Geologic and Hydrogeologic Framework for the Spring Valley Area

Presentation to the Office of the Nevada State Engineer

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SOUTHERN NEVADA WATER AUTHORITY

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Gary L. Dixon and Peter D. Rowley, consultants to the Southern Nevada Water Authority (SNWA) prepared this report entitled *"Geologic and Hydrogeologic Framework for the Spring Valley Area"*, June, 2006. This report is one of several reports prepared in support of SNWA groundwater applications 54003 through 54021 in Spring Valley (Hydrographic Area 184).

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List of Acronyms and Abbreviations

AMT	Audiomagnetotellurics
ft	foot (feet)
GSLDFS	Great Salt Lake Desert Flow System
km	kilometers
m	meters
Ma	million years
MVFS	Meadow Valley Flow System
NTS	Nevada Test Site
RMU	Regional Model Unit
SNWA	Southern Nevada Water Authority
US 50	US Highway 50
US 6	US Highway 6
USGS	U.S. Geological Survey
WRFS	White River Flow System

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ES.1.0 EXECUTIVE SUMMARY

Spring Valley is a 110-mile-long, north-trending valley in eastern White Pine and northeastern most Lincoln Counties, Nevada. The valley is a closed basin with an elevation of its floor between 5,600 and 7,000 feet (ft). The valley is bounded on either side by abrupt mountain ranges, as high as 13,000 ft. By far the longest among these are the Schell Creek Range on the west and the Snake Range on the east. Spring Valley and its neighboring basins and ranges are part of the Great Basin subprovince of the Basin and Range physiographic province. As such, Spring Valley is a structural basin (the geologic term is a graben) bounded by and downthrown along large high-angle normal and oblique-slip faults formed by regional east-west extension, that is pulling apart in an east and west direction. Most of this extension took place in the last 10 million years, namely in middle Miocene, Pliocene, and Quaternary time, during the structural episode known as basin-range tectonism. This tectonism produced the present topography, characterized by alternating north-trending basins and ranges.

The geology of Spring Valley produces faults that trend north. The adjacent mountains are similarly bounded by these faults, but the ranges are upthrown along these faults (called horsts). The vertical throw along some of these faults locally exceeds 30,000 ft. After subsidence along faults, the structural graben that is beneath Spring Valley was filled by sediments derived from erosion of the adjacent ranges. These basin-fill sediments are up to 6,000 ft thick beneath some parts of Spring Valley. Faulted bedrock units underlie the basin-fill sediments and make up the ranges surrounding Spring Valley. These units consist largely of (1) Late Proterozoic to Early Cambrian quartzite confining units as much as 9,000 ft thick, (2) Middle Cambrian to Permian carbonate rocks as much as 30,000 ft thick, not including the Mississippian Chainman Shale confining unit of about 2,000 ft thick midway in this part of the stratigraphic section, and (3) Tertiary volcanic rocks as much as 4,000 ft thick. Cretaceous and Tertiary stocks intrude these rocks, and in the Snake Range a Jurassic batholith is prominently exposed; these intrusions are confining units. The presence of confining units in the ranges that surround Spring Valley act as barriers to most flow through the ranges

Groundwater is abundant beneath Spring Valley. Previous studies interpret water level data to indicate that groundwater generally flows southward. Spring Valley is part of the Great Salt Lake Desert Groundwater Flow System. Water-level measurements indicate that parts of the groundwater in Spring Valley exit the southern part of the valley eastward through the low, narrow Limestone Hills, just south of the Snake Range. From there the groundwater enters northern Hamlin Valley and southern Snake Valley, then flows northward and northeastward to its ultimate sink beneath the Great Salt Lake Desert. Movement of groundwater in the valley and the ranges is largely along fault zones. Passage of groundwater out of Spring Valley, as previously stated, is supported geologically in the Limestone Hills because the Hills are topographically low, are cut by cross faults, and consist of brittle, fractured limestone with no significant confining units at or below the water table. Several other places on the margins of the valley are low and are cut by faults, but here passage of water out of the valley, while geologically permissible, is either more speculative or would appear to be minor.

