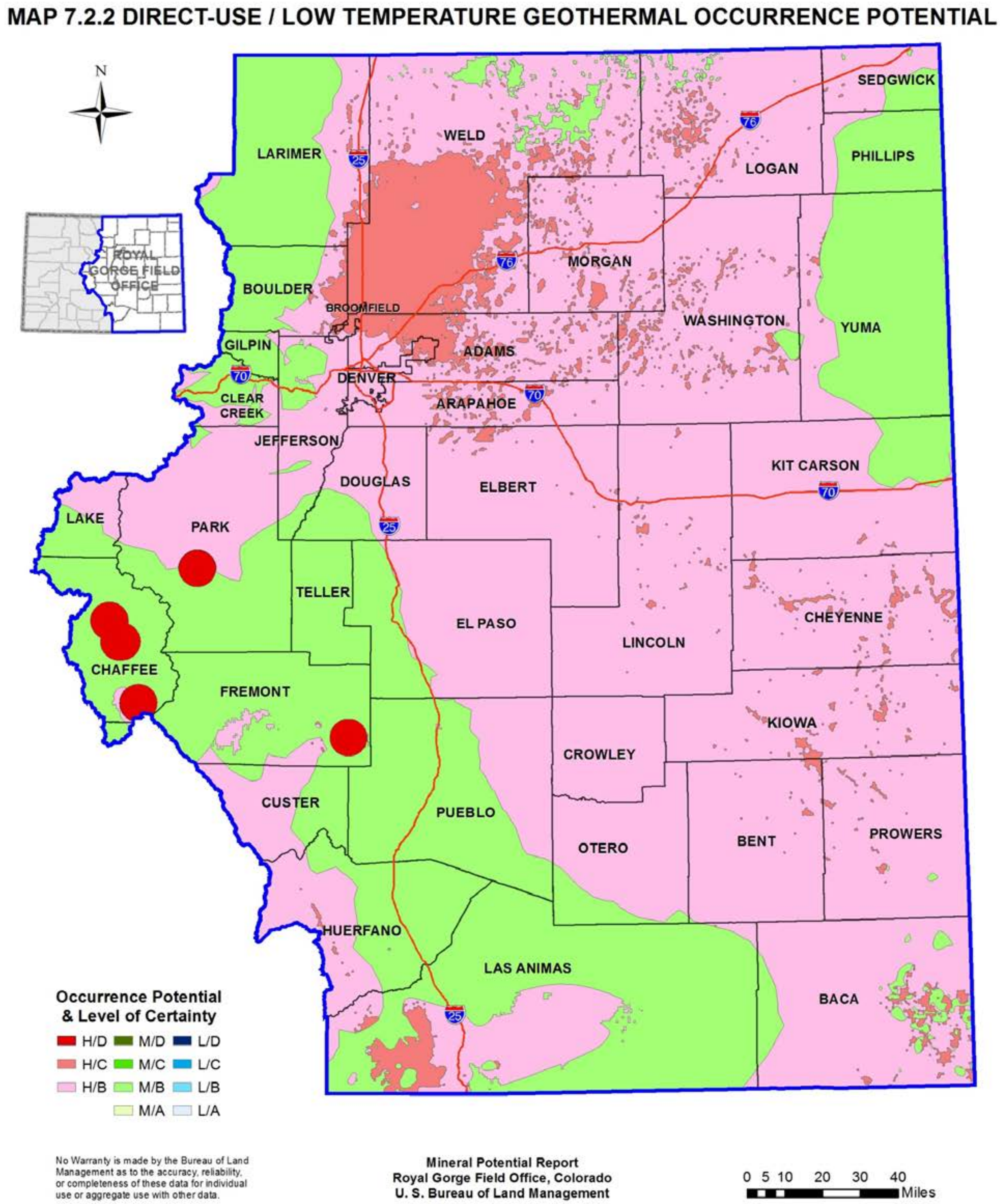
7.2 Geothermal

7.2.1 Traditional / EGS Geothermal

MAP 7.2.1 TRADITIONAL / EGS GEOTHERMAL OCCURRENCE POTENTIAL

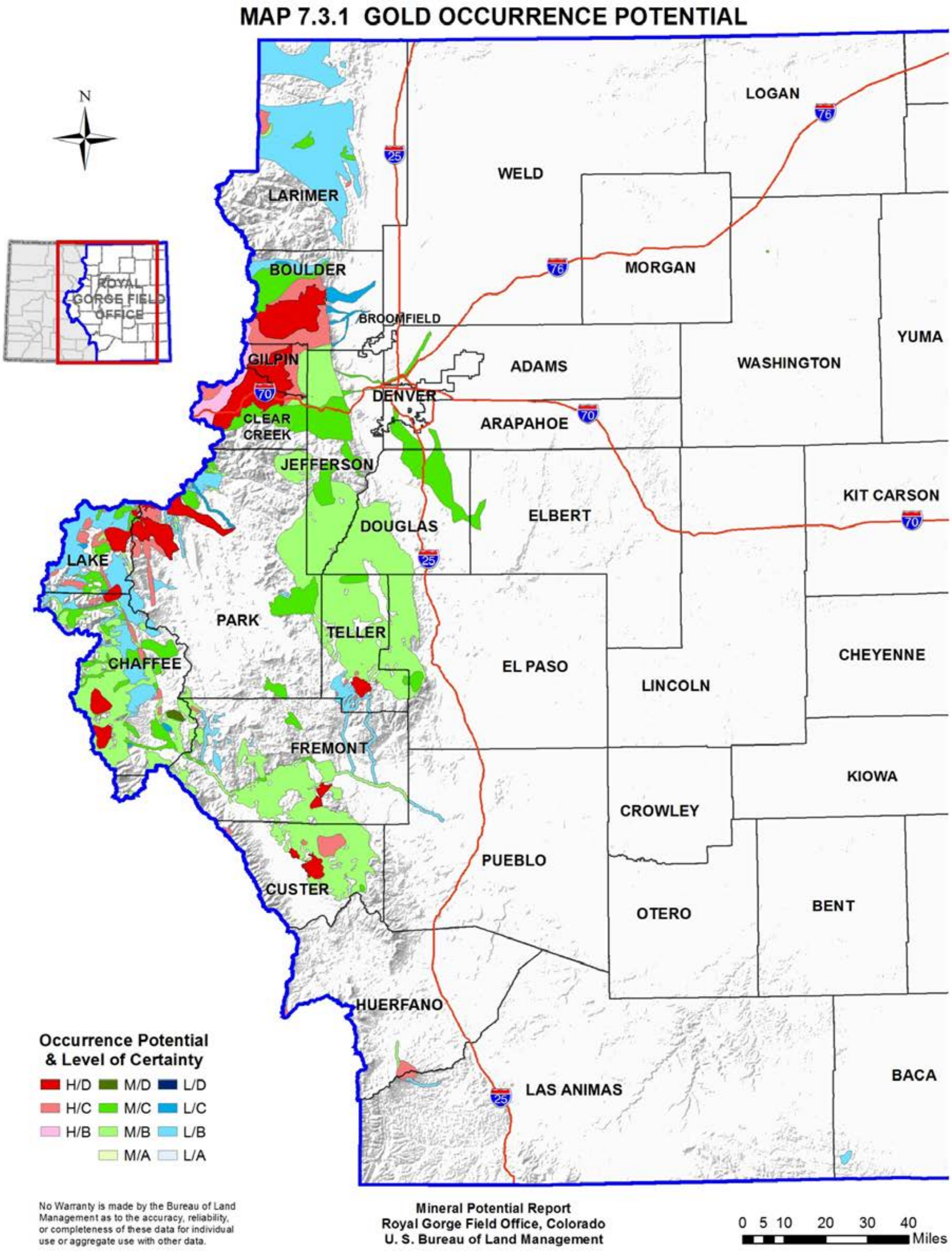


7.2.2 Direct-use / Low Temperature Geothermal



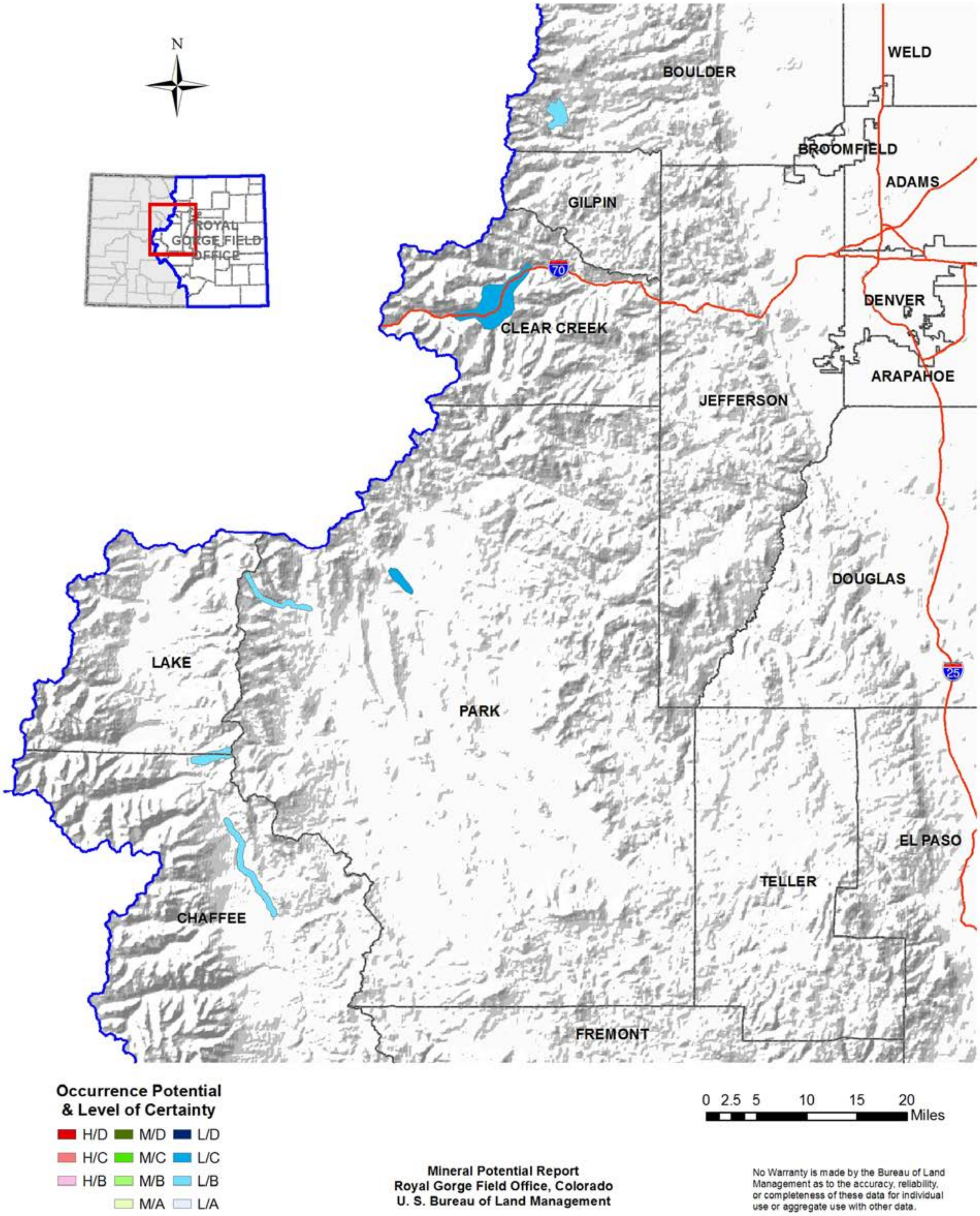
7.3 Precious Metals

7.3.1 Gold

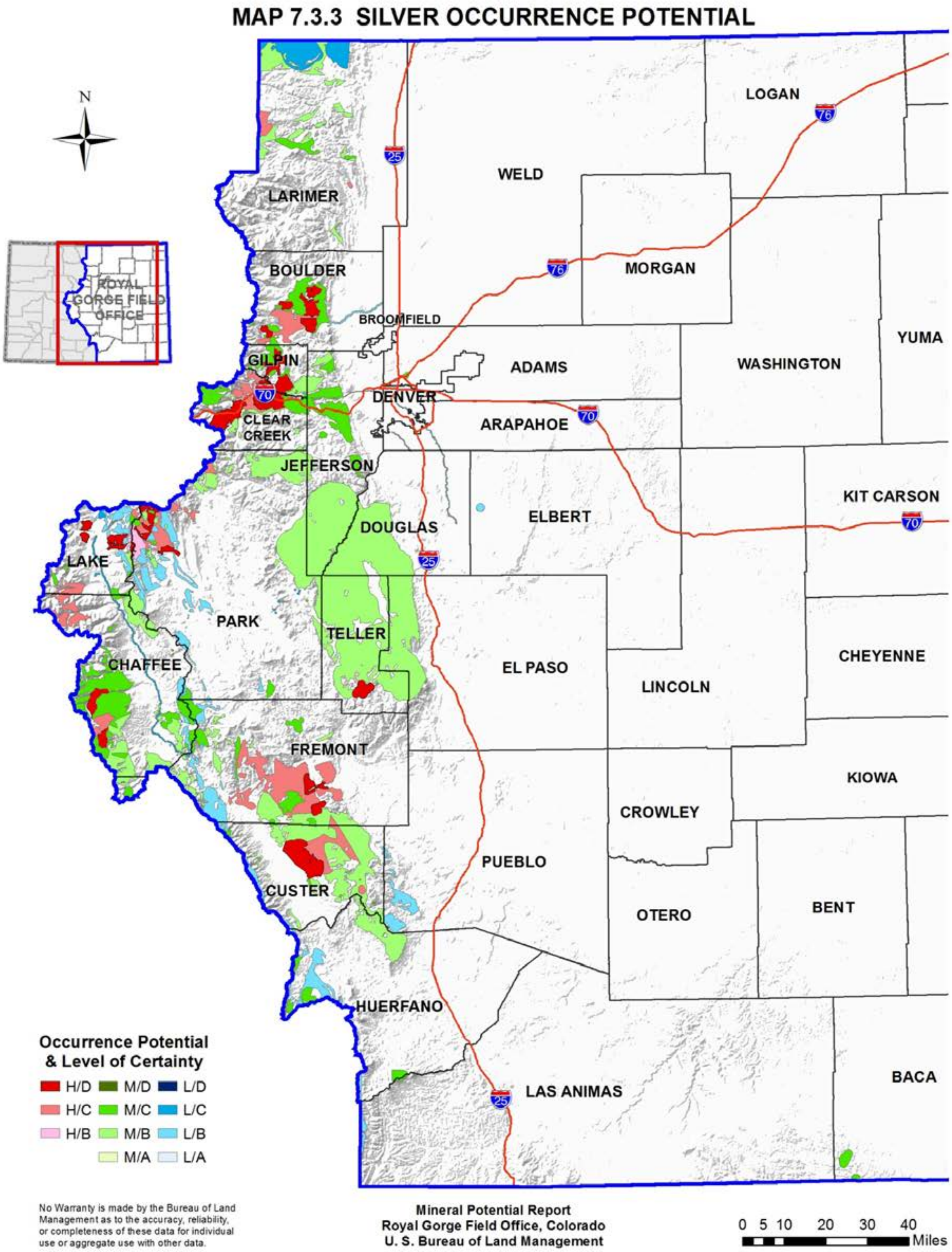


7.3.2 Platinum-group Metals

MAP 7.3.2 PLATINUM GROUP METALS OCCURRENCE POTENTIAL



7.3.3 Silver


MAP 7.3.3 SILVER OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
LARIMER
WELD
LOGAN
BOULDER
MORGAN
BROOMFIELD
GILPIN
ADAMS
WASHINGTON
YUMA
CLEAR CREEK
DENVER
ARAPAHOE
JEFFERSON
DOUGLAS
ELBERT
KIT CARSON
LAKE
PARK
TELLER
CHAFFEE
EL PASO
LINCOLN
CHEYENNE
FREMONT
KIOWA
CROWLEY
PUEBLO
CUSTER
OTERO
BENT
HUERFANO
LAS ANIMAS
BACA
25
70
76
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
