Appendix F3.2

Geologic Resources

Geologic Resources

Geologic History of the Project Area

The geologic history of the eastern Great Basin is preserved in rocks and geologic structures that span more than a billion years, ranging from Precambrian sedimentary and metamorphic[1] rocks to Quaternary alluvial basin deposits (Sweetkind et al. 2007) (**Table F3.2-1**). The geologic evolution of the project area can be divided into three general phases (Levy and Christie-Blick 1989). These phases are described below.

Late Precambrian to the Middle Paleozoic. This period was dominated by sedimentation on the western continental margin of the North American plate. Limestones, shales, and sandstones were deposited in shallow to deep marine environments on a relatively stable continental shelf environment similar to that found today along the Atlantic and Gulf Coast margins of the Unites States (U.S.) (Blakey 1997). Carbonate[2] rocks formed in a "carbonate platform" geologic setting that contained shallow water reef and backreef sediments along with forereef and deep water sediments to the west. Sedimentary rocks accumulated to a maximum thickness of about 30,000 feet during this phase and these rocks constitute the vast majority of rocks found in the project area (Sweetkind et al. 2007).

Middle Paleozoic through Early Tertiary. The Antlers orogeny[3] during late Devonian and Mississippian interrupted the deposition of carbonate platform sediments and resulted in the thrusting of volcanic and sedimentary rocks eastward over the carbonate rocks. This gradual thrusting took place over millions of years and resulted in the deposition of a thick sequence of siliciclastic[4] rocks over the carbonate rocks in advance of the slowly moving thrust plates (Poole and Sandberg 1977). Carbonate deposition resumed in the late Paleozoic (Pennsylvanian and Permian periods) and generated a thick sequence of sediments. During the early to middle Mesozoic in the southern part of the project area, sedimentary rocks were deposited in both continental and shallow marine environments. A second deformation event started in the late Jurassic and lasted through the early Tertiary. This major compressive event, referred to as the Sevier orogeny, resulted in regional folding, thrusting, igneous intrusions, and deformation of all previous sedimentary rocks and created the complex stratigraphic patterns found in the mountain ranges of the region of study today.

Middle through Late Cenozoic. The last period includes the Basin and Range faulting that created the alluvial basins and mountain ranges of the project area. The third major phase of geologic history in the project area began with extensive volcanism that started in the Eocene (early Tertiary) and lasted through the Miocene. Huge caldera[5] complexes formed throughout the Great Basin and covered most of the exposed geologic units with extensive sheets of ash-flow and air-fall tuffs (Best et al. 1989). The Paleozoic and Mesozoic geologic units deformed by the Sevier orogeny had been mostly eroded by the beginning of this third geologic phase, and the terrain onto which the extensive volcanic and volcaniclastic units were deposited was relatively level. Major ash-flow units, such as the Needles Range Tuff, which erupted from the Indian Peak Caldera in western Utah, can be traced for tens of miles in both Utah and eastern Nevada. Following this period of volcanism came extensional faulting, block uplifting, and formation of the Basin and Range topography that characterizes the region of study today. In summary, the mountain ranges of the project area are comprised of carbonate and clastic rocks from the Paleozoic and Mesozoic overlain by volcanic rocks of Tertiary age.

[1] Rocks modified in their mineralogy and texture resulting from high pressures and temperatures.
[2] Calcium carbonate or limestone.
[3] An episode of mountain building.
[4] Sedimentary rocks formed from transported rock fragments largely composed of silicate minerals.
[5] Caldera is a term for large basins or craters created by explosive volcanic eruptions.

Table F3.2-1 Summary of the Geologic History of the Project Area

Era	Period		Millions of Years Before Present	Major Geologic Events
Cenozoic	Quaternary	Holocene Pleistocene	1.6-0	Crustal extension continued resulting in additional mountain building, volcanism, and geothermal activity. Intermontane basins filled with alluvium and, locally, lacustrine deposits. Glaciers formed in the higher mountains more than 10,000 years before present, resulting in some of the topographic features of the higher mountains.
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	65-1.6	Crustal extension began 20 million years before present. The extension resulted in normal faulting, mass gravity sliding, and igneous activity. Several volcanic caldera complexes were emplaced during this period, and a large volume of Tertiary volcanics were extruded onto the surface. As extension continued and volcanic activity subsided, the basins began to fill with alluvial sediment.
Mesozoic	Cretaceous		144-65	During the Cretaceous, thrusting from Sevier Orogeny caused folding and faulting and movement of large sheets of rock from west to east. Several granitic intrusives were emplaced at this time, including some of those in the Ruth Mining District near Ely.
	Jurassic		208-144	Intrusion of igneous rock in the vicinity of the present-day Snake Range. The Aztec Sandstone was deposited in Clark County. Sedimentary rocks were not deposited or were later eroded in other areas of the region.
	Triassic		245-208	The Moenkopi, Chinle, and other formations were deposited in continental and shallow marine conditions over portions of the region.
Paleozoic	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian		286-245 320-286 360-320 408-360 438-408 505-438 570-505	During most of Paleozoic time, shallow marine conditions persisted resulting in the deposition of thousands of feet of limestone, shale, and lesser amounts of quartzite. During the early Cambrian, quartzites and shales were deposited, followed by the deposition of carbonates throughout most of the rest of the Paleozoic Era. The Antler Orogeny occurred from the Devonian through the Mississippian, creating a topographic high in north-central Nevada. During this time, clastic rocks of the Chainman Shale, Diamond Peak Formation, and other units were deposited in east-central Nevada. The deposition of carbonates resumed after the end of the Antler Orogeny. In the Permian Period, the sediments became more clastic, with the deposition of sands interbedded with the carbonates.
Precambrian			1,450-570	Igneous and metamorphic rocks formed on ancient crust. Eventually a stable continental margin is formed resulting in deposition of the Johnnie Formation, the McCoy Group, the Prospect Mountain Quartzite, which overlaps into the Cambrian, and other clastic units. The stable continental margin persisted throughout most of Paleozoic time.