The quantity and quality of groundwater beneath Spring Valley are directly due to the geology of Spring Valley and its adjacent mountains and valleys. Groundwater is partly stored and carried in large rock aquifers, most of them consisting of poorly cemented basin-fill alluvium, volcanic rocks, and brittle carbonate (limestone and dolomite). Delineation of aquifers is based on the study and understanding of the properties and extents of all rock types in the study area. Where rocks have been subjected to structural deformation, especially high-angle faulting, storage and transport of groundwater has been significantly enhanced in the fractured aquifers. Furthermore, the faults themselves store groundwater and provide both local barriers to groundwater flow and/or, more importantly, conduits to flow. The type and extent of these effects require an understanding of the episodes of regional deformation that the study area has undergone over time.

Determining the location and effect of aquifers and structures in the Spring Valley study area began by assembling and compiling all available geologic maps of the area. These provide the two-dimensional picture of the geologic framework that contains groundwater. The third dimension is provided by constructing geologic cross sections, based on interpretation of the maps, with data points constrained by subsurface information from published geophysics and oil- and water-well logs. In additional, new geophysical data, primarily gravity surveys and audiomagnetotellurics profiles, were contracted through the U.S. Geologic Survey. Following assembly of geologic maps and sections, hydrogeologic maps and sections were compiled by reordering stratigraphic units into hydrogeologic units, which are based on their properties as aquifers versus confining units. All maps and sections were done in a Geographic Information System digital format. These products were provided to hydrologists to create a groundwater flow model of the study area.

1.0 INTRODUCTION

This report describes the geology of all or parts of eight north-trending valleys in southeasternmost Elko, eastern White Pine, and northeastern Lincoln Counties, Nevada, and western Juab, Millard, Beaver, and Iron Counties, Utah. This report describes the geologic framework of an area of east-central and southeastern Nevada and adjacent western Utah to evaluate the effects of the geology on groundwater movement. The geologic framework was then incorporated into a groundwater model of the area.

Based upon previous studies which defined groundwater flow systems, four of these valleys are within the Great Salt Lake Desert Flow System (GSLDFS) (Harrill and Thomas, 1988). These are Spring Valley near the central part of the study area, Hamlin Valley to the southeast of Spring Valley, Snake Valley north of Hamlin Valley and east of Spring Valley, and Tippett (Antelope) Valley to the north, between northern Spring and Snake Valleys. Another valley, Steptoe Valley, part of the north-flowing Goshute Valley Flow System, is west of Spring Valley. Yet another valley, Lake Valley (northern Lake Valley), belongs to the south-flowing Meadow Valley Flow System (MVFS), which is part of the White River Flow System (WRFS). Lake Valley is southwest of Spring Valley. The seventh and eighth valleys, Cave Valley and northern Dry Lake (Muleshoe) Valley, belong to the WRFS and are respectively west and southwest of Lake Valley. The eight valleys are described below in this order. The geology of the mountain ranges adjacent to each valley is discussed first, from north to south and west to east, followed by the geology of each valley (Plate 1). The geophysics of the study area is then discussed.

Spring Valley is a 110-mile-long valley between both the north-trending Schell Creek Range and the north-northwest-trending Fortification Range on the western side of the valley, and the north-trending Antelope Range, Snake Range, and Limestone Hills on the east (Plate 1). All these ranges and hills are in Nevada. Of the ranges, the main ones are the long and high Schell Creek and Snake Ranges. Both commonly exceed 10,000 feet (ft) elevation, with peaks in the central Schell Creek Range close to 12,000 ft high, and peaks in the Snake Range (including Wheeler Peak, the centerpiece of Great Basin National Park) at about 13,000 ft. Spring Valley has closed surface drainage, resulting in two subbasins, one north of US Highway 6 (US 6) and US Highway 50 (US 50), and the other south of US 6/US 50. Groundwater flow, however, is southward through the valley, then at least partly into adjacent valleys. The floor of the northern subbasin of Spring Valley drops from about 7,000 ft elevation at the northern end to about 5,600 ft in its central playa. The floor of the southern subbasin trends north-northwest and drops from an elevation at its southern end of about 6,000 ft, where adjacent to the Limestone Hills, to about 5,800 ft in its central playa. At the point where southern Spring Valley bends from south to south-southeast, to follow the eastern side of the Fortification Range, a low northwest-trending cuesta of Paleozoic carbonate rocks stretches from the Schell Creek Range to the northern end of the Fortification Range and separates Spring Valley on the north from

Lake Valley on the south. Geologically this cuesta may be a drainage divide between Spring and Lake Valleys. Water-level data suggest that groundwater moves farther southeast in Spring Valley, and geology supports an interpretation that some groundwater flows east through the Limestone Hills into northern Hamlin Valley and from there north into Snake Valley. All Southern Nevada Water Authority (SNWA) water applications in Spring Valley are in the southern half of the valley, primarily on the western side and southern end.