No Warranty is made by the Bureau of Land Management as to the accuracy, reliability, or completeness of these data for individual use or aggregate use with other data.
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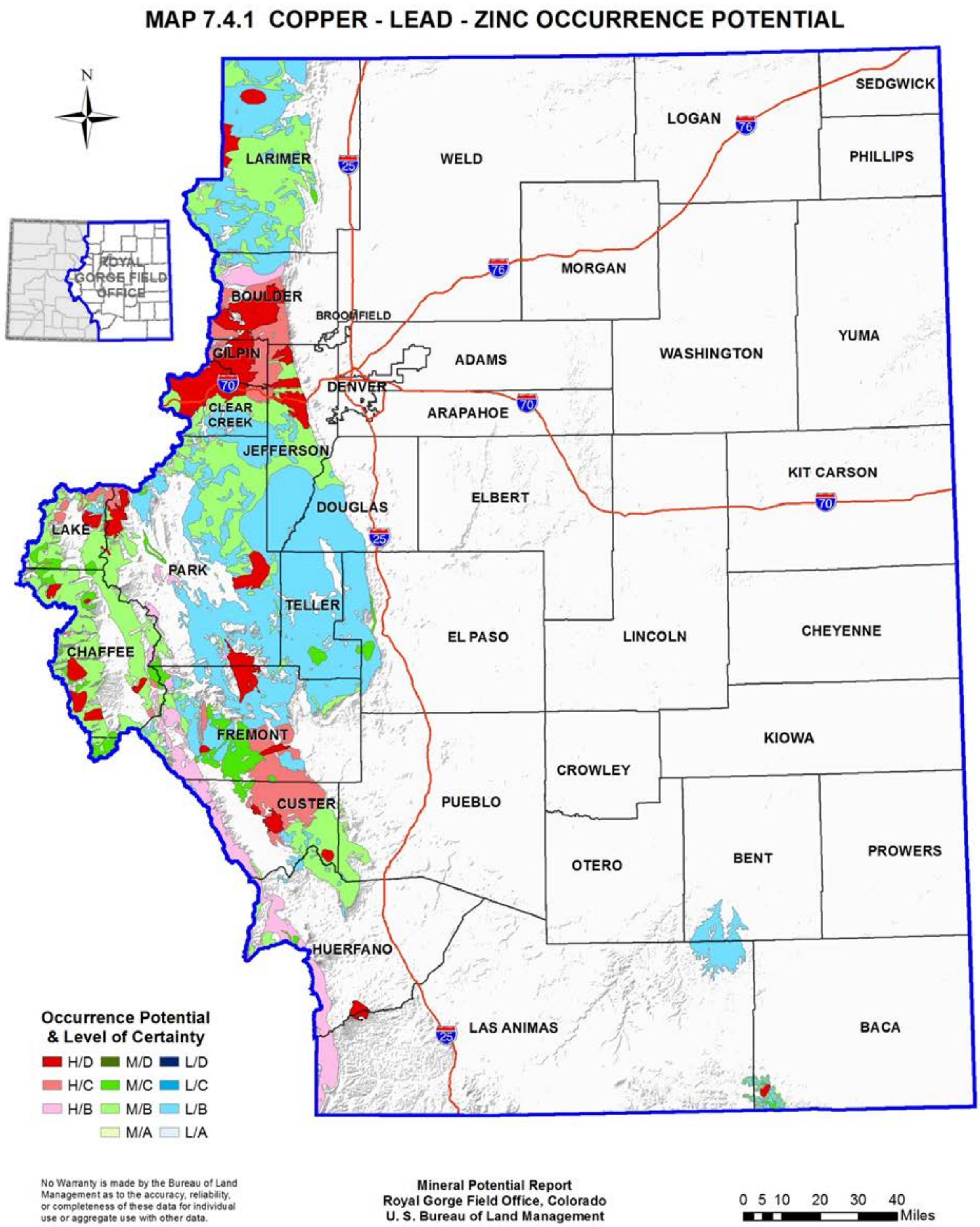
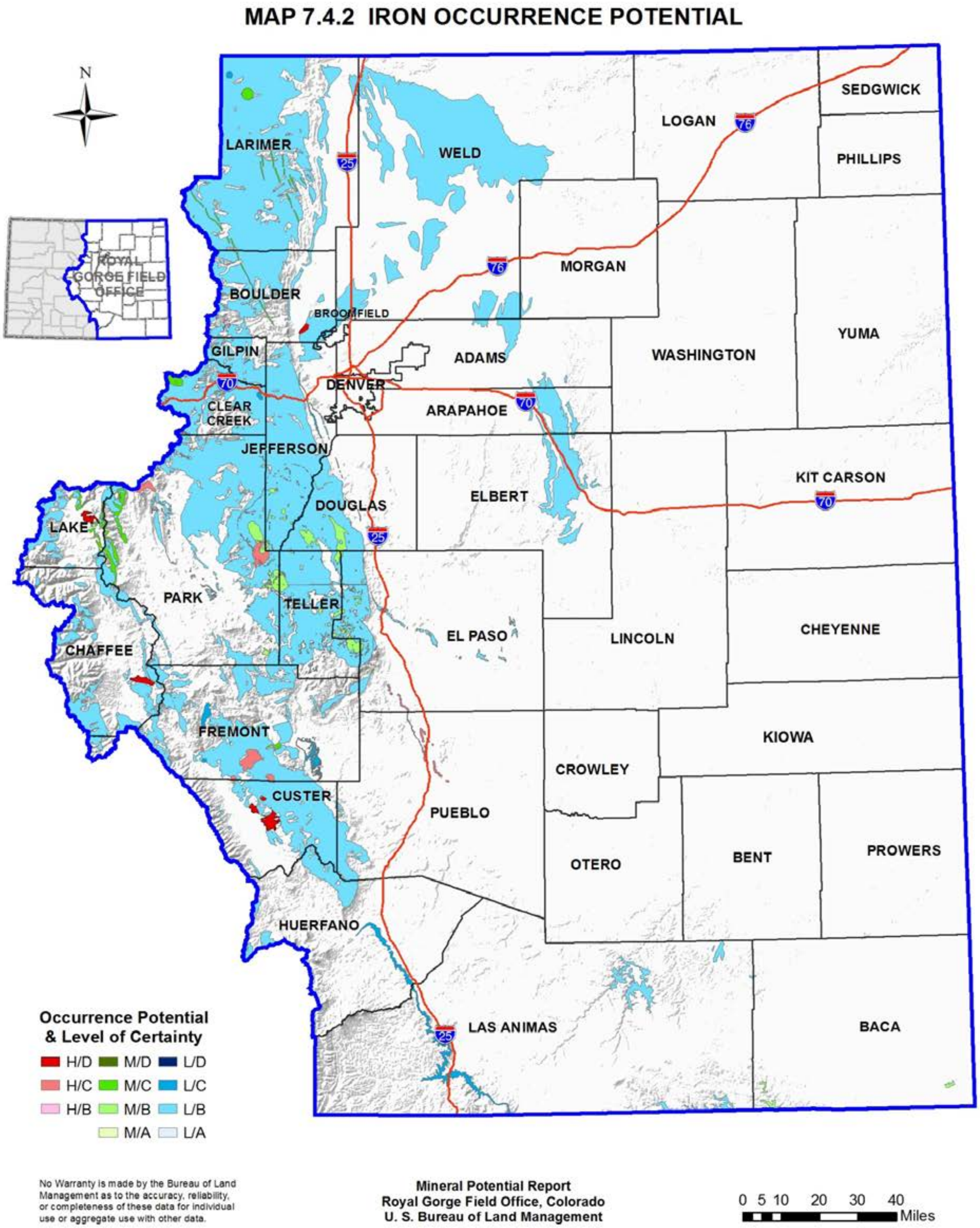
7.4 Base Metals

7.4.1 Copper-Lead-Zinc



7.4.2 Iron


MAP 7.4.2 IRON OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
LARIMER
WELD
LOGAN
SEDGWICK
PHILLIPS
MORGAN
BOULDER
BROOMFIELD
GILPIN
ADAMS
WASHINGTON
YUMA
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
KIT CARSON
DOUGLAS
ELBERT
LAKE
PARK
TELLER
EL PASO
LINCOLN
CHEYENNE
CHAFFEE
FREMONT
KIOWA
CROWLEY
CUSTER
PUEBLO
OTERO
BENT
PROWERS
HUERFANO
LAS ANIMAS
BACA
25
70
76
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
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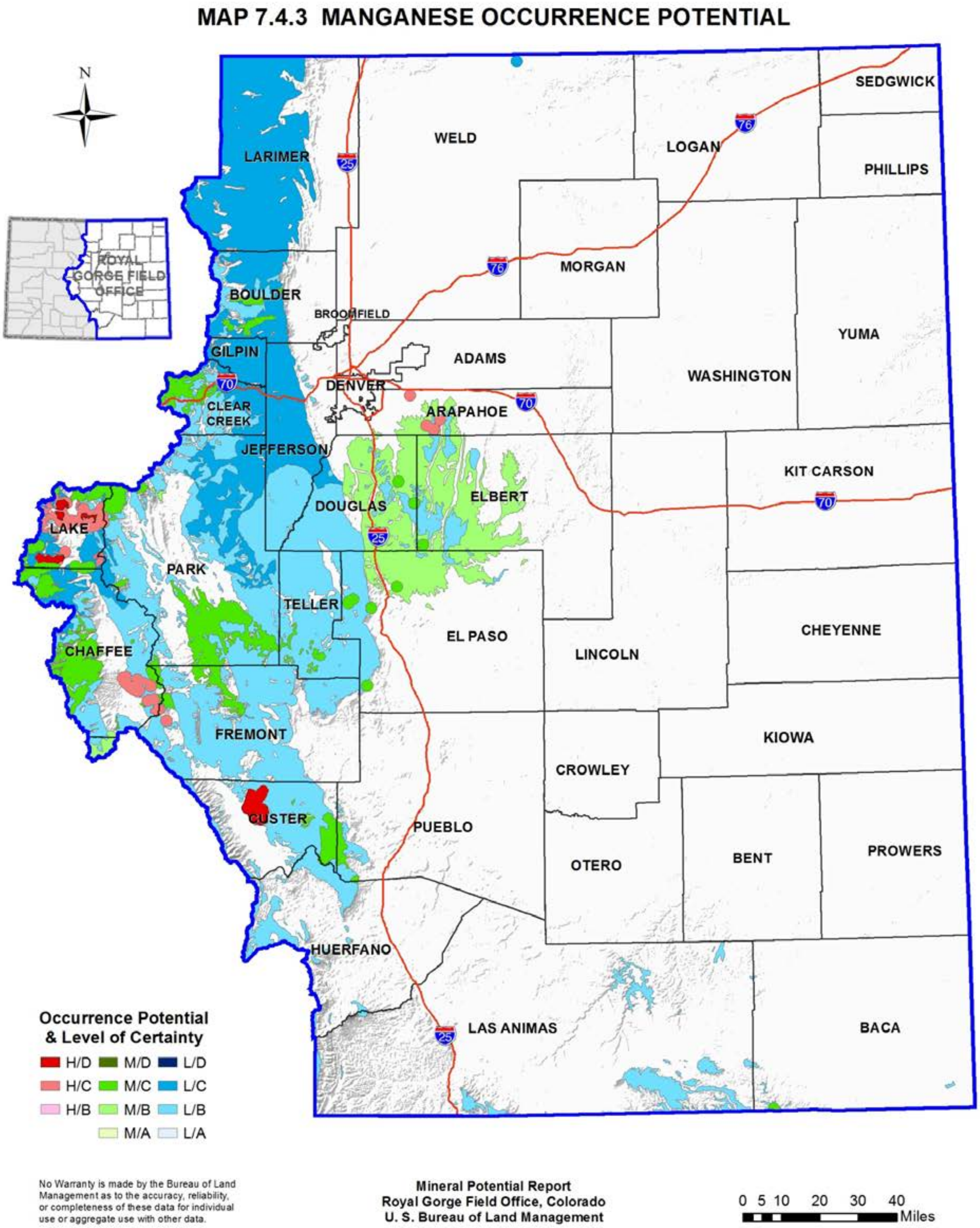
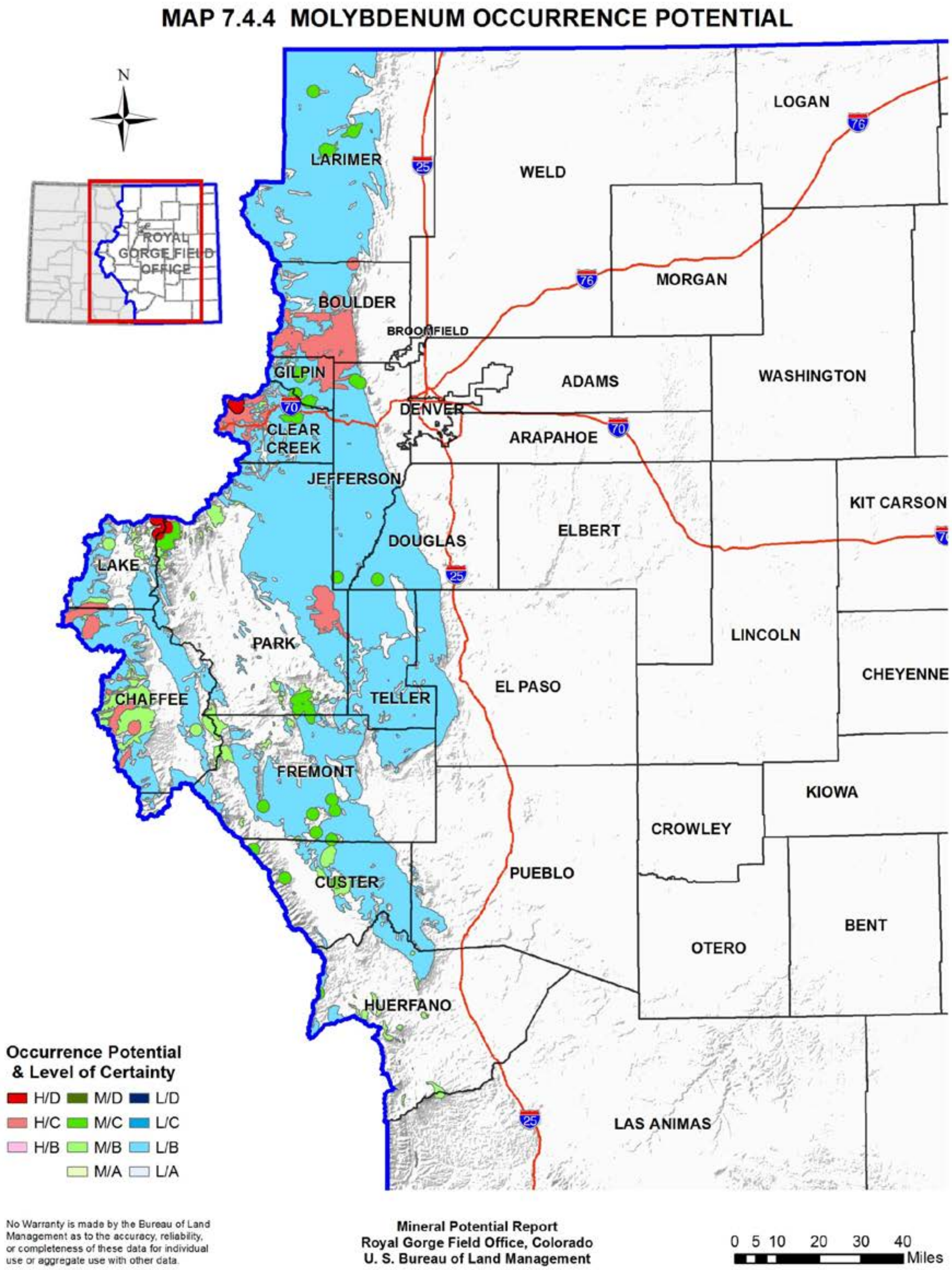
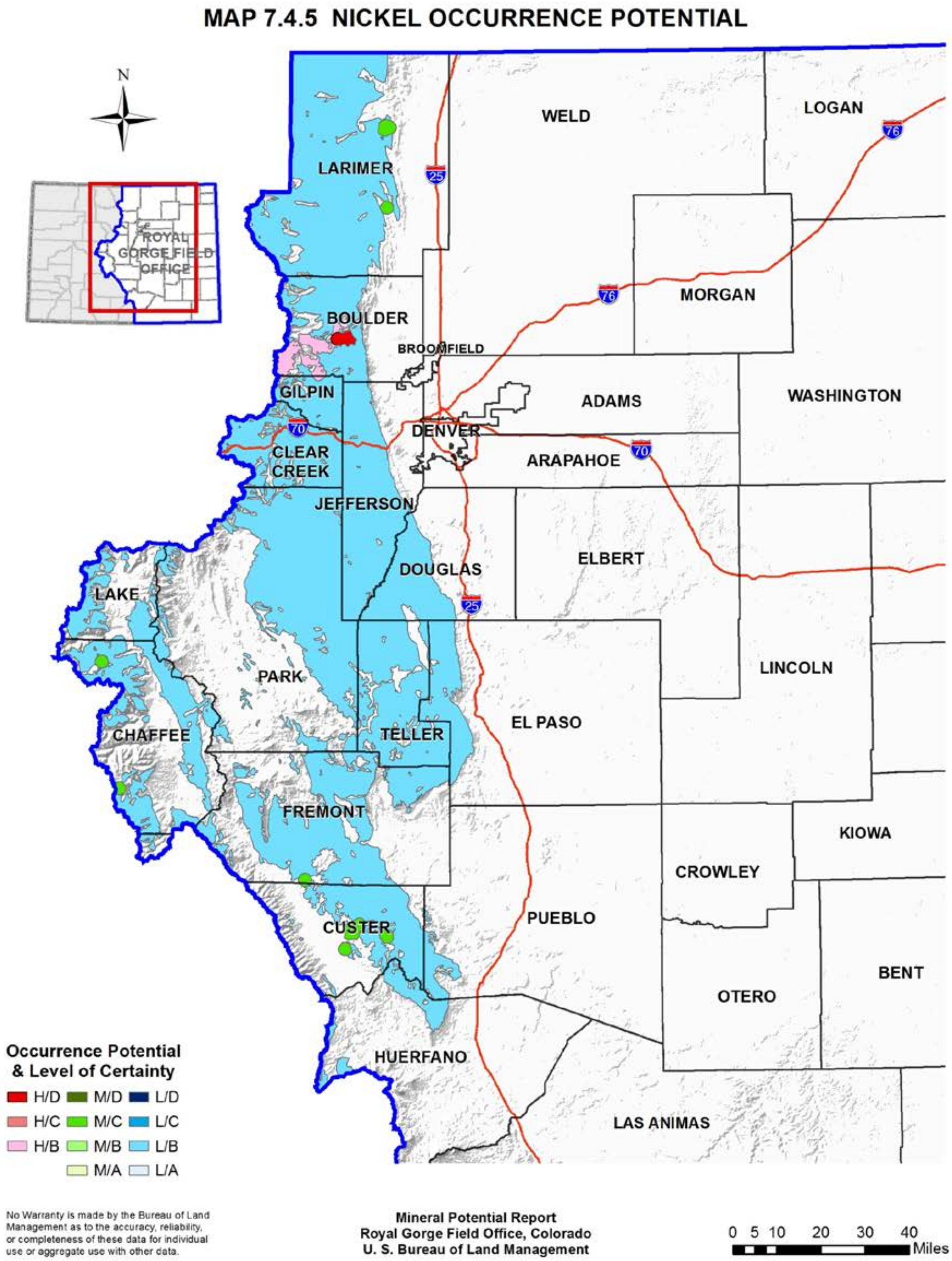
7.4.3 Manganese