Sources: Tschanz and Pampayan 1970; Hose et al. 1976; Price 2004; Peterson and Grow 1995; Rowley and Dixon 2001.

Stratigraphy

The geologic units in the study area range from Precambrian in age (more than 570 million years ago [Ma]) to recent deposits (**Table 3.2-1**). **Figure F3.2-1** is a composite stratigraphic column of White Pine County that illustrates the formation sequence through time. This figure also includes the geologic map symbols shown on **Figure F3.2-2** and the associated hydrogeologic units (HGUs) developed by SNWA and BLM (2008). The HGUs were developed by grouping geologic map units with similar lithologic properties and inferred ability to transmit water. These units are further described in Section 3.3.3 1, Hydrogeologic Conditions, and in **Table 3.3-12**. Aquifer Characteristics in the Region of Study. Composite stratigraphic columns are presented for Lincoln County, Nevada (**Figure F3.2-3**), Clark County, Nevada (**Figure F3.2-4**), and Western Utah (**Figure F3.2-5**). The following paragraphs provide a regional overview of the stratigraphic sequences, from oldest to most recent.

The Precambrian rocks consist of metamorphic and igneous rocks overlain by later Precambrian quartzites and argillites. The Precambrian quartzites and argillites are found in the Johnnie Formation, the McCoy Creek Group, the lower part of the Prospect Mountain Quartzite, the latter of which overlaps into the Cambrian, and other quartzitic units (Tschanz and Pampeyan 1970; Hose et al. 1976).

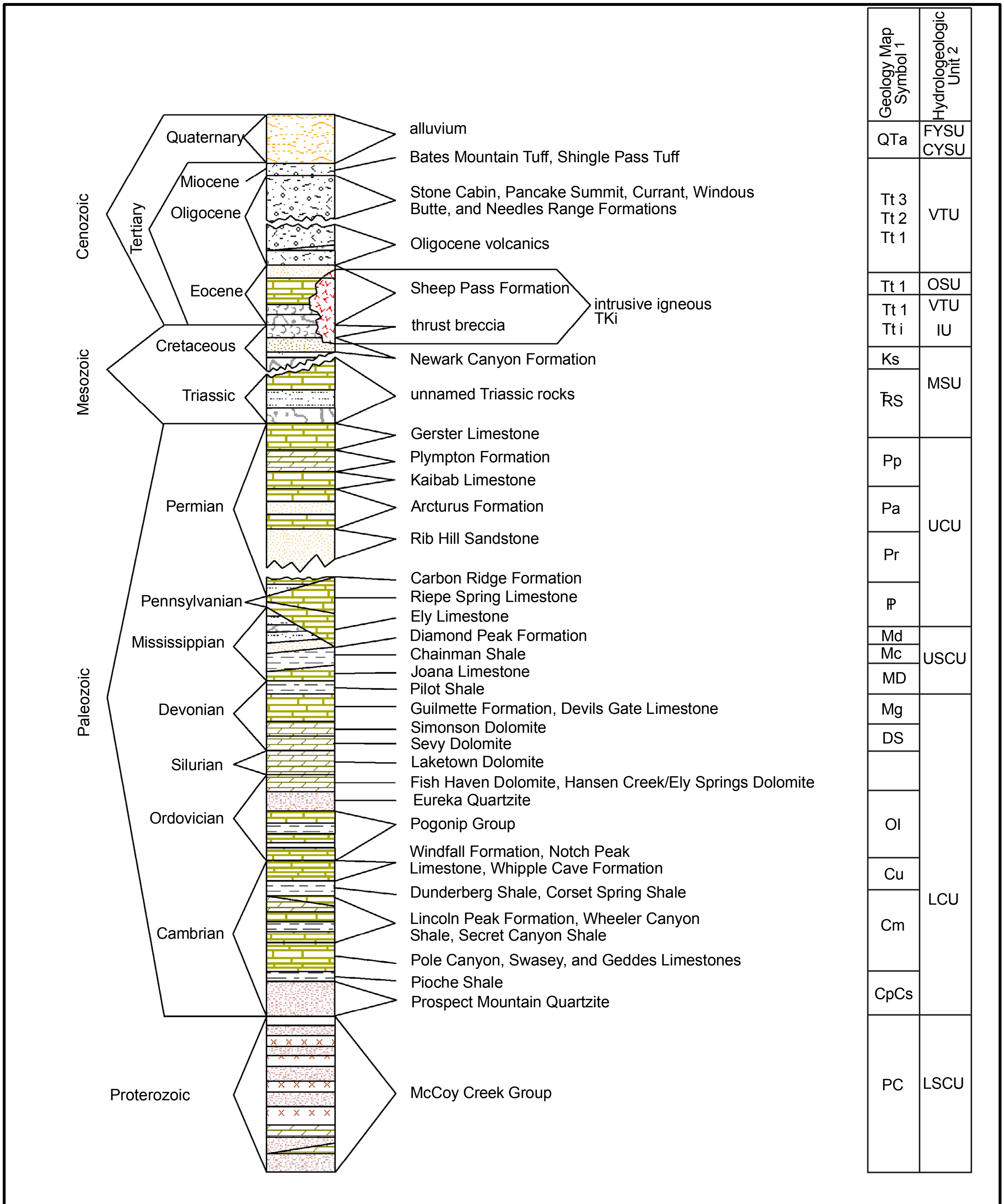
The entire section of sedimentary rock from Cambrian through Permian (Paleozoic Age) is up to 35,000 feet thick and consists primarily of limestone, dolomite, shale, sandstone, and quartzite. The Paleozoic section also includes metamorphic rocks derived from tectonic events or altered by emplacement of igneous rocks (Tschanz and Pampeyan 1970).