Hamlin Valley is a 55-mile-long valley that is tributary to Snake Valley, entering Snake Valley from the southwest. On the western side of Hamlin Valley are, from north to south, the Limestone Hills and the White Rock Mountains, which are almost entirely in Nevada. The Limestone Hills only locally exceeds 7,500 ft elevation, whereas summits in the White Rock Mountains generally range from 8,000 to 9,000 ft. On the eastern side is the Needle Range, Utah, with summits that range from 8,000 to 9,500 ft. The floor of Hamlin Valley ranges from 6,800 ft at its southern end to 5,500 ft at its northern end, where it passes imperceptibly into Snake Valley. Surface water and, based on water-level data, groundwater flow northward in Hamlin Valley and into Snake Valley.

Snake Valley is a 95-mile-long, north- to north-northeast-trending valley east of the Snake Range that empties northward and northeastward into the Great Salt Lake Desert. The valley is forked at its southern end, with its eastern fork passing southeastward into tributary Pine Valley. The western fork passes southward into tributary Hamlin Valley, with no perceptible topographic break between the two. We define the location of the boundary between northern Hamlin Valley and southern Snake Valley at just east of the northern end of the Limestone Hills. On the western side of Snake Valley are, from north to south, the north-trending Deep Creek Range, Kern Mountains, and Snake Range. The Deep Creek Range attains elevations of about 12,000 ft, and the Kern Mountains attains elevations of more than 9,000 ft. All these mountains, except for the Deep Creek Range and eastern tip of the Kern Mountains, are in Nevada. On the eastern side of Snake Valley are the north- or northeast-trending Middle Range, Confusion Range, Conger Range, Burbank Hills, Tunnel Spring Hills, and northern Needle Range, all in Utah. These ranges are generally low, with summits not much more than 7,000 ft elevation, except for the northern end of the Needle Range, with summits approaching 9,000 ft. Tule Valley is east of the Confusion Range, and Pine Valley is east of the Needle Range. Where Snake Valley joins the Great Salt Lake Desert, east of the central Deep Creek Range, the elevation of the floor is about 4,400 ft. The communities of Baker, Nevada, and Garrison, Utah, are in central Snake Valley, east of the Snake Range and west of the Burbank Hills. Surface water and, based on water-level data, groundwater flow northward, toward their ultimate sink in the Great Salt Lake Desert.

Tippett Valley, also known as Antelope Valley, lies between the Antelope Range on the west and an unnamed series of low hills as well as the Kern Mountains on the east. The valley is 30 miles long in the project area, then continues through a narrow opening in bedrock another 30 miles farther north in Elko County to join Steptoe Valley. The Antelope Range and Kern Mountains rise to more than 9,000 ft elevation. The part of Tippett Valley in the project area is a closed basin at less than 6,000 ft elevation. However, based on water-level data, groundwater appears to travel northeast through the unnamed hills on its way to the Great Salt Lake Desert.

Steptoe Valley is 100 miles long in the project area, then continues north of the Currie Hills in southern Elko County another 40 miles to join Goshute Valley. On the western side of Steptoe Valley in the project area are the north-trending Cherry Creek and Egan Ranges, and on the eastern side is the Schell Creek Range. The Cherry Creek and Egan Ranges rise to more than 10,000 ft. Steptoe Valley is a closed basin in the project area, with most surface drainage flowing north to the playa of dry Goshute Lake adjacent to the Currie Hills and at less than 5,900 ft elevation; the southern end of the valley floor is at about 7,000 ft. Steptoe Valley contains the towns of Ely and McGill, Nevada. The major east-west transportation route, US 6/US 50, passes east through Ely, crosses the Schell Creek Range at Connors Summit, and crosses the Snake Range at Sacramento Pass; both passes are below 8,000 ft elevation.