7.4.4 Molybdenum



7.4.5 *Nickel*



MAP 7.4.5 NICKEL OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
LARIMER
WELD
LOGAN
MORGAN
BOULDER
BROOMFIELD
GILPIN
ADAMS
WASHINGTON
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
DOUGLAS
ELBERT
LAKE
PARK
LINCOLN
CHAFFEE
TELLER
EL PASO
FREMONT
KIOWA
CROWLEY
CUSTER
PUEBLO
BENT
OTERO
HUERFANO
LAS ANIMAS
25
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Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
No Warranty is made by the Bureau of Land Management as to the accuracy, reliability, or completeness of these data for individual use or aggregate use with other data.
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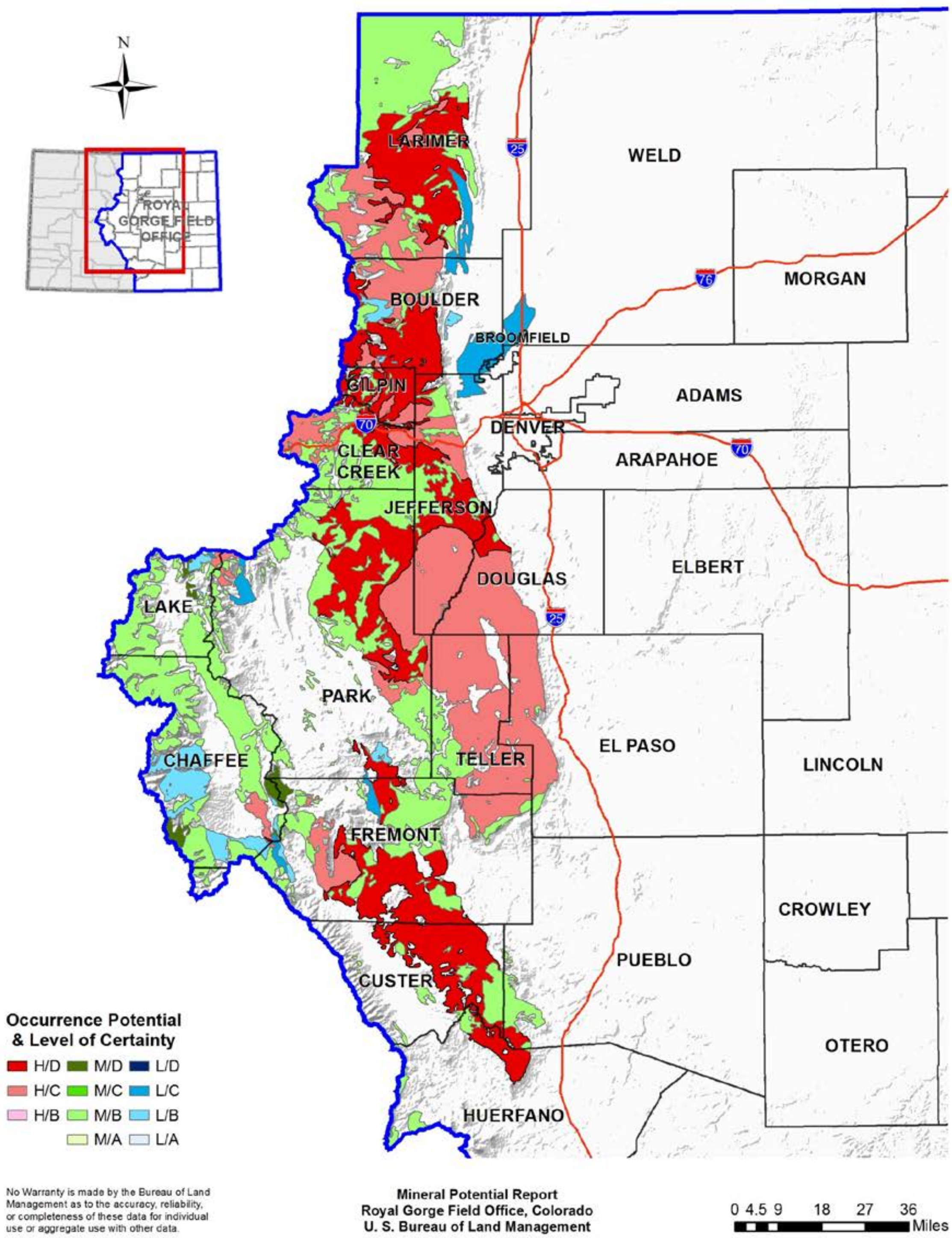
7.4.6 Tungsten