Sedimentary rocks of the Mesozoic Age consist primarily of sandstone and shale, are up to about 10,000 feet thick, and belong to the Moenkopi and Chinle Formations and the Aztec Sandstone. The Mesozoic rocks are found primarily in southeast Lincoln County and in Clark County. Jurassic and Cretaceous intrusive igneous rocks consisting of monzonite, quartz monzonite, and granodiorite are exposed locally throughout the region (Longwell et al. 1965; Tschanz and Pampeyan 1970; Hose et al. 1976).

The Tertiary section is composed primarily of sedimentary deposits and volcanic rocks. The Tertiary sedimentary formations described below are not continuous over the area and are defined in local areas. Equivalents may be present from basin to basin, but are not identified as distinct formations. These sedimentary deposits are part of the basin-fill sediments that range in age from lower Tertiary to Recent. The thickness of the basin fill varies from basin to basin, but can be thousands of feet thick. The oldest sedimentary unit is the Sheep Pass Formation that is slightly more than 3,000 feet thick and is composed of lake-derived limestone, sandstone, and siltstone (Hose et al. 1976). The type section for the Sheep Pass Formation is located on the crest of the Egan Range. The lower part of the formation is a conglomerate that is composed of fragments from older Paleozoic formations. Invertebrate and vertebrate fossils in the formation indicate that it is Eocene in age, but Peterson and Grow (1995) also indicate that it also may be Paleocene. Age equivalent lacustrine limestones and clastic rocks were also deposited in other areas of the region, as in the North Pahroc Range.

Other later Tertiary-age sedimentary deposits include the Pliocene Muddy Creek and Panaca Formations that are found in the southern part of the area. The units were deposited in lakes and consist of sand, silt, clay, and limestone (Tschanz and Pampeyan 1970). Other younger Tertiary sedimentary deposits are present in the district, but have no specific formation names, but were dated on the basis of the presence of vertebrate fossils (Hose et al. 1976).

Much of the Tertiary rocks are composed of volcanic-derived materials, primarily ash-flow and ash-fall tuffs, that erupted from a number of volcanic centers or calderas. The Tertiary volcanic rocks range in age from late Eocene to Pliocene, but the thickness is undetermined. Some measured sections are over 2,000 feet thick (Cook 1965). However, there is a general trend that the Tertiary volcanic rocks are thicker in the south (possibly from 5,000 to 10,000 feet thick) and thinner to the north (Tschanz and Pampeyan 1970; Hose et al. 1976). In some areas, the Tertiary sediments and volcanics are interbedded and some of the sedimentary deposits are composed primarily of volcanic materials. Tertiary intrusive rocks also are exposed locally in several of the ranges in the region. The intrusives include granite, granodiorite, monzonite, quartz monzonite, and diorite. These intrusives may have been the source for the rhyolitic, dacitic, quartz latitic, and andesitic volcanic ash-flow tuffs.