Lake Valley, as the name is used here, is 35 miles long. On its western side are the southern Schell Creek and Fairview Ranges. On its eastern side are the Fortification and northern Wilson Creek Ranges. The southern Schell Creek Range contains peaks of almost 11,000 ft elevation (Mount Grafton, west of the Geyser Ranch), but range heights decrease farther south, and south of Patterson Pass they are as low as 7,500 ft. Summit elevations in the Fairview Range are from 7,000 to 8,800 ft. Range heights in the Fortification and northern Wilson Creek Ranges are as much as 8,000 to 9,000 ft, but a pass between the two ranges is only as high as 6,400 ft. Technically Lake Valley continues another 30 miles farther south, past the town of Pioche, Nevada, but the name Patterson Valley is applied here to southern Lake Valley. Lake Valley, as used here, is a closed basin of less than 6,000 ft elevation, whereas Patterson Valley is integrated to the drainage of Meadow Valley Wash.

Cave Valley is a 45-mile-long valley between the Egan Range on the west and the Schell Creek Range on the east. White River Valley, containing the communities of Preston and Lund, Nevada, is west of the Egan Range. Cave Valley is south of Steptoe Valley, the two valleys being separated by a narrow, northwest-trending rib of faulted Cambrian to Permian rocks that connects the two ranges. From this rib, at about the latitude of Lund, Nevada, the elevation of the valley floor falls from about 7,000 ft elevation to about 6,000 ft at the southern end of Cave Valley. Based on water-level data, this rib is a drainage divide for groundwater as well as surface water: groundwater in Steptoe Valley flows north, whereas groundwater in Cave Valley flows south. The southern end of Cave Valley is blocked where the two ranges come together in a faulted, low mass of Paleozoic and Tertiary rocks that become the North Pahroc Range farther south. Cave Valley consists of two distinct but connected portions, the northern part in White Pine County containing far thinner basin-fill sediments than the southern part, in Lincoln County.

Dry Lake Valley is a 65-mile-long valley, but for this report we discuss only the northern 20-mile-long part, also known as Muleshoe Valley, that is partly separated from the main part of Dry Lake Valley by several small, low hills of volcanic rocks that extend eastward across part of the valley floor. The ranges surrounding northern Dry Lake Valley are generally low, attaining elevations of 8,000 ft or more only locally in the southern Schell Creek and Fairview Ranges. The floor of northern Dry Lake Valley falls from about 6,400 ft at the north to about 5,200 ft in the south.

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2.0 TECHNICAL APPROACH

2.1 Geology and Hydrogeology - Purpose

The purpose of this report is to provide an overview of the geology of the map area and how that geology relates to the hydrogeology of that area. Certain geologic units have characteristics that make them capable of storing and transmitting groundwater. Alluvial material commonly has a relatively high storage capacity and hydraulic conductivity. However, portions of the alluvium may be clay-rich, reducing both storage capacity and hydraulic conductivity; this is also true when thick sequences of evaporates are interfingered with alluvium. Carbonate rocks are brittle and therefore have very high hydraulic conductivity along the resulting fractures, especially where solution cavities have formed along faults, joints, and bedding planes. Overall storage capacity of carbonate rocks thus is good. Sandstones may be moderately good aquifers in some areas where intergranular pore space or fractures are high, but in areas where the pores are filled with carbonate or silica cement, the sandstone may be a poor aquifer. This geologic investigation is, in part, an attempt to differentiate between aquifers and confining units with high and low hydraulic conductivity, respectively.

The geology is shown on a 1:250,000-scale digital geologic map (Plate 1) and cross sections (Plate 3). The explanation of the geologic units on the map and sections is given on Plate 2. In addition, a digital hydrogeologic map (Plate 4) and cross sections (Plate 5) show major hydrogeologic units that were compiled from the stratigraphic units of the geologic map.

A second purpose of this report is to evaluate the potential continuity of groundwater flow. The relative position of aquifers and confining units may have a major impact on the ability of groundwater to flow between one groundwater basin and another. A mountain range cored by a confining unit may all but prevent groundwater flow across the range. Another range underlain by carbonate rocks may allow groundwater flow between basins. Faults may also allow groundwater flow between basins even through poorly transmissive units, units that normally retard groundwater flow. Sedimentary confining units may retard flow in the vertical direction, as between carbonate rock aquifers. However, if there is faulting with considerable offset, the carbonate aquifers above and below the confining unit may be juxtaposed, thereby allowing groundwater flow between the aquifers. This geologic investigation also attempts to distinguish areas of confining units of sufficient thickness to prevent vertical flow except in areas of major faulting, defined here where offsets are at least 1,000 ft.