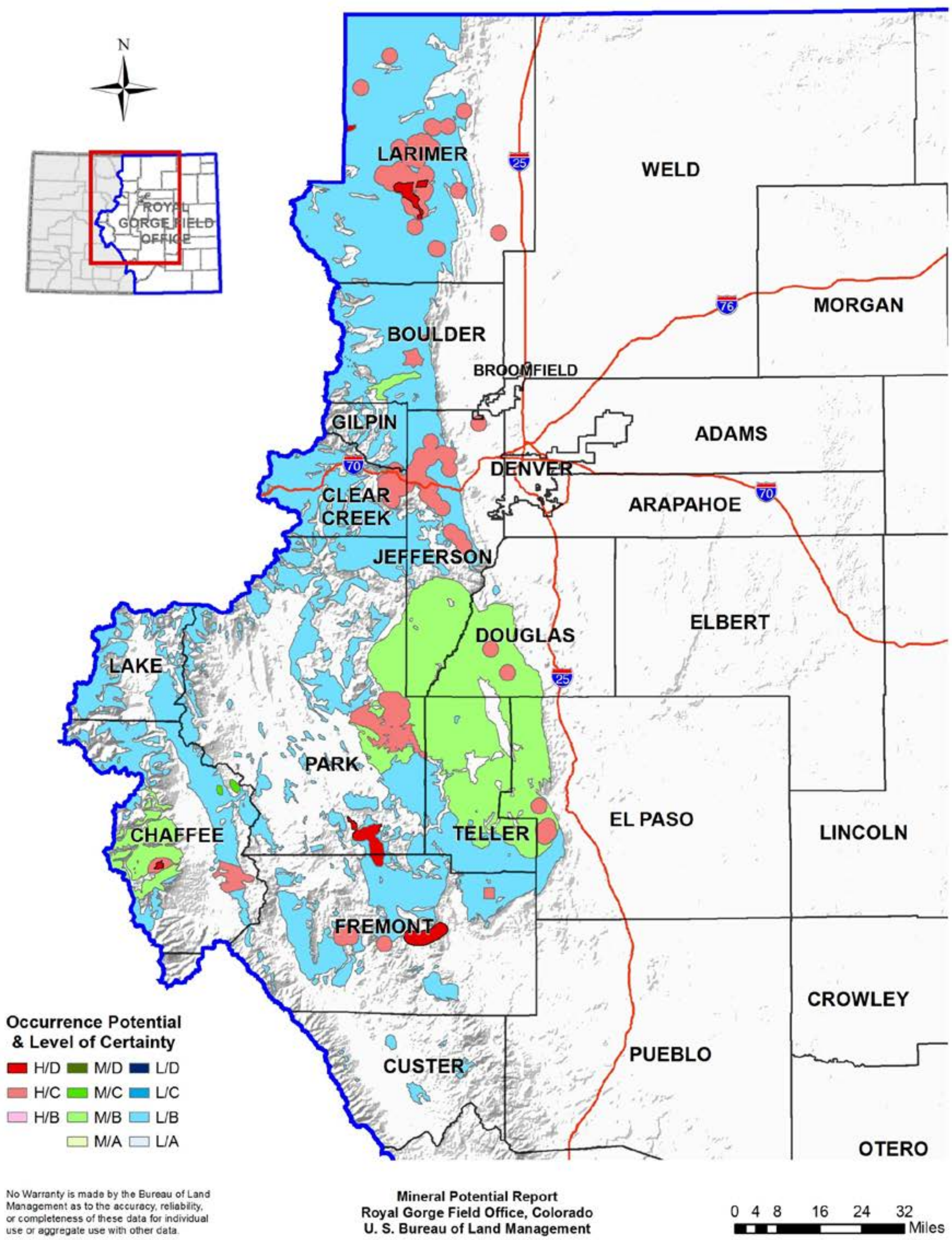
MAP 7.4.6 TUNGSTEN OCCURRENCE POTENTIAL



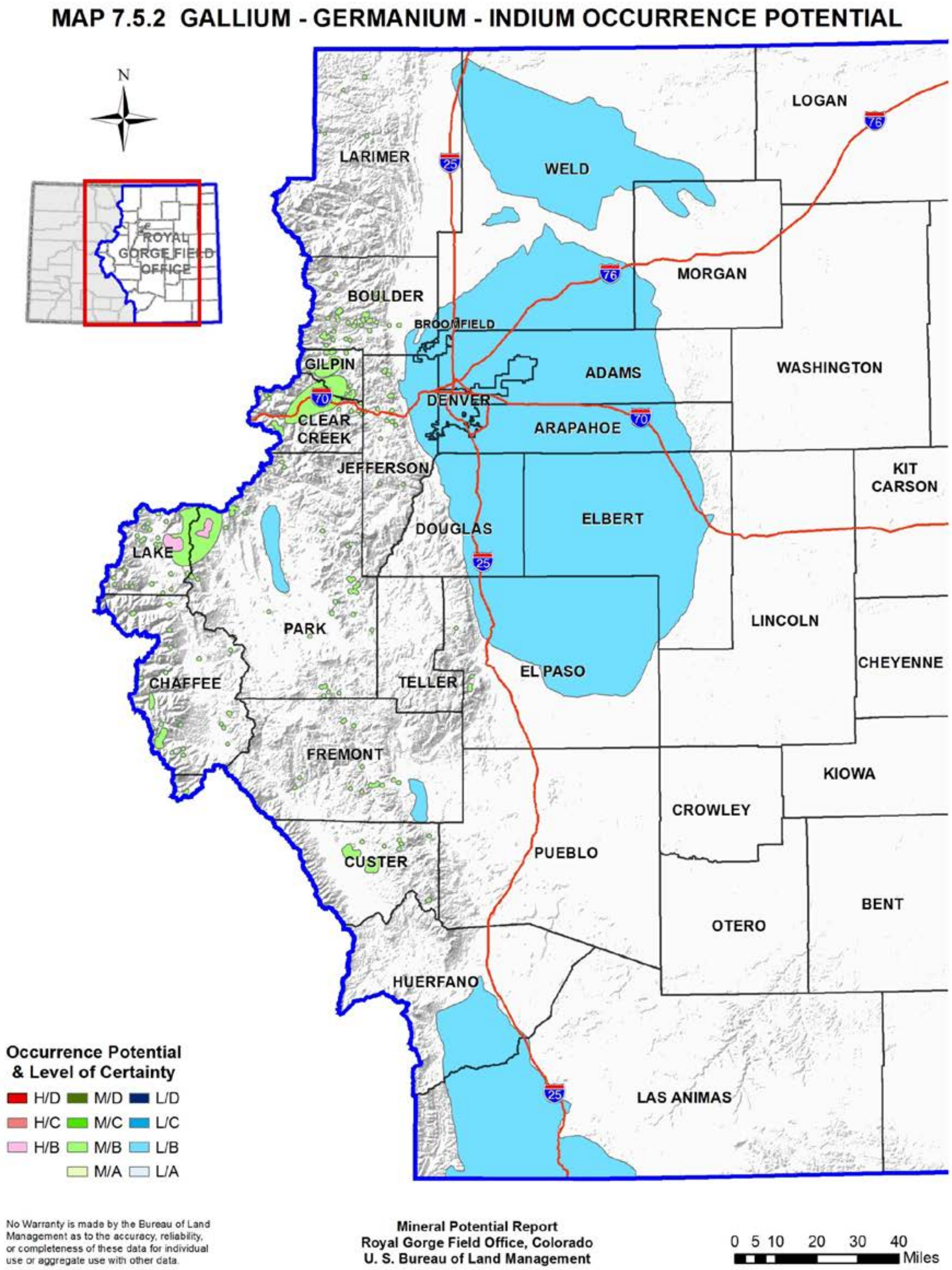
7.5 Minor Metals

7.5.1 Beryllium

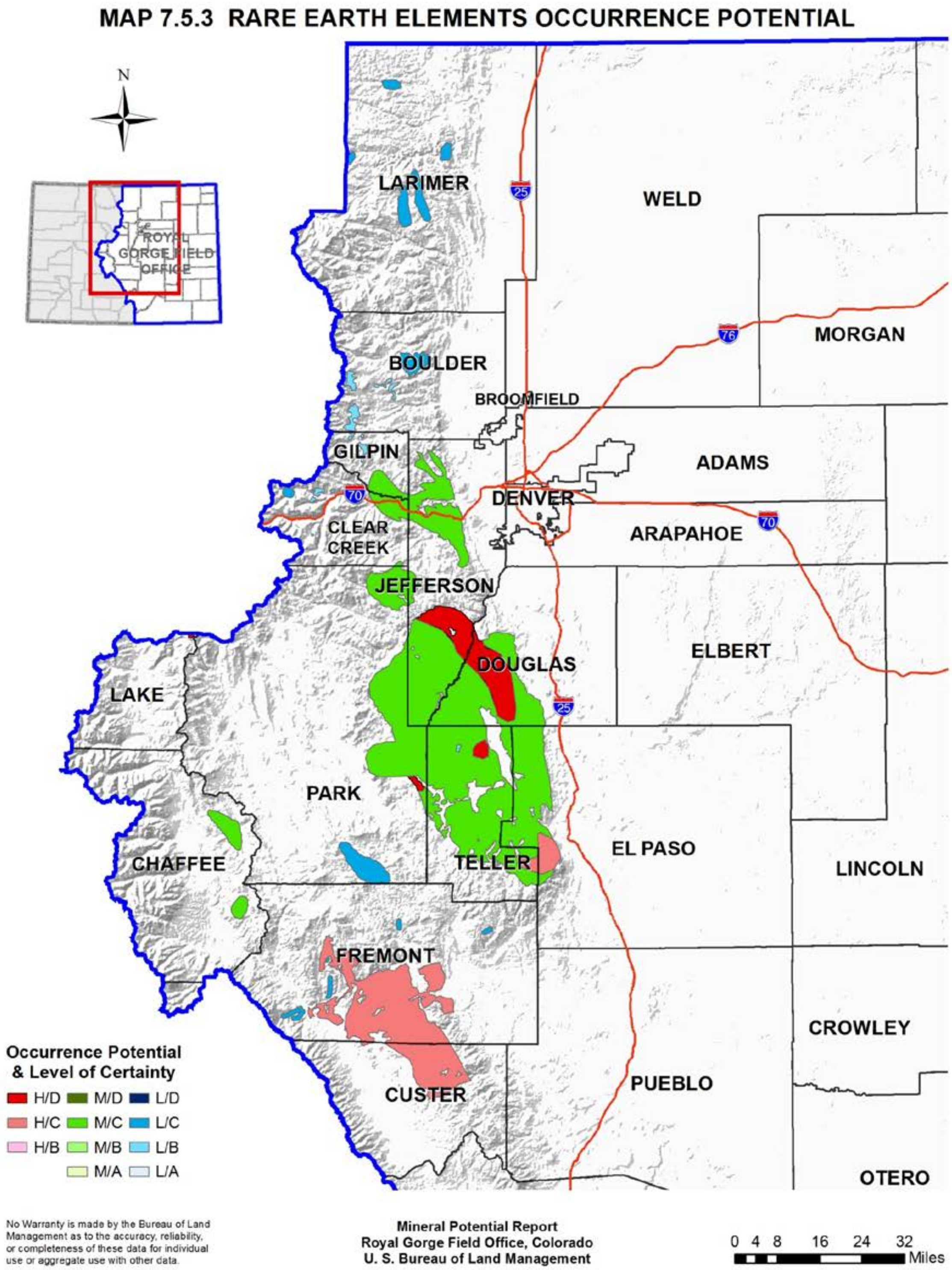
MAP 7.5.1 BERYLLIUM OCCURRENCE POTENTIAL