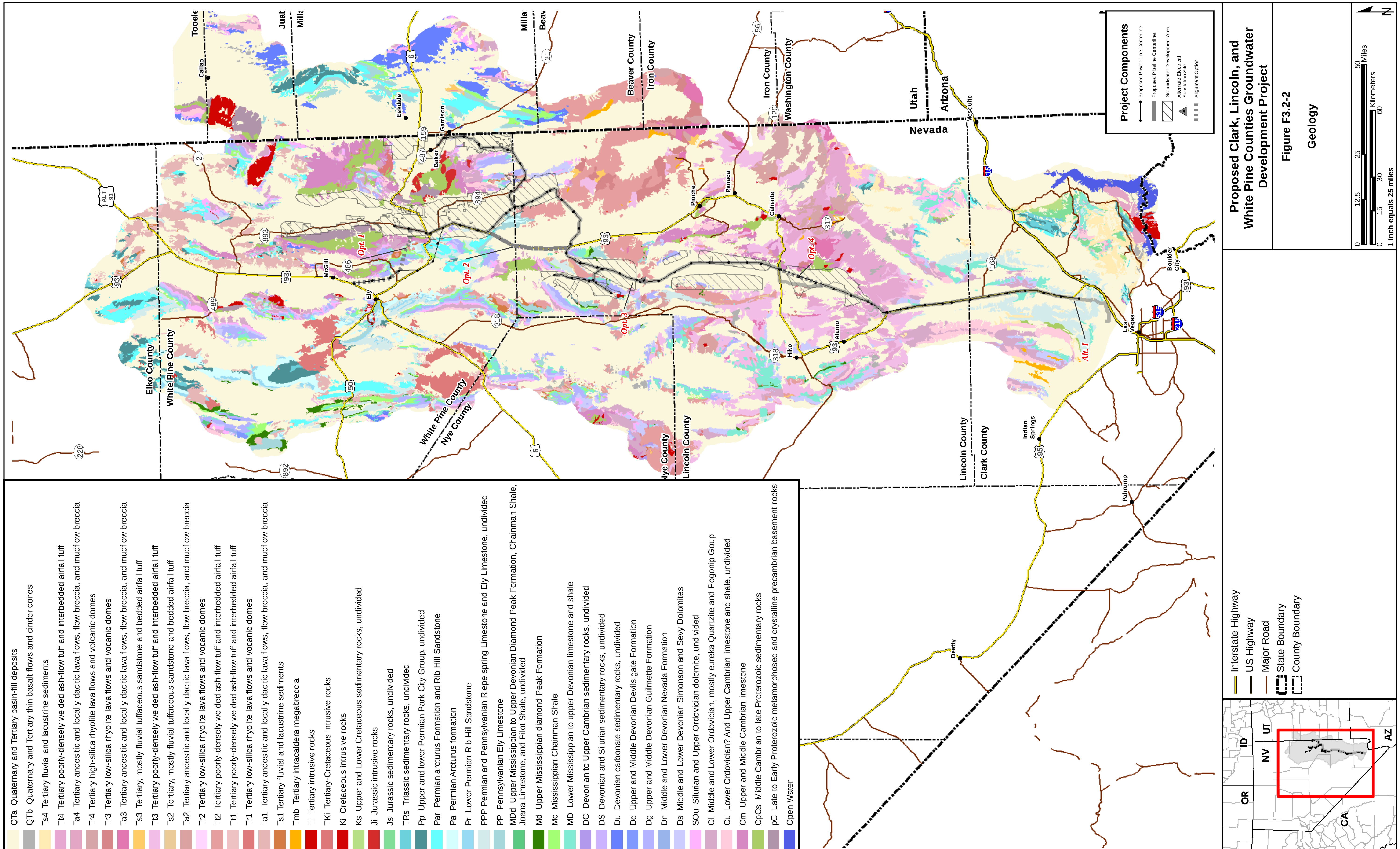
Notes:
1. Figure F3.2-2
2. Table F3.2-1

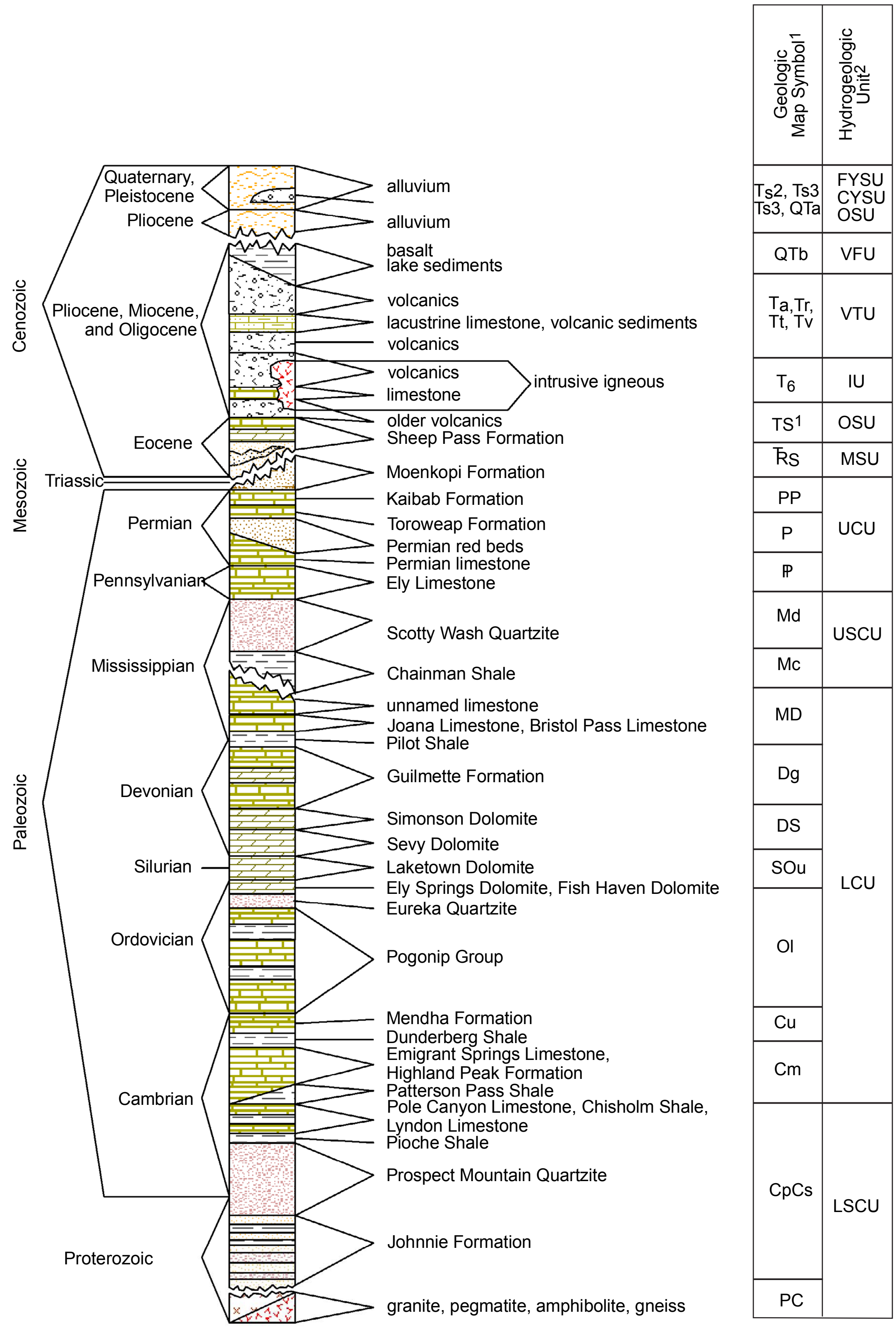
Proposed Clark, Lincoln, and White Pine Counties Groundwater Development Project

Figure F3.2-1

Composite Stratigraphic Column White Pine County, Nevada

Sources: Hose and Blake (1976) as cited in SNWA and BLM (2008)


Proposed Clark, Lincoln, and White Pine Counties Groundwater Development Project
Figure F3.2-2
Geology
Project Components
Proposed Power Line Centerline
Proposed Pipeline Centerline
Groundwater Development Area
Alternate Electrical Substation Site
Alignment Option
Interstate Highway
US Highway
Major Road
State Boundary
County Boundary
0 12.5 25 50 Miles
0 15 30 60 Kilometers
1 inch equals 25 miles
QTa Quaternary and Tertiary basin-fill deposits
QTb Quaternary and Tertiary thin basalt flows and cinder cones
Ts4 Tertiary fluvial and lacustrine sediments
Tt4 Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Ta4 Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Tr4 Tertiary high-silica rhyolite lava flows and volcanic domes
Tr3 Tertiary low-silica rhyolite lava flows and vocanic domes
Ta3 Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Ts3 Tertiary, mostly fluvial tuffaceous sandstone and bedded airfall tuff
Tt3 Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Ts2 Tertiary, mostly fluvial tuffaceous sandstone and bedded airfall tuff
Ta2 Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Tr2 Tertiary low-silica rhyolite lava flows and vocanic domes
Tt2 Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Tt1 Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Tr1 Tertiary low-silica rhyolite lava flows and vocanic domes