2.2 Background

The map area (Figure 2-1) is in the Great Basin subprovince of the Basin and Range physiographic province (Fenneman, 1931). The Basin and Range region is made up of parallel to sub-parallel,

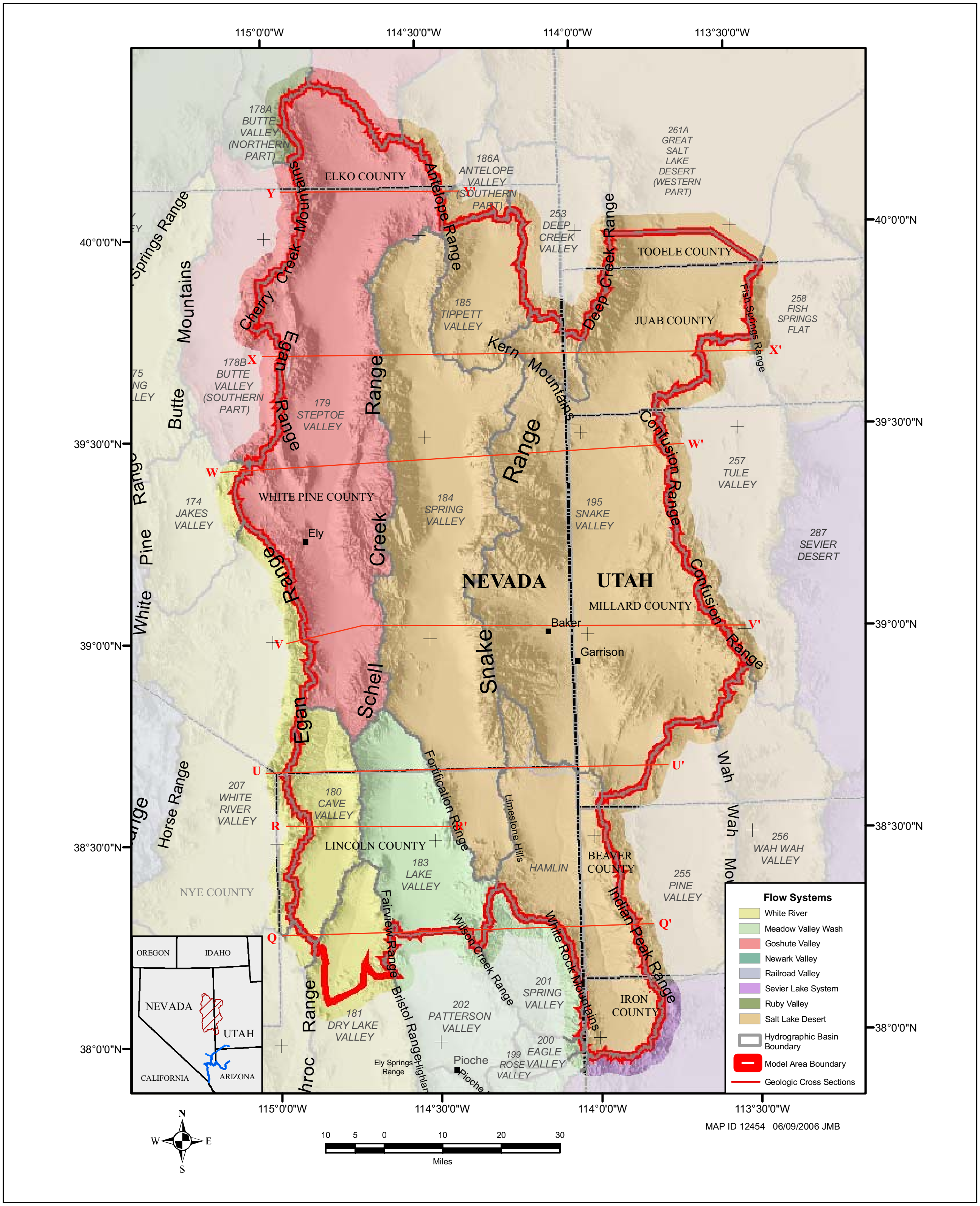

Figure 2-1
Hydrographic Areas, Ranges, and Flow Systems in the Study Area

north-trending mountain ranges separated by elongated alluvial valleys. These formed because the region was subjected to some of the most severe structural extension (pulling apart) of continental crust in the world (Rowley and Dixon, 2001). The pulling apart, which is continuing, is in an east-west direction, resulting in the basin-range episode of north-striking normal faults that bound most of the ranges and structural basins (valleys).