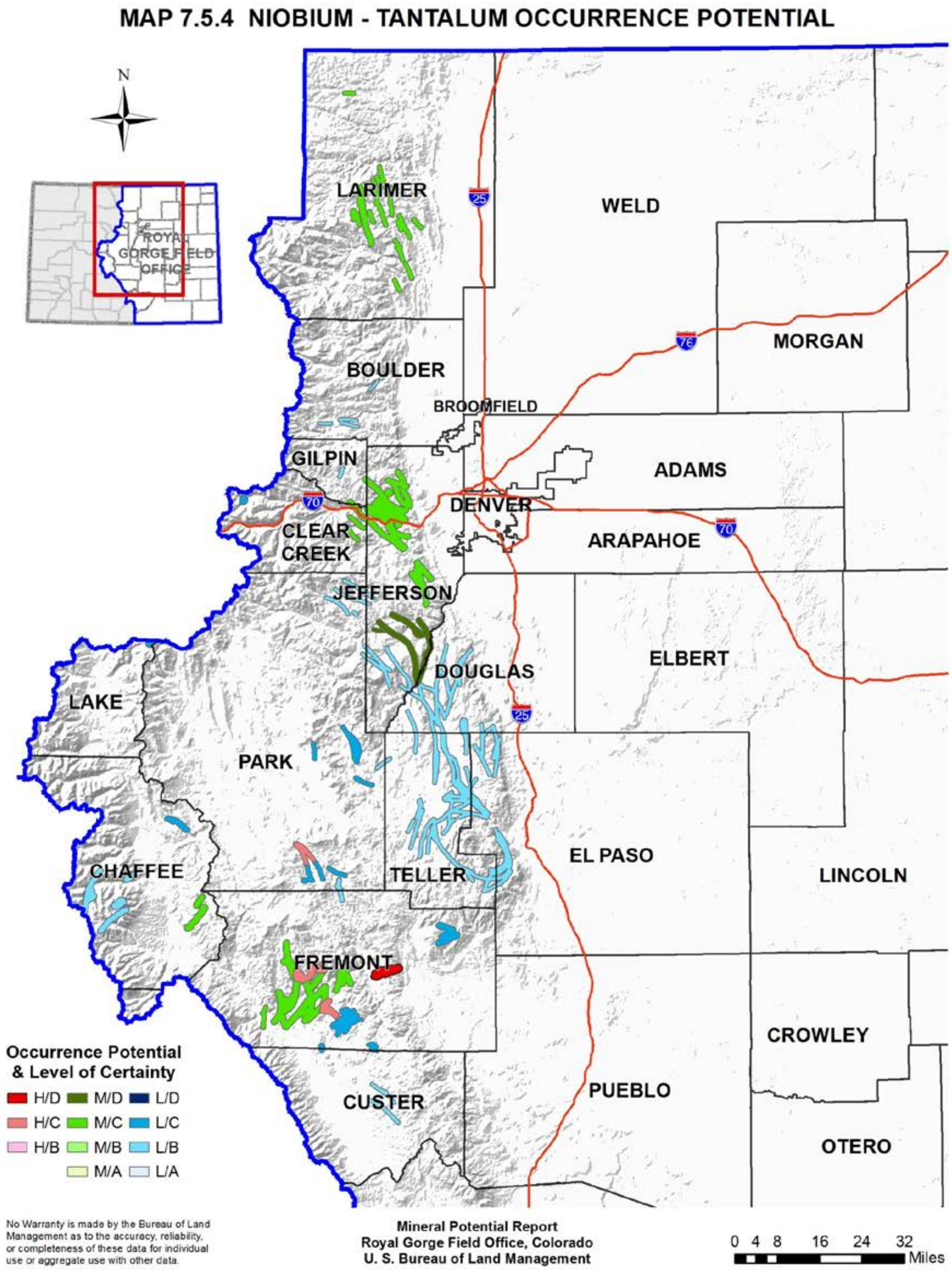
7.5.2 Gallium-Germanium-Indium



7.5.3 Rare Earth Elements

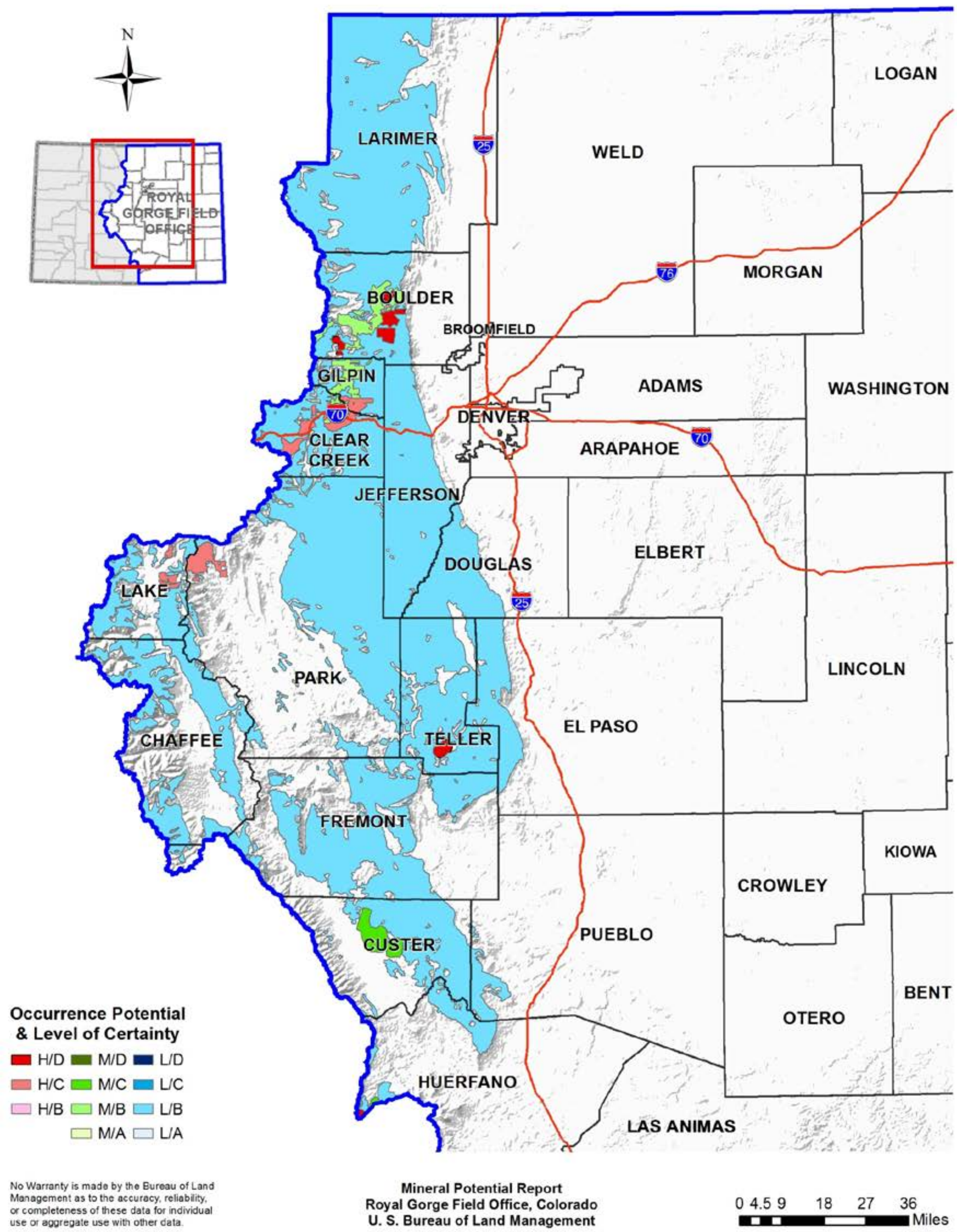


7.5.4 Niobium-Tantalum

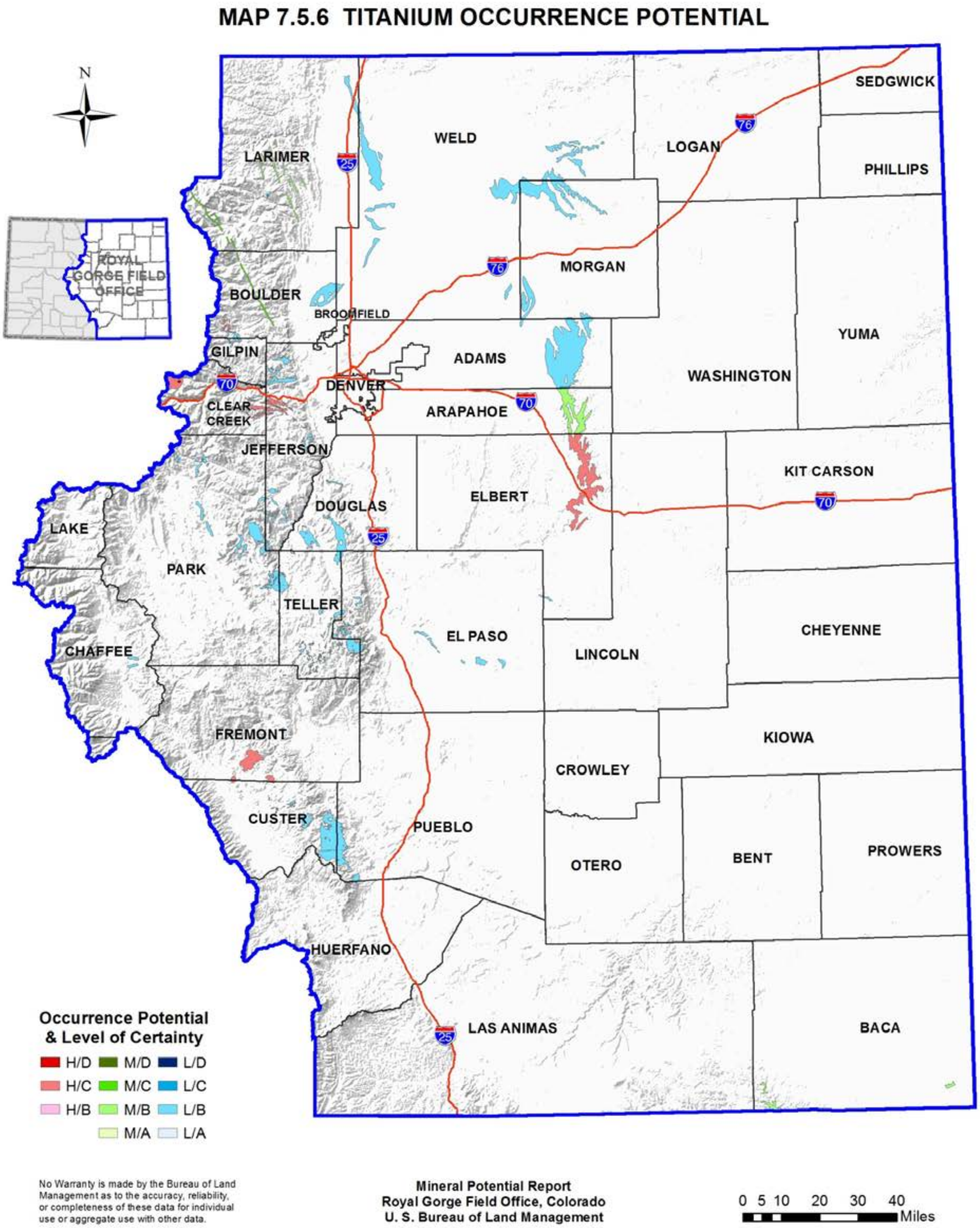


7.5.5 Tellurium

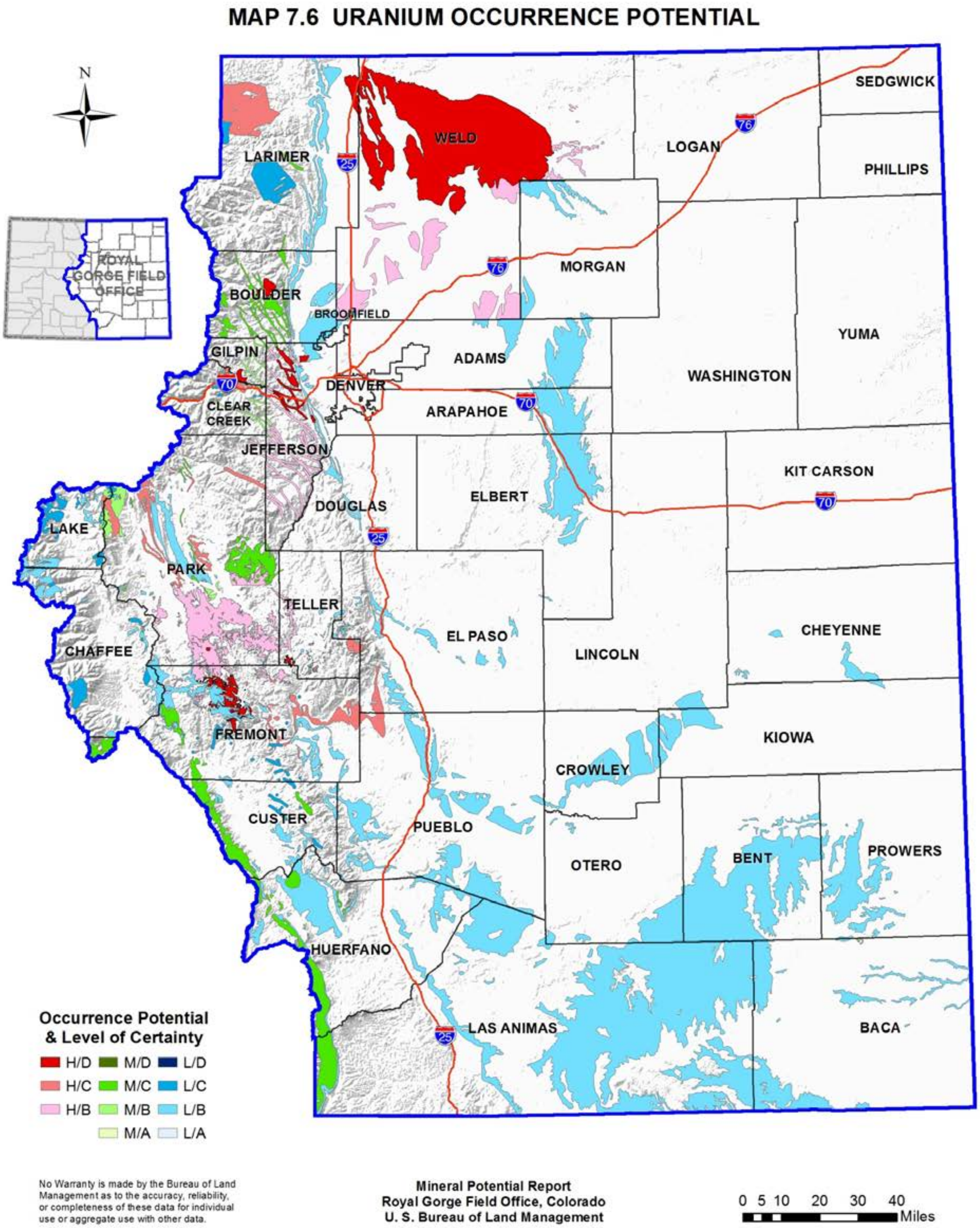
MAP 7.5.5 TELLURIUM OCCURRENCE POTENTIAL



7.5.6 Titanium



7.6 Uranium


MAP 7.6 URANIUM OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
SEDGWICK
LOGAN
PHILLIPS
WELD
LARIMER
MORGAN
BOULDER
BROOMFIELD
YUMA
GILPIN
ADAMS
WASHINGTON
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
KIT CARSON
ELBERT
DOUGLAS
LAKE
PARK
TELLER
CHEYENNE
EL PASO
LINCOLN
CHAFFEE
FREMONT
KIOWA
CROWLEY
CUSTER
PUEBLO
PROWERS
BENT
OTERO
HUERFANO
LAS ANIMAS
BACA
25
76
70
Occurrence Potential & Level of Certainty
H/D
M/D
L/D
H/C
M/C
L/C
H/B
M/B
L/B
M/A
L/A
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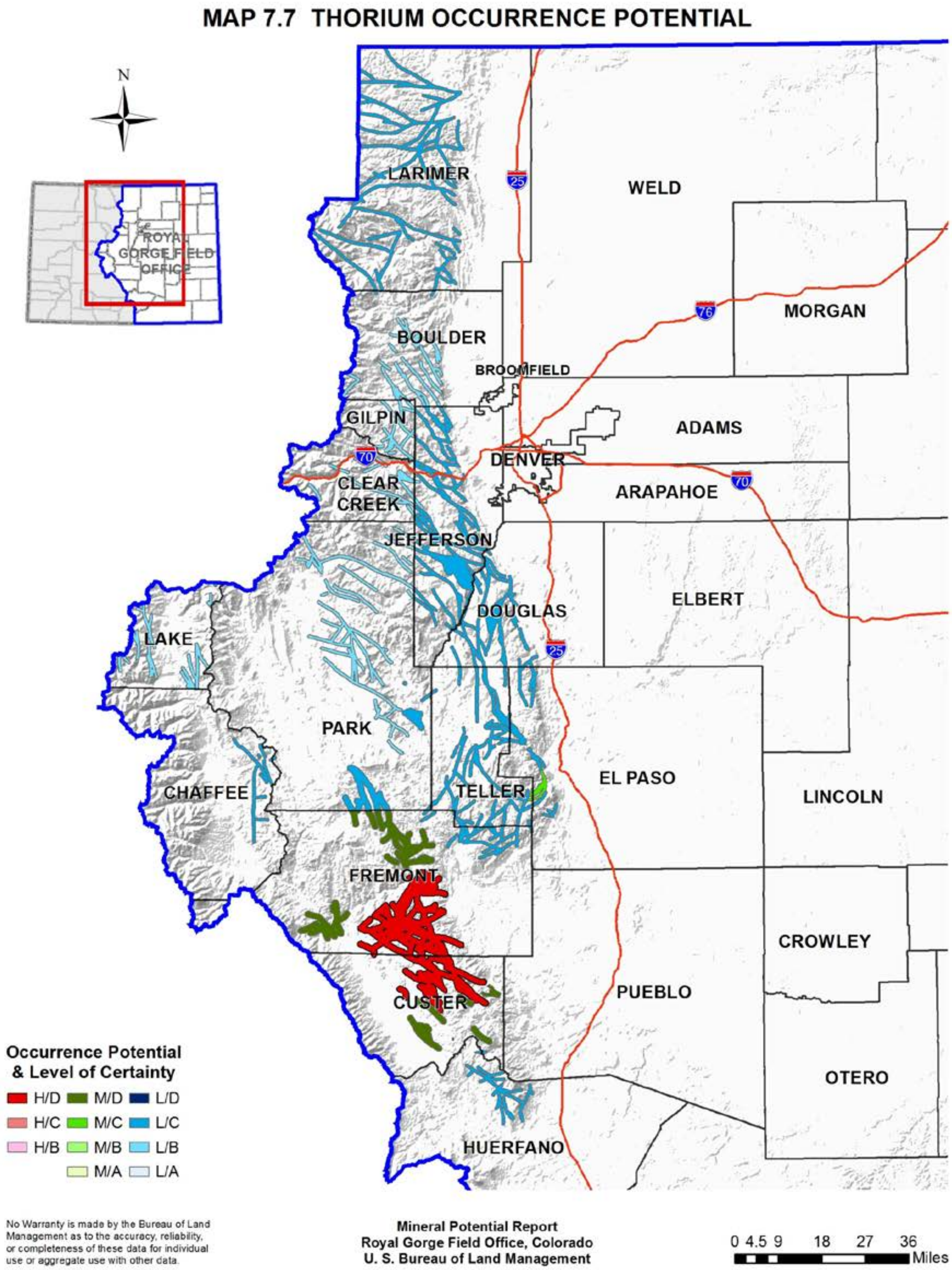
0 5 10 20 30 40
Miles

7.7 Thorium


MAP 7.7 THORIUM OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
LARIMER
WELD
MORGAN
BOULDER
BROOMFIELD
GILPIN
ADAMS
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
DOUGLAS
ELBERT
LAKE
PARK
CHAFFEE
TELLER
EL PASO
LINCOLN
FREMONT
CROWLEY
CUSTER
PUEBLO
OTERO
HUERFANO
25
76
70
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
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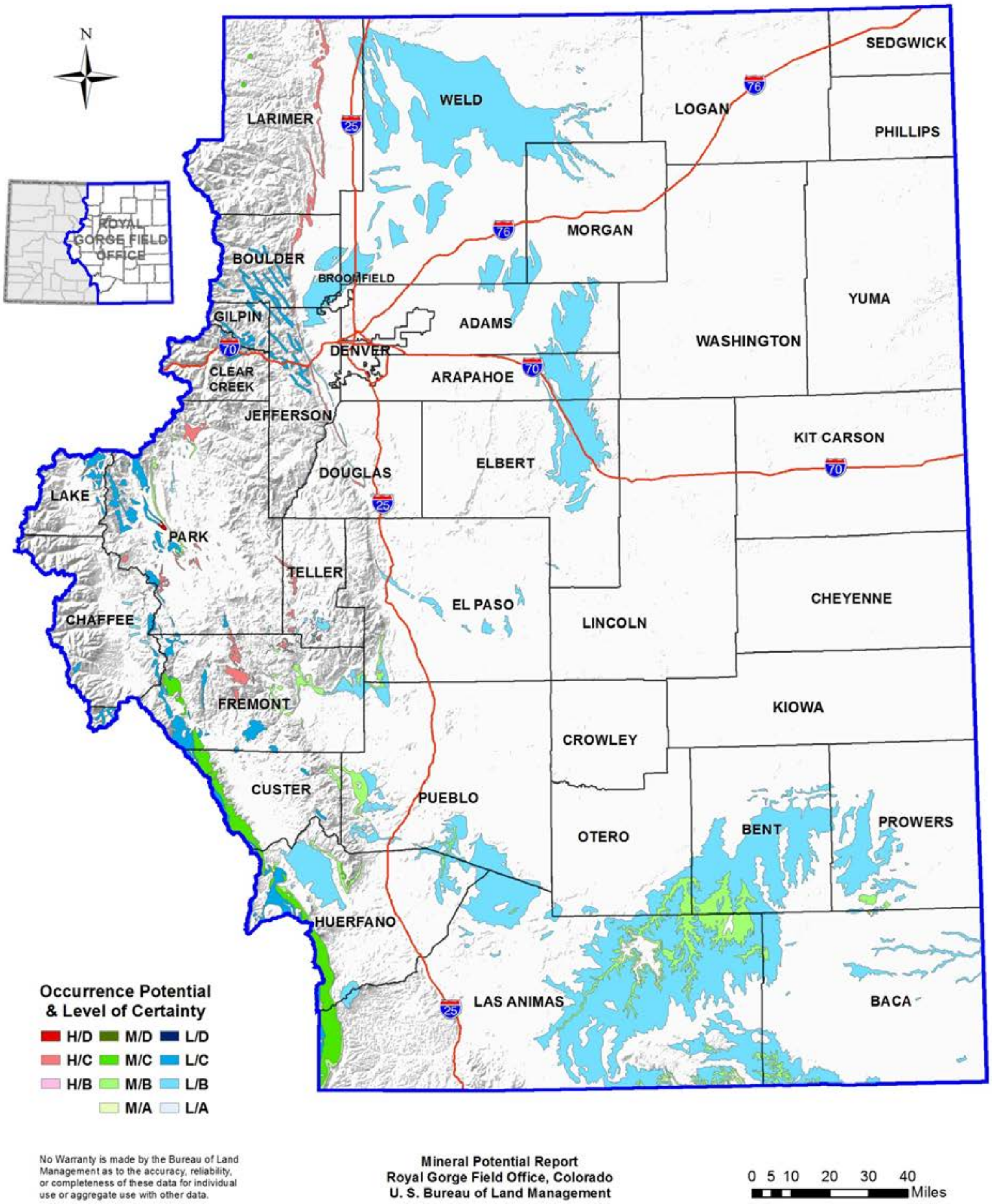
U. S. Bureau of Land Management
0 4.5 9 18 27 36
Miles