Ta1 Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Ts1 Tertiary fluvial and lacustrine sediments
Tmb Tertiary intracaldera megabreccia
Ti Tertiary intrusive rocks
TKi Tertiary-Cretaceous intrusive rocks
Ki Cretaceous intrusive rocks
Ks Upper and Lower Cretaceous sedimentary rocks, undivided
Ji Jurassic intrusive rocks
Js Jurassic sedimentary rocks, undivided
TRs Triassic sedimentary rocks, undivided
Pp Upper and lower Permian Park City Group, undivided
Par Permian arcturus Formation and Rib Hill Sandstone
Pa Permian Arcturus formation
Pr Lower Permian Rib Hill Sandstone
PPP Permian and Pennsylvanian Riepe spring Limestone and Ely Limestone, undivided
PP Pennsylvanian Ely Limestone
MDd Upper Mississippian to Upper Devonian Diamond Peak Formation, Chainman Shale, Joana Limestone, and Pilot Shale, undivided
Md Upper Mississippian diamond Peak Formation
Mc Mississippian Chainman Shale
MD Lower Mississippian to upper Devonian limestone and shale
DC Devonian to Upper Cambrian sedimentary rocks, undivided
DS Devonian and Silurian sedimentary rocks, undivided
Du Devonian carbonate sedimentary rocks, undivided
Dd Upper and Middle Devonian Devils gate Formation
Dg Upper and Middle Devonian Guilmette Formation
Dn Middle and Lower Devonian Nevada Formation
Ds Middle and Lower Devonian Simonson and Sevy Dolomites
SOu Silurian and Upper Ordovician dolomite, undivided
Ol Middle and Lower Ordovician, mostly eureka Quartzite and Pogonip Goup
Cu Lower Ordovician? And Upper Cambrian limestone and shale, undivided
Cm Upper and Middle Cambrian limestone
CpCs Middle Cambrian to late Proterozoic sedimentary rocks
pC Late to Early Proterozoic metamorphosed and crystalline precambrian basement rocks
Open Water
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.