The Great Basin is that part of the province making up nearly all of Nevada and adjacent parts of California, Idaho, and Utah characterized by internal drainage, in which surface water is confined to individual closed basins. Just west and south of our map area, however, drainage in the structural basins is tributary to the perennial Virgin River, Muddy River, Las Vegas Wash, and others that are in turn connected to the Colorado River system. The structural basin of White River Valley, just to the west of the map area, is tributary to the Muddy River but the streams in White River Valley are intermittent. Integration of formerly closed basins in and downstream of White River Valley took place during wetter periods of late Pleistocene time, as recently as 10,000 to 15,000 years before present.

Despite the intermittent nature of surface water, groundwater is abundant beneath most of the map area. The groundwater exists in aquifers within and between a number of groundwater basins, and it flows through these aquifers in definable regional groundwater flow systems. These systems may include a dozen or more closed or integrated topographic basins that are interconnected in the subsurface (Figure 2-1). These regional flow systems are defined by evidence that their groundwater flowpaths pass beneath topographic divides and continue beneath adjacent basins and ranges.

The names and distribution of groundwater flow systems covered in this report come from Harrill et al. (1988) and Harrill and Prudic (1998), given in Figure 2-1. Groundwater flow systems that have been identified in the map area include the White River, Goshute Valley, Great Salt Lake Desert, and Meadow Valley groundwater flow systems.

The primary regional aquifers in the flow systems consist of Paleozoic carbonate rocks, volcanic rocks (generally Tertiary ash-flow tuffs), and Miocene to Holocene basin-fill sediments. The primary regional confining units within the flow systems are Precambrian to Cambrian schist, quartzite, slate, and shale, Mississippian shale, Mesozoic clastic sedimentary rocks, and Jurassic to Tertiary plutonic rocks.

Fault-based conduits to groundwater flow are generally “damage zones” as defined by Caine et al. (1996) to consist of small faults and extensional fractures on both sides of an interior “core zone” of a fault, where most deformation has taken place. The “damage zones” of fractures along the outer portion of fault zones are parallel to the faults that formed them. Where the damage zones are in carbonate rocks, solution of the carbonate rocks along the fractures can create greater potential for groundwater flow. Fault-based barriers to flow include fault gouge zones that typically occur along the interior “core zones” of fault zones (Caine et al., 1996; Dixon and Katzer, 2002; Fairly and Hinds, 2004; Rowley and Dixon, 2004; Page et al., 2005a).

2.3 Objectives

The primary objective of this geological analysis is to provide a digital representation of the geologic framework for use in a groundwater flow model for the study area. The geologic information compiled provides data on reasonable model boundaries, reasonable internal boundaries, extents of hydrogeologic units, and structures that influence groundwater flowpaths and flow barriers. The geologic framework also provides aquifer and confining unit thickness for the modeled area. The objective of geologic evaluations outside of the model area was to provide a basis for groundwater interactions across model boundaries, including potential groundwater interactions between groundwater flow systems internal to the model and groundwater flow systems outside of the modeled area. This geologic analysis was manifested through the creation of geologic and hydrogeologic maps and cross sections of the study area.

The objective of the geologic maps and geologic cross sections is to provide, in digital form, the geologic framework for the eastern carbonate aquifer systems of Nevada and western Utah as an aid in developing numerical groundwater flow models of groundwater flow systems. Framework data that were acquired include the distribution, geometry, thickness, composition, and physical properties of geologic units to define hydrogeologic units and potential aquifers and confining units. Such information will assist in ascertaining the rock units that are most likely to provide pathways for groundwater flow and which rock units are most likely to retard or divert flow.

An important aspect of the geologic maps is the portrayal of the distribution and attitude of faults, especially those formed during the youngest (basin-range) episode of deformation. Faults may serve as barriers and/or conduits to groundwater flow. In flow systems in the study area, basin-range faults may either direct groundwater flow through a system of barriers and fault conduits and/or impede groundwater flow toward otherwise downgradient groundwater basins. Part of the objective of this report is to evaluate how these faults act as either barriers or conduits to groundwater flow. Another objective of this report is to evaluate which faults are most likely to provide conduits and/or barriers to groundwater flow so that they can be properly incorporated into a groundwater model of the region.

2.4 Investigation Area for the Geologic Study

The area covered by this geologic investigation, known as the study area, map area, or project area, includes several hydrogeographic basins, also called hydrographic areas, within the GSLDFS. The area also includes adjacent basins within several other flow systems that potentially may be in hydrogeologic connection with those of the GSLDFS. The purpose of including adjacent basins is to investigate potential conduits and barriers to flow between all basins shown and to provide a geologic estimate of the extent of those conduits and barriers to flow. These conduits and barriers include the various aquifers, confining units, and fault boundaries.