7.8 Vanadium

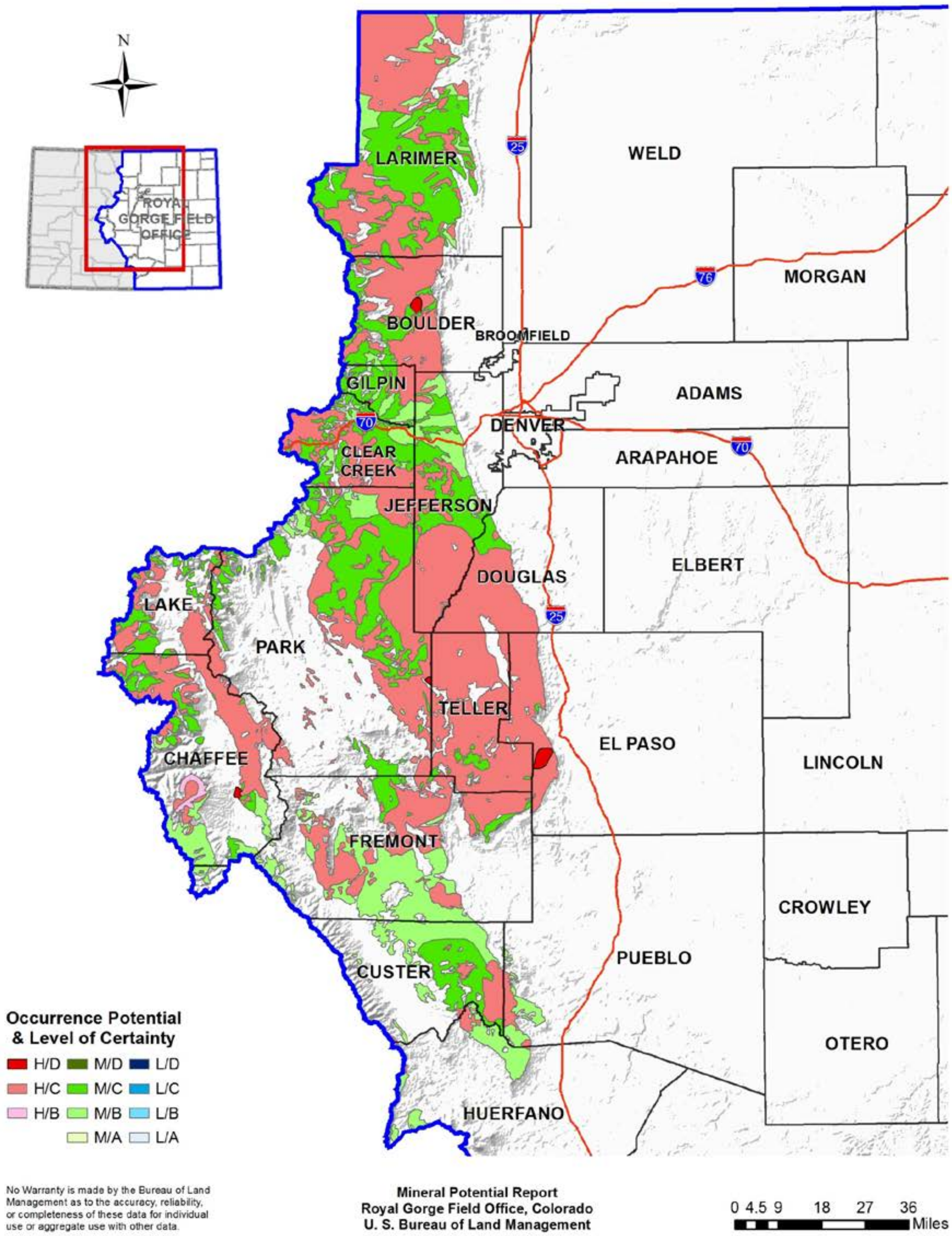
MAP 7.8 VANADIUM OCCURRENCE POTENTIAL



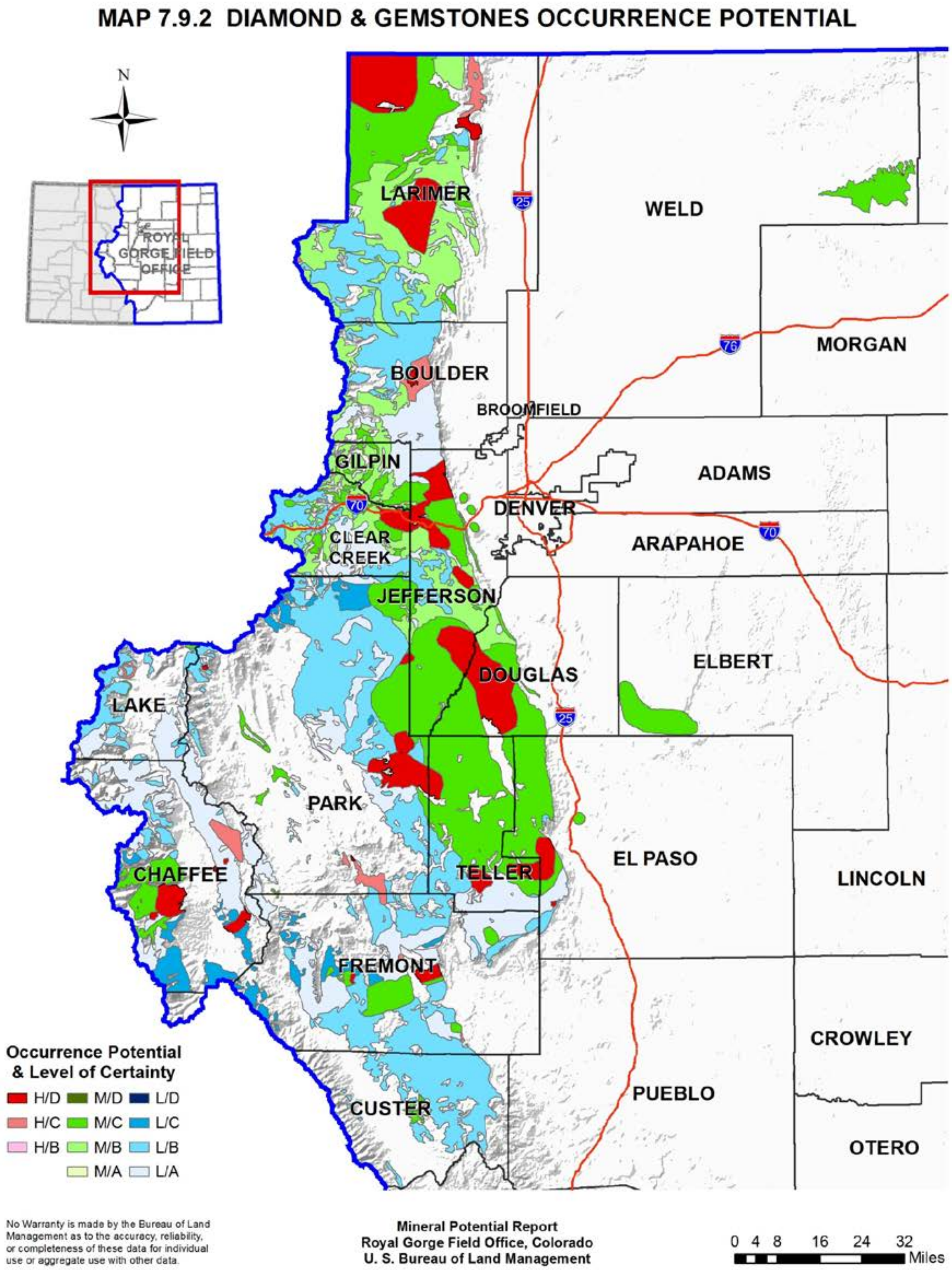
7.9 Nonmetallic Minerals / Industrial Minerals

7.9.1 Fluorspar

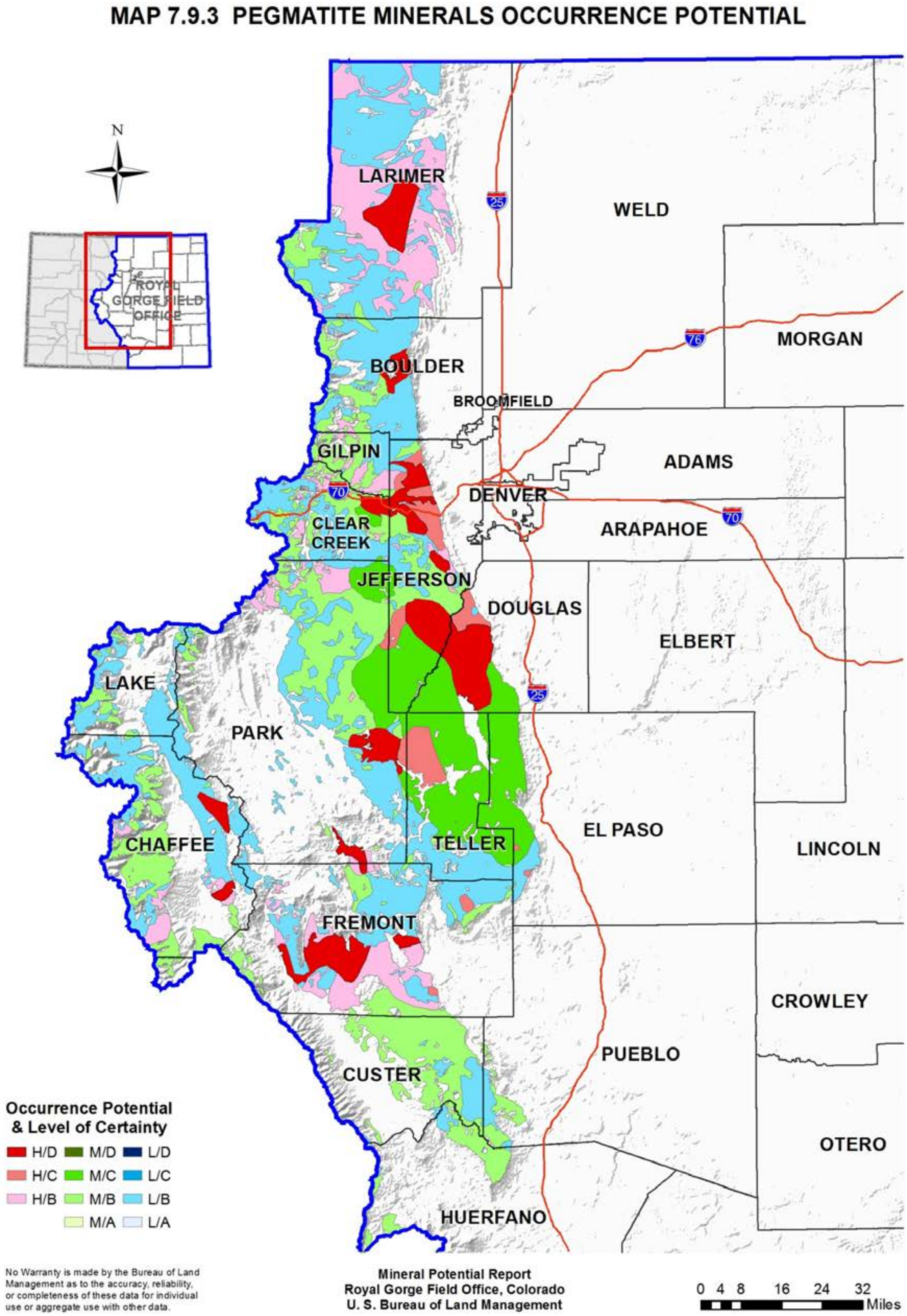
MAP 7.9.1 FLUORSPAR OCCURRENCE POTENTIAL