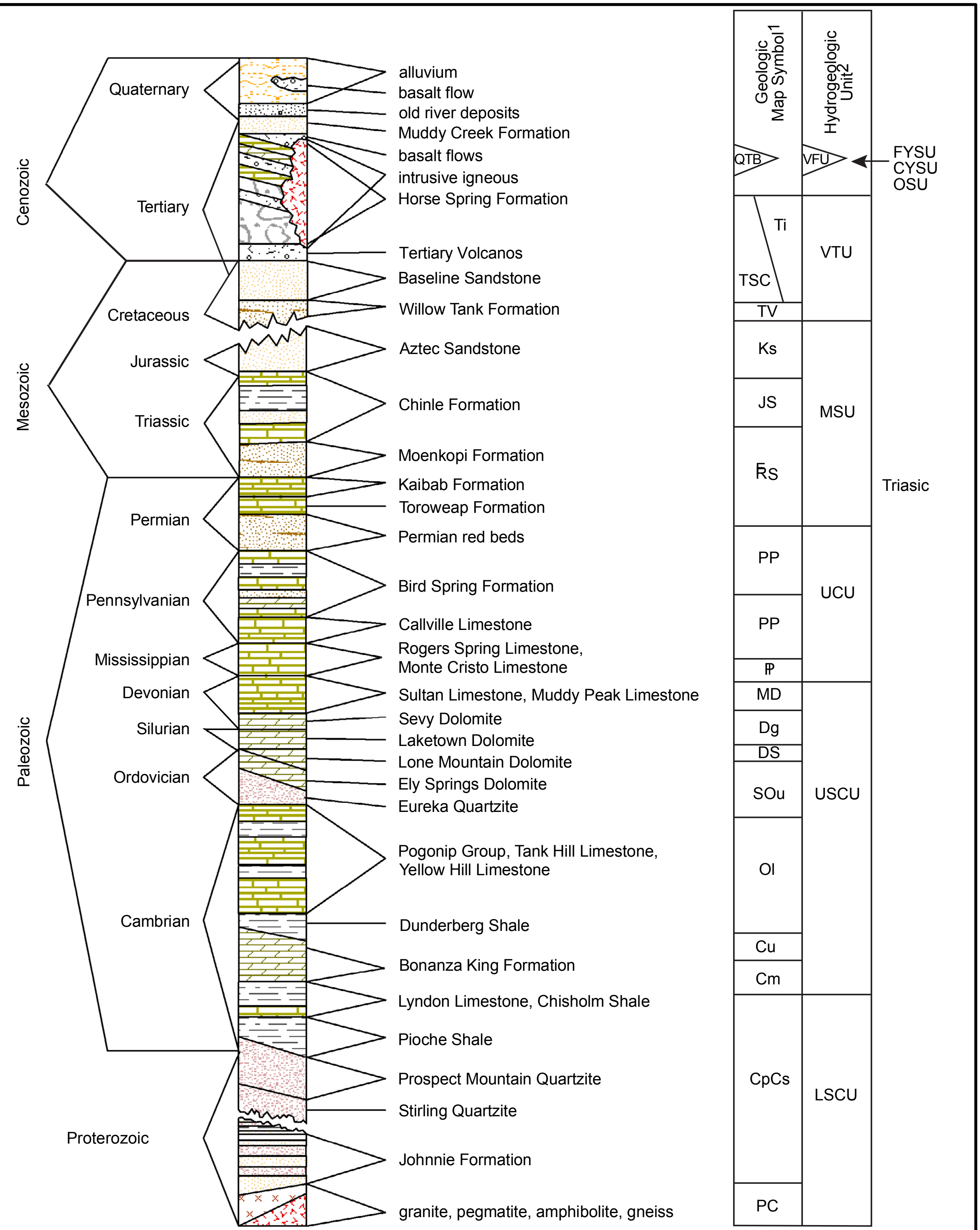
Source: Tschantz and Pampayan (1970) as cited in SNWA and BLM (2008)