2.5 Approach

The approach used in this investigation was to combine published and unpublished geologic information from all known (numerous citations) geologic work done in the area. These data were collected, compiled, and analyzed by the authors, who are familiar with the geology of the region and adjacent areas. In addition, a study was made of borehole information from oil-test wells and water wells. Another source of information was geophysical studies of the region generated by the U.S. Geological Survey (USGS) and other entities, particularly preliminary data from gravity surveys performed by the USGS in 2003 to 2005. These latter studies are not ready for publication, but they have given insight as to depth of valley fill and underlying rocks within several basins. A final source of evidence is geologic field work done in the area by the authors of this report.

Based on the evaluation of the above material and the expertise of the geologists involved in this report, digital geologic maps were constructed for the area of the groundwater model (Plate 1). Digital geologic cross sections were constructed, also based on the above evidence (Plate 3), and these cross sections were tied into the geologic maps. Because of the complexity of the geology of the area, the map and cross sections represent a current understanding, inasmuch as new data on cross-cutting faults, bedding surfaces, intrusions, volcanic sequences, and other geologic units and geologic relationships must be continuously evaluated and revised.

The geologic units were combined into broad units of similar hydrogeologic properties termed hydrogeologic units. These broad units make up the aquifers, confining units, and units of intermediate permeability of the area of this report. These hydrogeologic units are displayed in Plate 4. Cross sections of these units were compiled using the geologic cross sections of Plate 3 as a basis. These cross sections are displayed in Plate 5. Based on the digital hydrogeologic maps and cross sections, the extents of aquifers, confining units, and intermediate-permeability rocks could be evaluated, along with potential fault barriers and fault conduits to groundwater flow. The hydrogeologic map, cross sections, and hydrogeologic interpretations were used to compile the geologic framework for the groundwater model. The hydrogeologic map and cross sections helped to evaluate probable groundwater flowpaths and flow barriers within the model area.

Following creation of the geologic and hydrogeologic maps and cross sections, the area to be modeled was divided into flow compartments. These flow compartments are based largely on major fault structures within the modeled area and do not necessarily correspond to hydrographic basin boundaries. Concurrently, extent maps and structure-contour maps for each of the hydrogeologic units were made. These extents and structure-contour maps were specifically developed for regional model units (RMUs) that formed the units of the groundwater model. The contours were developed on the bottom elevation of each of the RMUs for incorporation into the model. An exception was that only the top elevation of intrusive and basement rocks was contoured, as these units do not have a known base.

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3.0 Data Compilation Evaluation

3.1 Geologic Data Compilation

The compilation of geologic data was performed through a number of avenues, including literature review, review of State Engineer's records, review of SNWA files, review of oil-test well and other borehole data, evaluation of studies performed by the USGS, and consultation with geologic experts in the area of the model. The reviewed literature was compiled into a database in the SNWA system. This literature was reviewed and compared with other literature and other sources of geologic information prior to incorporation into the geologic maps and cross sections.

Geologic data from wells were compiled from reports to the State Engineer when available. Data on oil- and gas-test wells drilled in the area of the model were compiled. Although not every well had geologic information, most of them did have useful information to assist in compiling the geologic and hydrogeologic cross sections.

The SNWA files include a number of previous reports for the various basins of the flow systems covered in this report; these reports are included in the literature references. All these reports, files, and other sources of information were analyzed and discussed in reports and in a SNWA database.

3.2 Preparation of Geologic Maps and Sections

Much of the surface geology shown on the geologic map (Plate 1) was compiled from Nevada county 1:250,000-scale geologic maps and from the Utah 1:500,000-scale state geologic map and two 1:100,000-scale maps. The Nevada county maps were of White Pine County (Hose and Blake, 1976), Lincoln County (Tschanz and Pampeyan, 1970), and southern Elko County (Coats, 1987). In Utah, the most helpful references were the state map (Hintze, 1980), a summary report on the geology of Utah (Hintze, 1988), the Millard County report (Hintze and Davis, 2003), and the two 1:100,000 maps (Hintze and Davis, 2002a and b).