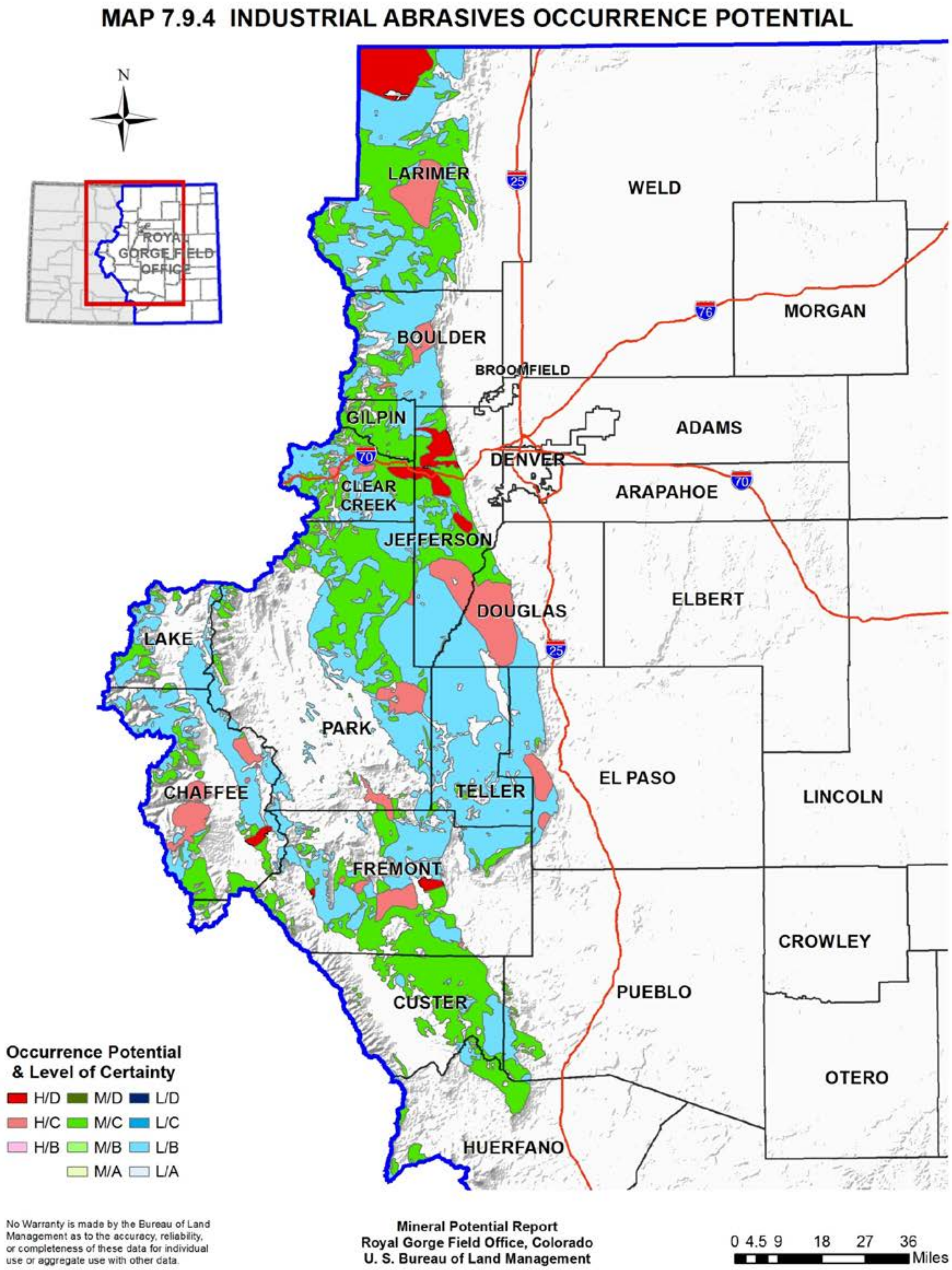
7.9.2 Diamond and Gemstones



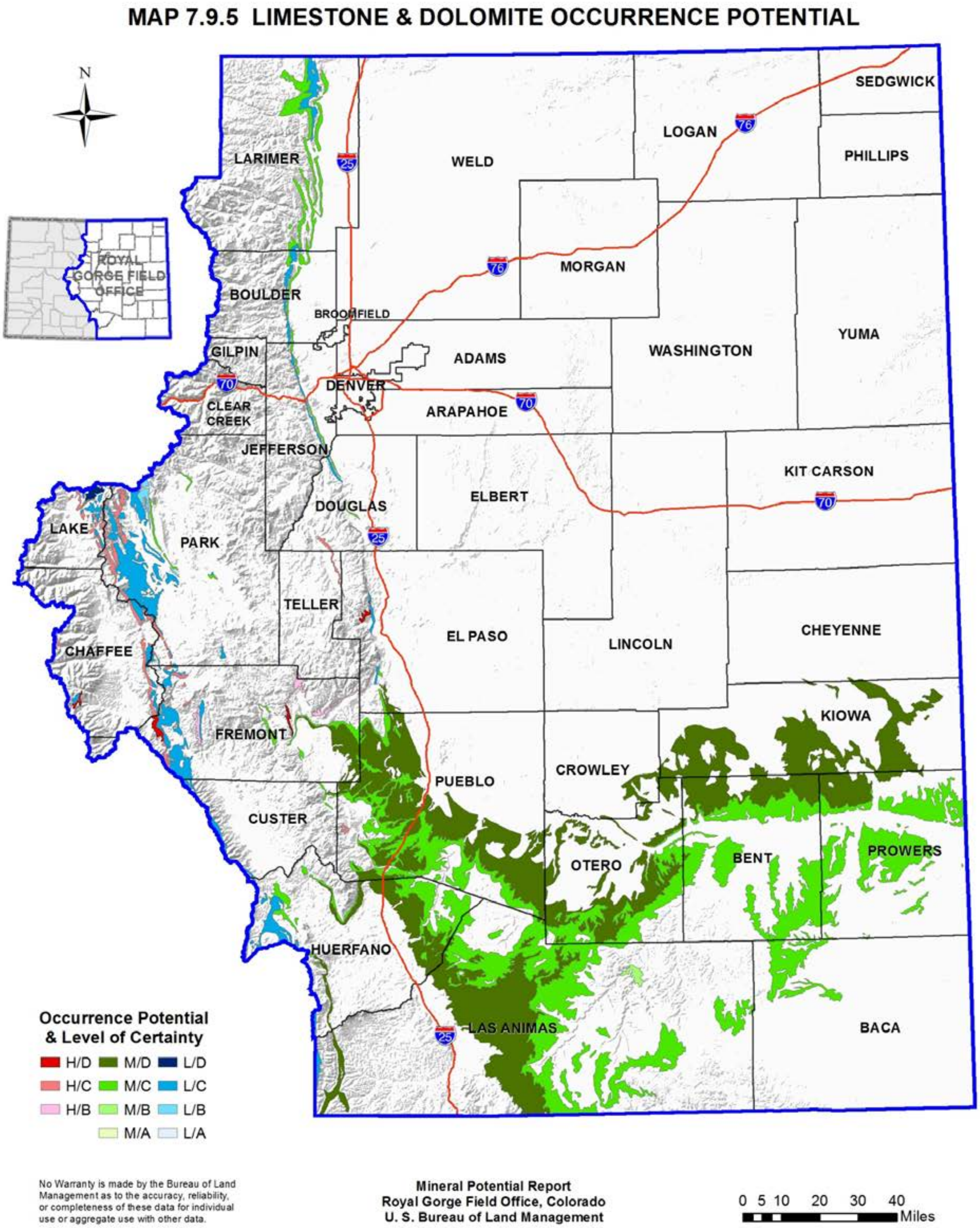
7.9.3 Pegmatite Minerals



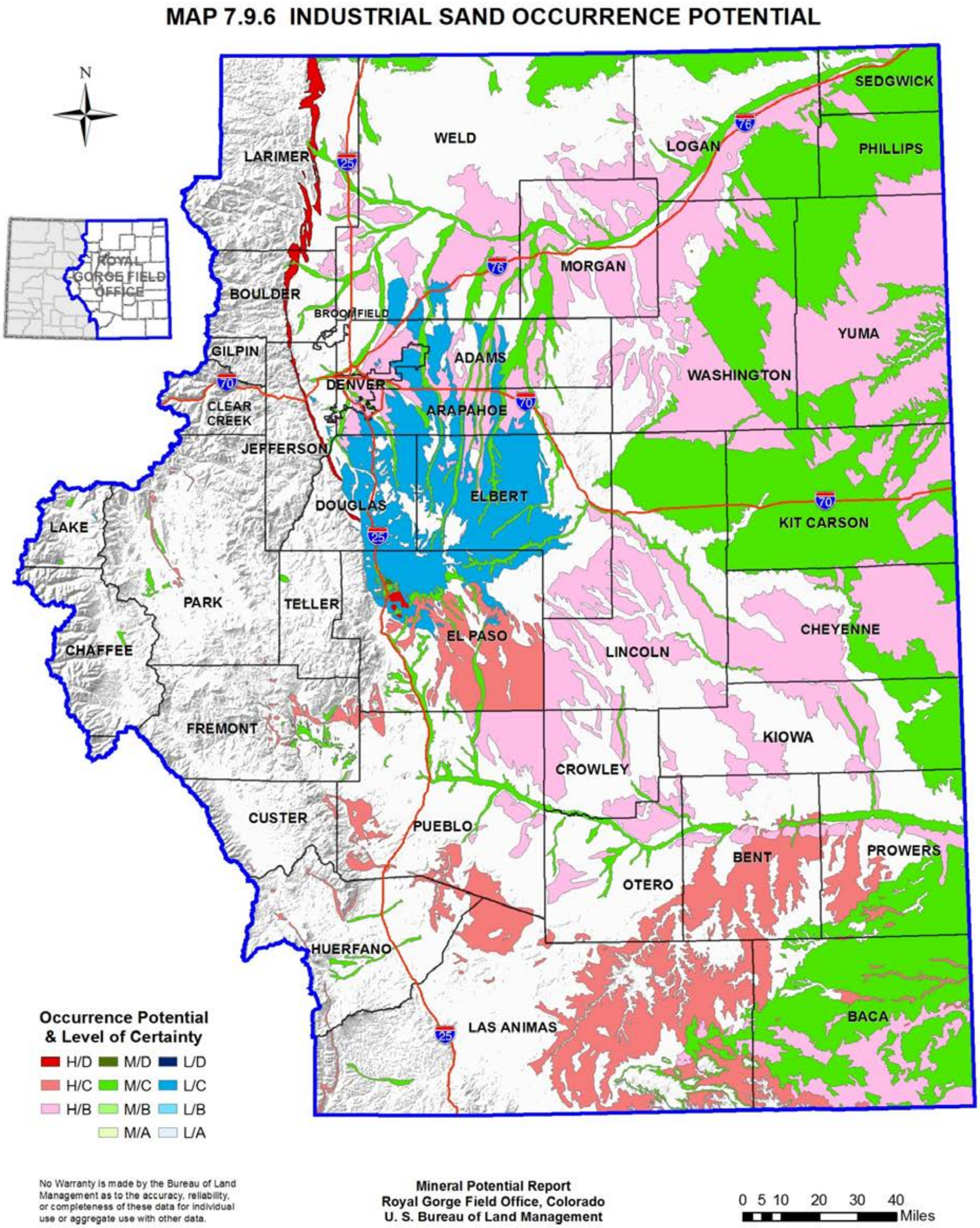
7.9.4 *Industrial Abrasives*



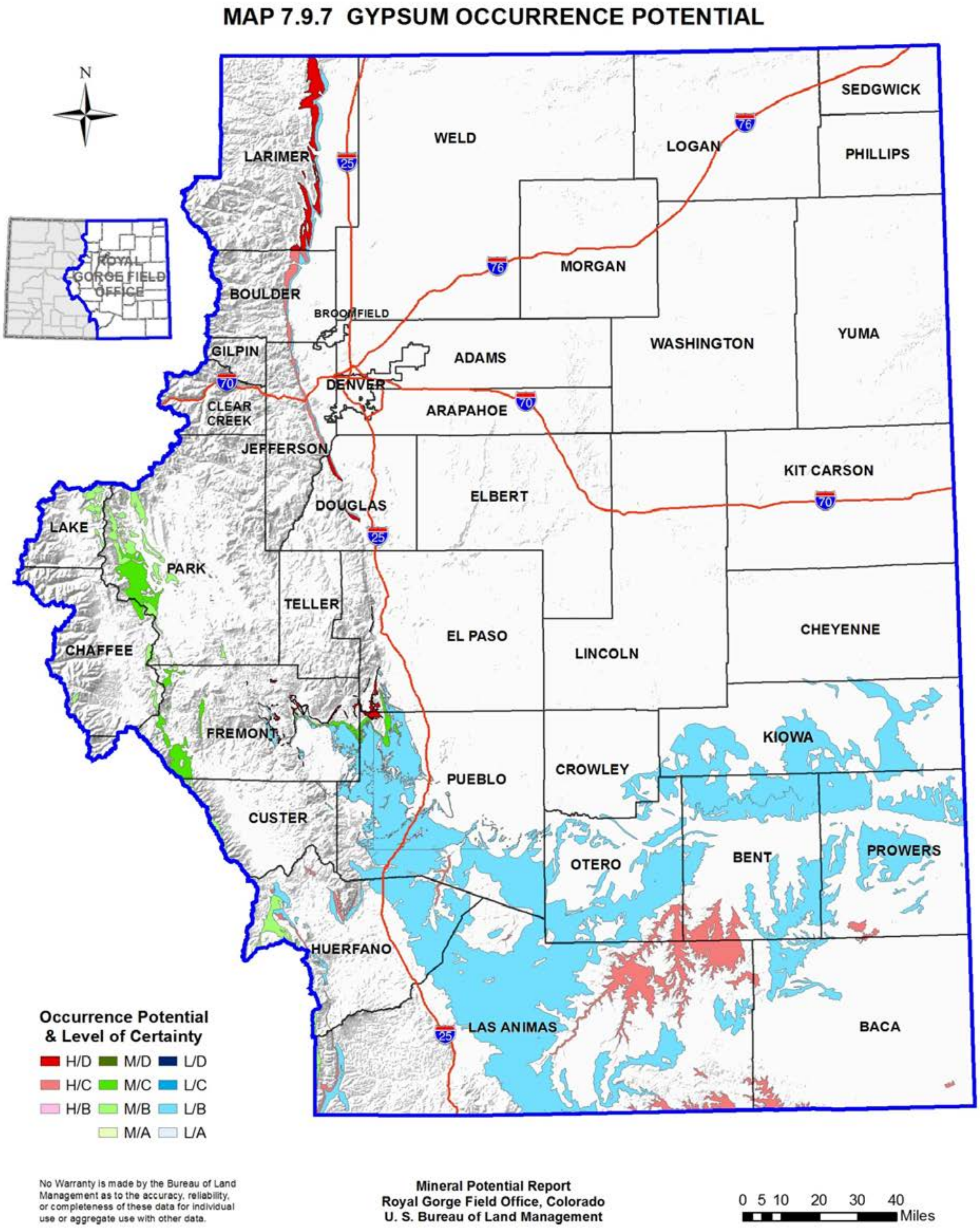
7.9.5 *Limestone and Dolomite*



7.9.6 Industrial Sand



7.9.7 Gypsum


MAP 7.9.7 GYPSUM OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
LARIMER
WELD
LOGAN
SEDGWICK
PHILLIPS
MORGAN
BOULDER
BROOMFIELD
GILPIN
ADAMS
WASHINGTON
YUMA
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
KIT CARSON
DOUGLAS
ELBERT
LAKE
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TELLER
EL PASO
CHEYENNE
CHAFFEE
LINCOLN
FREMONT
KIOWA
CROWLEY
PUEBLO
CUSTER
OTERO
BENT
PROWERS
HUERFANO
LAS ANIMAS
BACA
25
70
76
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
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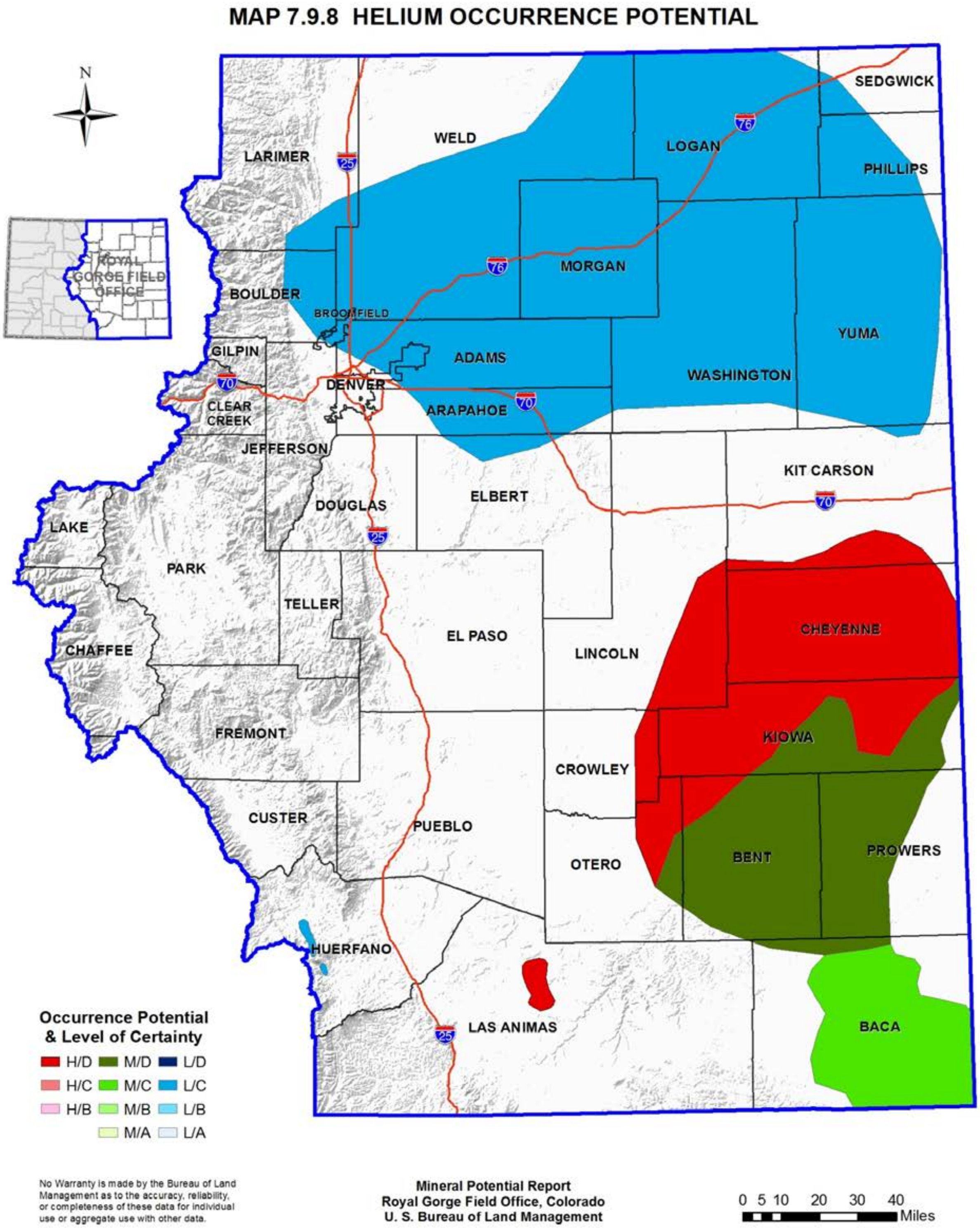
0 5 10 20 30 40
Miles

7.9.8 Helium


MAP 7.9.8 HELIUM OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
SEDGWICK
WELD
LOGAN
LARIMER
PHILLIPS
MORGAN
BOULDER
BROOMFIELD
YUMA
GILPIN
ADAMS
WASHINGTON
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
KIT CARSON
ELBERT
DOUGLAS
LAKE
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CHEYENNE
EL PASO
LINCOLN
CHAFFEE
KIOWA
FREMONT
CROWLEY
CUSTER
PUEBLO
BENT
PROWERS
OTERO
HUERFANO
LAS ANIMAS
BACA
Occurrence Potential & Level of Certainty
H/D M/D L/D
H/C M/C L/C
H/B M/B L/B
M/A L/A
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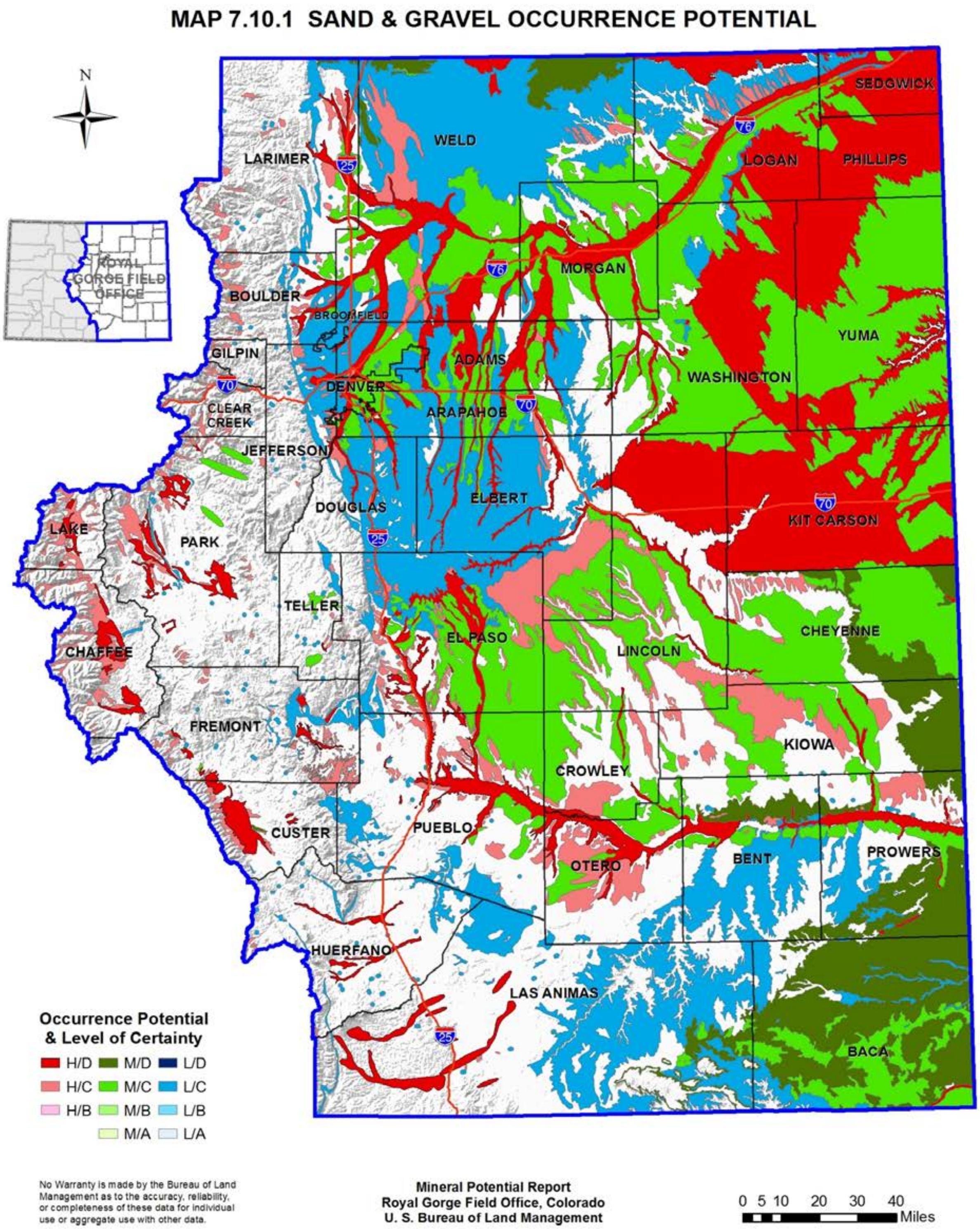
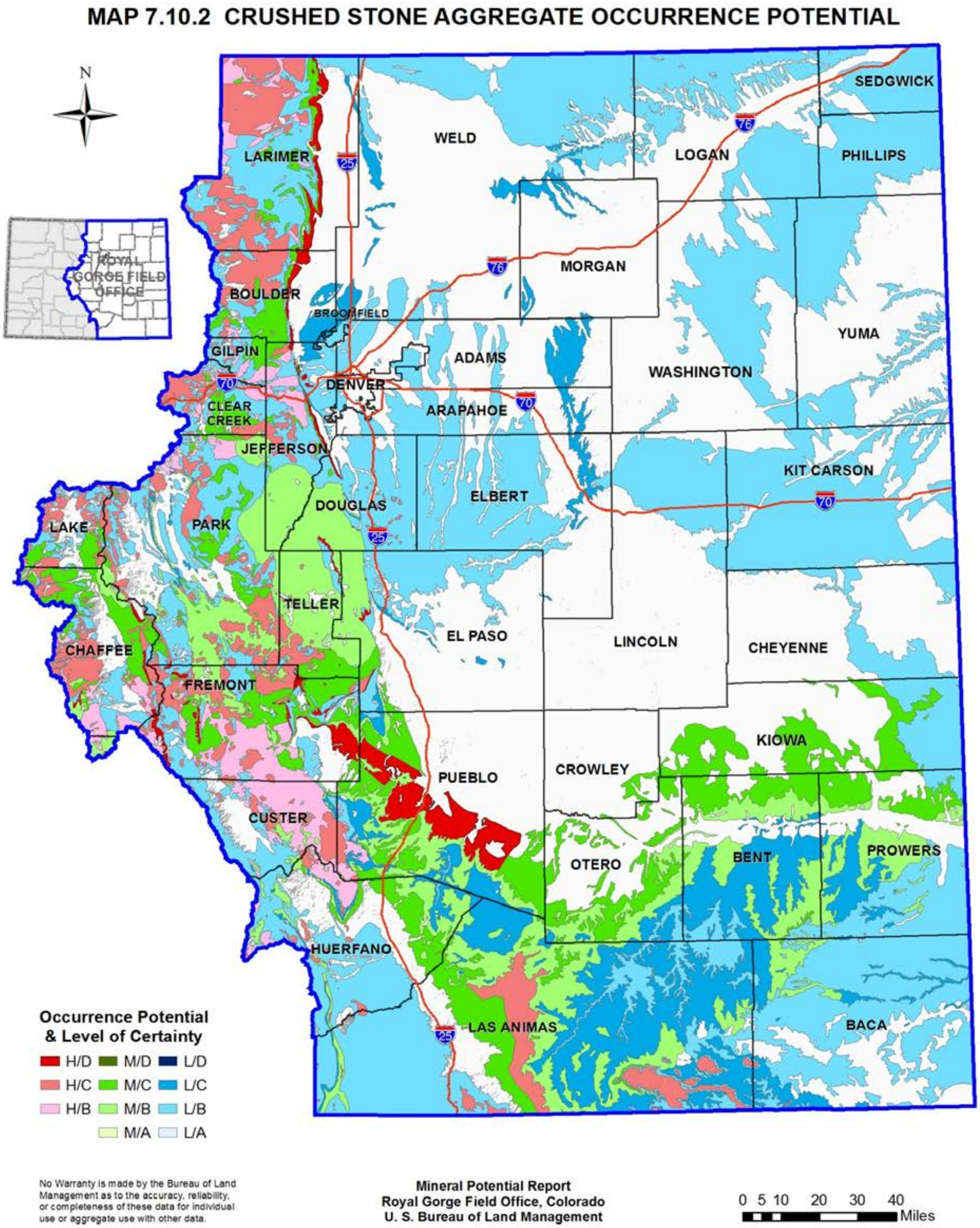
0 5 10 20 30 40 Miles