Notes:
1. Figure F3.2-1
2. Table F3.2-1

Proposed Clark, Lincoln, and White Pine Counties Groundwater Development Project

Figure F3.2-3

Composite Stratigraphic Column, Lincoln County, Nevada



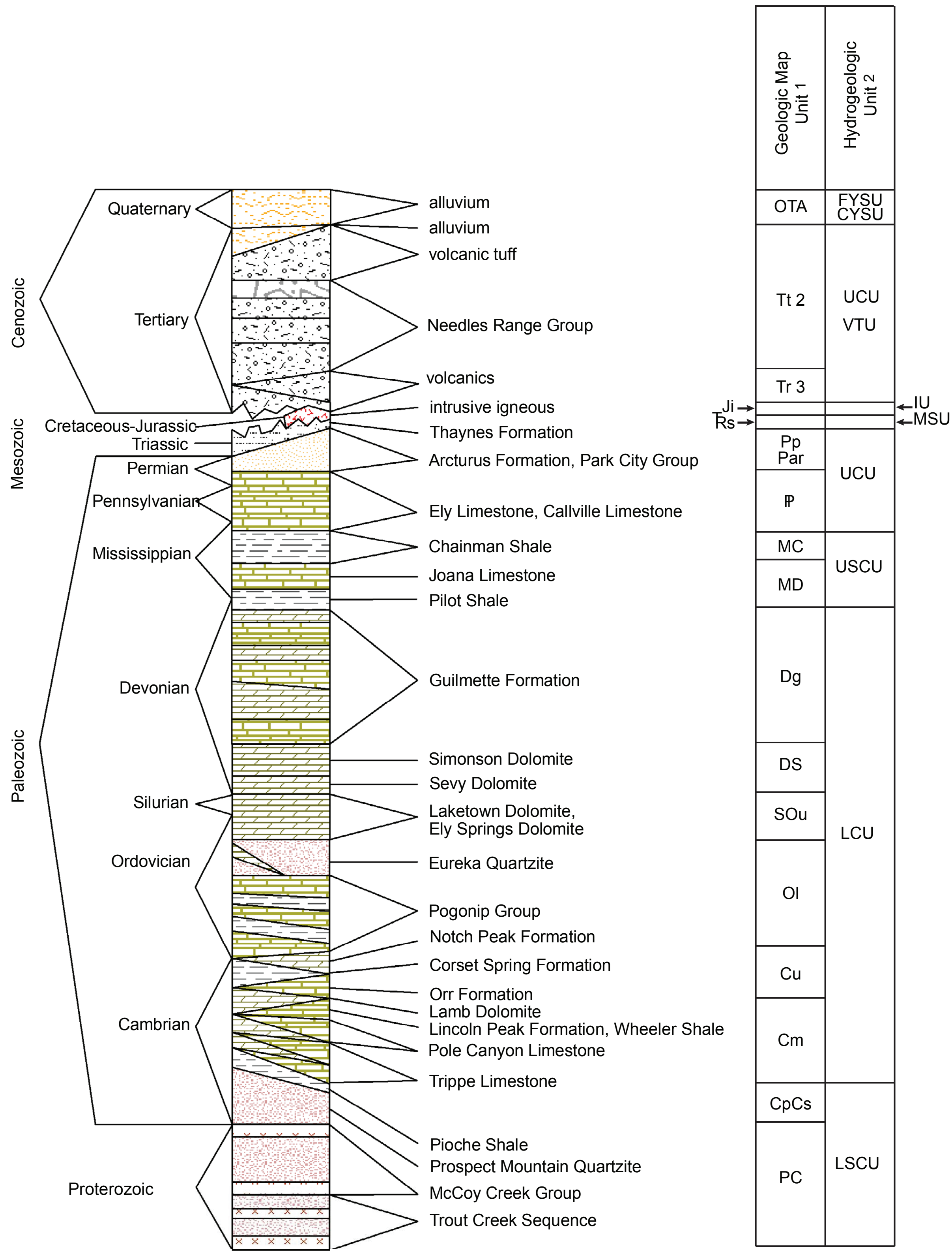
Source: Longwell et al., (1965) as cited in SNWA and BLM (2008)

Notes:
1. Figure F3.2-1
2. Table F3.2-1

Proposed Clark, Lincoln, and White Pine Counties Groundwater Development Project

Figure F3.2-4

Composite Stratigraphic Column, Clark County, Nevada



Source: Hintze, (1988) as cited in SNWA and BLM (2008)

Notes:
1. Figure F3.2-1
2. Table F3.2-1

Proposed Clark, Lincoln, and White Pine Counties Groundwater Development Project

Figure F3.2-5

Composite Stratigraphic Column Western Utah

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Unconsolidated sediments were deposited in all of the valleys in the region of study during the late Tertiary and Quaternary. These sediments (referred to as basin fill sediments) are generally unconsolidated, but may become increasingly semiconsolidated to consolidated with increasing thickness and depth. The thickness of these basin fill deposits varies between the basins with the maximum thickness generally ranging from approximately 1,000 feet to over 10,000 feet in individual basins (Welch et al. 2007). Sediments within the basin fill deposits include four different types of alluvial and lacustrine (i.e. lake) materials: 1) predominately coarse-grained sand and gravel deposited by streams as alluvial fans along the basin margins; 2) finer-grained silt and clay and playa deposits near the axis of the valley; 3) fine-grained silt, clay, sand and evaporites deposited within Pleistocene lakes; and 4) alluvial stream channel and floodplain deposits located near the central axis of the valley were valleys have active streams (such as the White River in White River Valley, and Pahranagat Creek and Pahranagat Wash in Pahranagat Valley and Coyote Springs Valley, respectively).