7.10 Construction Materials

7.10.1 Sand and Gravel

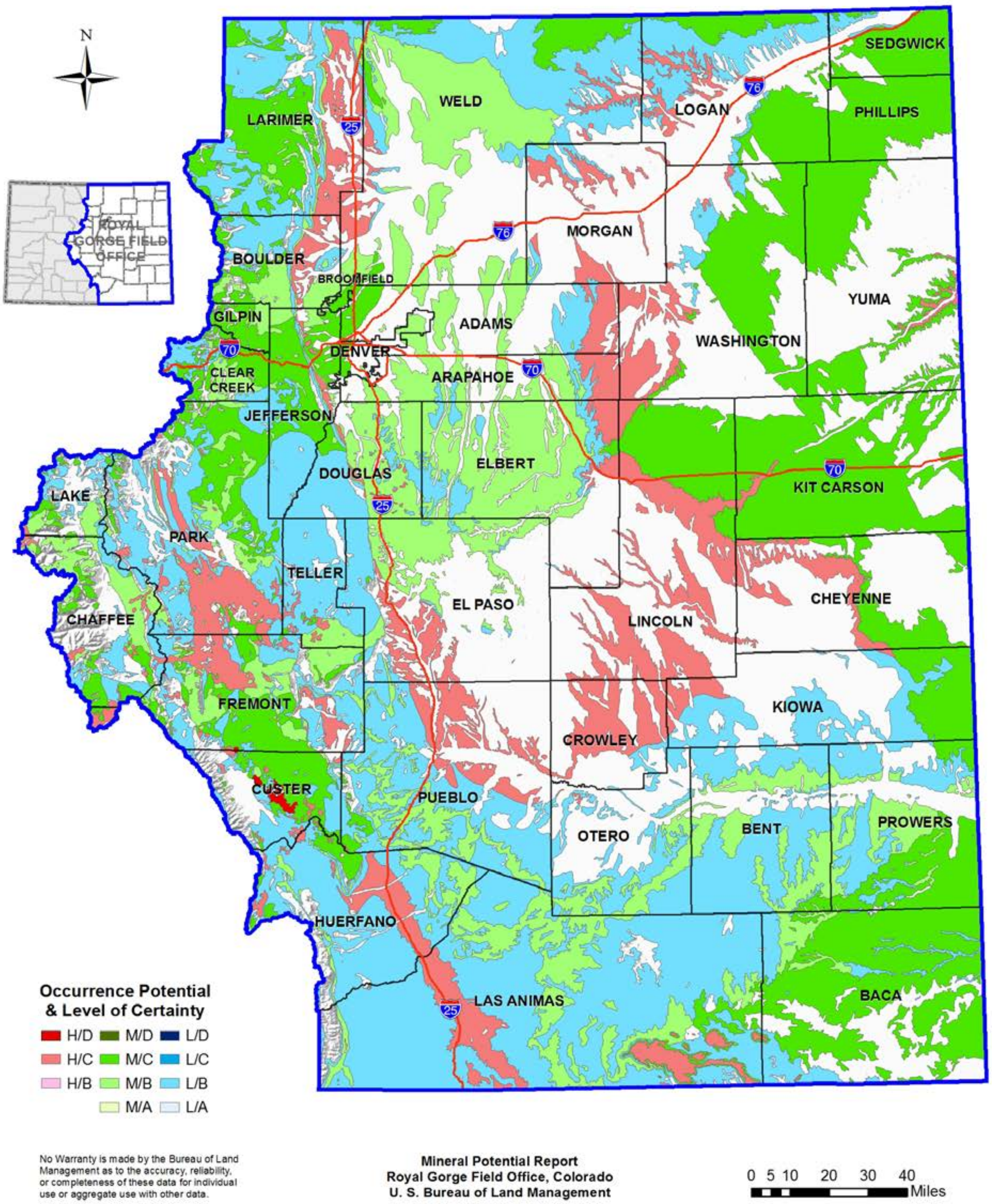


7.10.2 Crushed Stone Aggregate

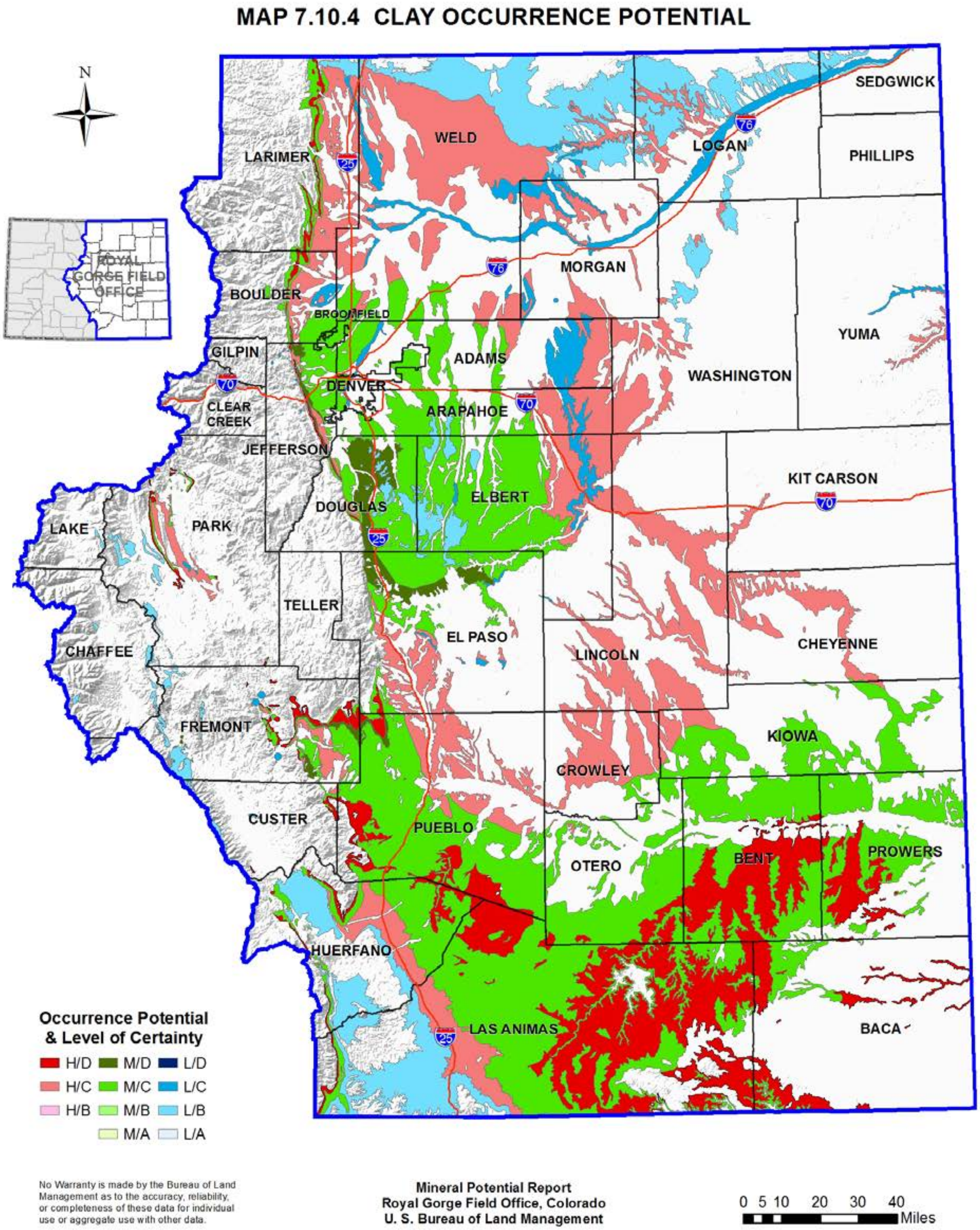


7.10.3 Lightweight Aggregate

MAP 7.10.3 LIGHTWEIGHT AGGREGATE OCCURRENCE POTENTIAL



7.10.4 Clay


MAP 7.10.4 CLAY OCCURRENCE POTENTIAL
N
ROYAL GORGE FIELD OFFICE
SEDGWICK
LOGAN
PHILLIPS
WELD
LARIMER
MORGAN
BOULDER
BROOMFIELD
YUMA
GILPIN
ADAMS
WASHINGTON
DENVER
CLEAR CREEK
ARAPAHOE
JEFFERSON
KIT CARSON
DOUGLAS
ELBERT
LAKE
PARK
TELLER
EL PASO
CHAFFEE
LINCOLN
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CUSTER
PUEBLO
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HUERFANO
LAS ANIMAS
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Occurrence Potential & Level of Certainty
H/D
M/D
L/D
H/C
M/C
L/C
H/B
M/B
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M/A
L/A
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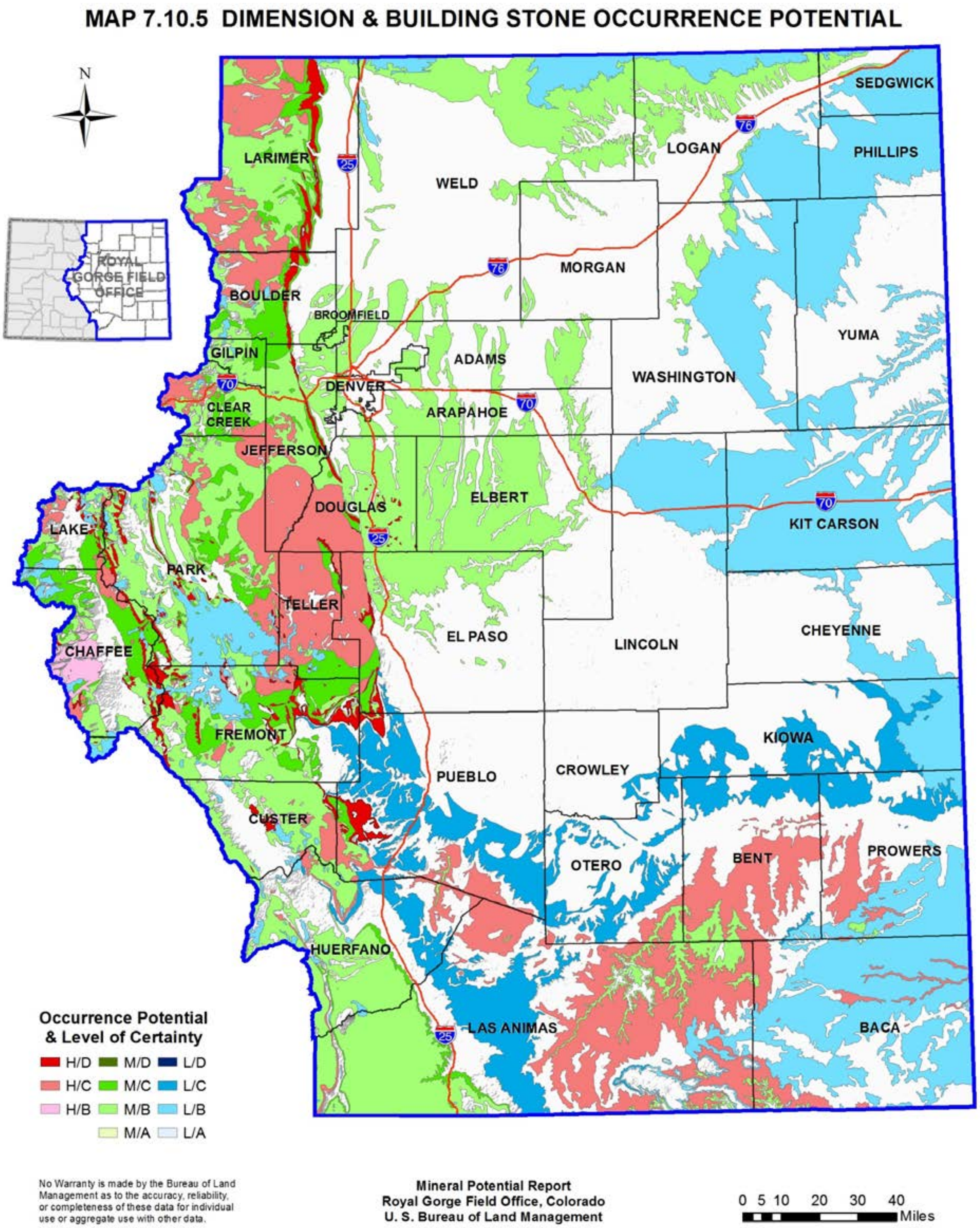
0 5 10 20 30 40
Miles

7.10.5 Dimension and Building Stone



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