Late Pleistocene lake deposits associated with Lake Bonneville are present in the in the north and central portion of Snake Valley and extend as far south as Baker (Welch et al. 2007). Lake Bonneville was a large ancient lake that existed at the end of the ice age and at its largest extent covered most of the area in northwestern Utah and smaller portions of eastern Nevada and southeastern Idaho. Lake deposits associated with smaller Pleistocene lakes restricted to individual closed basins also occur within the basin fill sediments in Spring Valley and Cave Valley (Reheis 1999).

Structural Geology

The tectonic evolution of the eastern Great Basin has resulted in a number of structural features, many of which overlap, that can affect the movement of groundwater and hydrothermal fluids. Because the structural features may play an important role in groundwater movement within the mountain ranges, between the mountain ranges and the valley sediments, and especially between mountain ranges, this section summarizes these structural features with reference to the time period during which they were formed in the project area. These structural relationships are further discussed in Section 3.3.2, Water Resources.

There are four main tectonic events in the geologic history of the eastern Great Basin that have produced the structural features found today in the mountain ranges and also in the alluvial valleys and the basement rocks that underlie the alluvial valleys. These four tectonic events are: 1) the late Devonian to late Mississippian Antler orogeny; 2) the late Jurassic to early Tertiary Sevier orogeny; 3) the early to middle Tertiary period of extensive volcanism and caldera development with associated fault development; and 4) the late Cenozoic Basin and Range extension with associated graben[3] formation, uplift of mountain ranges, and eruption of basaltic lavas.

The Antler Orogeny. The Antler orogeny was a compressive deformation that caused the folding and east-directed thrusting of early Paleozoic rocks in the northwestern part of the project area. This folding and thrusting formed a north-trending highland that shed sediments eastward in advance of the moving thrust plates. Some of these thrust plates deformed and moved over the sediments deposited in front of them as the deformation progressed (Langenheim and Larson 1973; Carpenter et al. 1994). Most of the structural features associated with this period of deformation that are preserved today are west of the project area (SNWA and BLM 2008). Many of the fine-grained clastic sediments deposited east of the thrust sheets are preserved today in the project area.

The Sevier Orogeny. The Sevier orogeny resulted in widespread compressive deformation throughout the eastern Great Basin and formed numerous north to northeast trending eastward-verging folds and thrust faults. Major thrust sheets emplaced Precambrian and Paleozoic rocks over younger Paleozoic and Mesozoic units (Armstrong 1968). Tectonic shortening caused by the deformation was in the range of 22 to 45 miles in southern Nevada (Stewart 1980). For many of the thrust plates developed during this deformation, the present-day leading edge of the thrust plate is east of the project area in Utah. The project area contains what has been referred to as the western hinterland of the deformation. The Timpahute Range, the Worthington Mountains, the Golden Gate Range, Grant Range, Pancake Range, and Newark Valley contain remnants of this period of deformation (Taylor et al. 2000). Thrust faults associated with this period of deformation are commonly in the southern part of the project area and often contain gouge or

[3] A downthrown block between two normal faults of parallel strike, but opposing dips.

mylonitic[4] zones along the thrust plane that can inhibit the movement of water. These extensive thrust sheets also shoved carbonate rocks over clastic rocks and Precambrian metamorphic rocks over carbonate rocks.

Early to Middle Tertiary Volcanism. Extensive volcanism in the early to middle Tertiary produced numerous calderas with their associated ring-fracture faulting. This period of volcanism covered the eastern Great Basin with thick aerially extensive ash-flow tuff sheets. Many of the calderas were formed along structural lineaments related to extensional faulting in eastern Nevada and western Utah. Associated with the calderas were intrusion of igneous stocks, alteration of volcanics and pre-existing bedrock geologic units, and mineralization along faults, fractures, and other permeable pathways.

Basin and Range Extension and Graben Formation. The development of the Basin and Range physiographic province in the western U.S. began around 20 to 25 Ma and continues today. This physiography is characterized by east-west extension and the formation of a horst[5] and graben topography with north-south trending mountain ranges separated by intervening basins developed by graben faulting along normal faults that parallel the mountain ranges. Basin development changed somewhat after 10 Ma and some older basins were uplifted as new ranges were developed. An example is the presence of Miocene lacustrine limestones in the North Pahroc and Pahranagat ranges that were originally deposited in earlier basins (Tschanz and Pampeyan 1970).

The dominant fault type developed during this period was the normal fault that allowed for the formation of grabens and half-grabens by the downward movement of large structural blocks. The corresponding uplift of mountain ranges sometimes produced a form of gravity slide fault called a “detachment” fault where an upper block of competent rock slides along a low angle fault over a less competent rock composed of shale or other deformable fine-grained rock. An example is the Snake Range decollement. This type of fault is often found above a metamophic core complex of older rocks that have been stretched and thinned by uplift (Miller et al. 1983; Gans et al. 1989, 1985).

Basin and Range graben formation and the associated uplift of mountain ranges has resulted in fracturing of many competent lithologic units, especially the carbonate rocks.

[4]A very fine lithified fault breccia commonly found in major thrust faults and produced by shearing and rolling during fault movement.
[5]An elongate, elevated block of crust forming a ridge or plateau, typically bounded by parallel, outward-dipping normal faults.

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