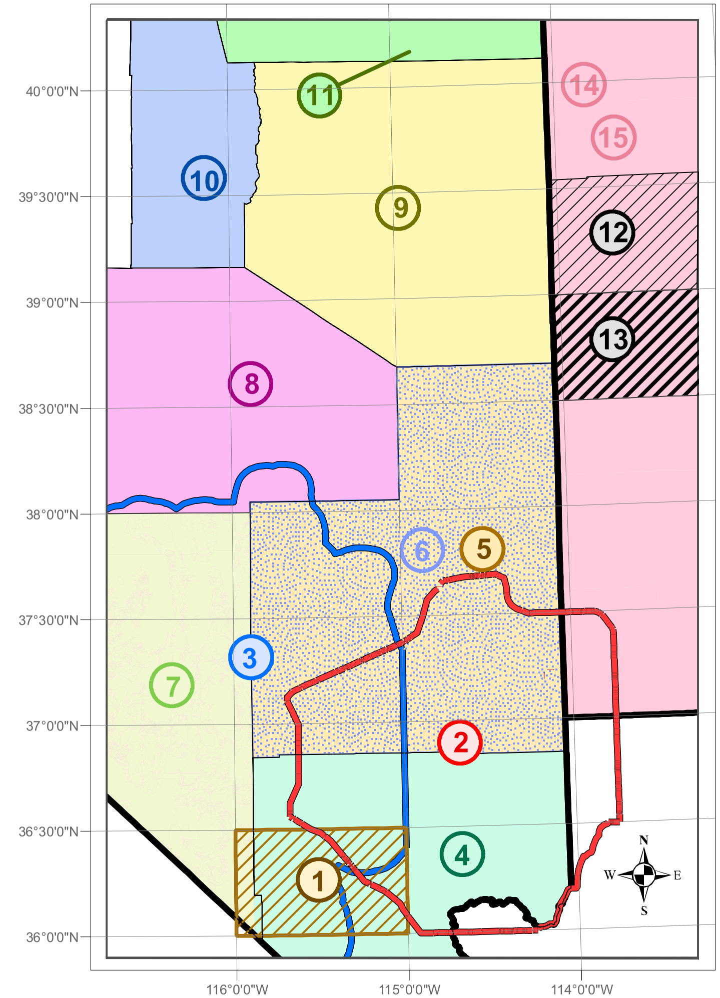
Many of the regional geologic maps were published decades ago. Many revisions and re-interpretations have been made to the geology of portions of those maps since that time. A significant part of the map area was compiled at 1:250,000-scale by Terrascan Group, Inc. (1987), but it used the same county maps used in the present map. Nevada is also covered by the 1:500,000-scale state geologic map (Stewart and Carlson, 1978). The revisions and re-interpretations of the older maps are from all known subsequent maps and reports of and near the map area. In addition, Plate 1 includes some new, unpublished field observations. These new data were incorporated into Plate 1 and in the discussions in this document. These maps are listed in Section 14.0 of this report.

The geologic and hydrogeologic maps and sections of the project area (Plates 1, 3, 4, and 5) show but a small north-central part of a much larger area of geologic and hydrogeologic maps and sections done by the authors. The area covered by these geologic maps, at 1:250,000 scale, is about 40,000 square miles in extent. It provides the regional geologic framework of several regional groundwater flow systems, notably the WRFS, extending as far south as the Lake Mead and Las Vegas area. It is intended that this larger map will be open filed or published by the Nevada Bureau of Mines and Geology. Much of the area of the larger map, like that of Plate 1, is based on compilation of older county and state maps. But the southern part of this entire map area, located south of the area of Plates 1 and 4, includes large areas of original mapping by the authors and colleagues. The purpose of this mapping was to define the geologic framework of the Death Valley Groundwater Flow System at 1:250,000 scale (Workman et al., 2002 and 2003), the WRFS at 1:250,000 scale (Page et al., 2005a), and the Las Vegas area at 1:100,000 scale (Page et al., 2005b). Inasmuch as many of the same stratigraphic units and structures, as well as the general geologic setting are the same as those in the project area, making all these maps and sections bears directly on the interpretations that went into the geologic interpretation of the project area. Large-scale geologic maps that went into making the maps of the project area and those to the south are indexed in Figure 3-1.

The geologic maps of Plates 1 and 4 included many changes of specific geologic units throughout the study area. In many places, facies changes resulted in major changes in lithology of a specific unit, and in other places, different formation names were used for essentially the same unit. In some places, a specific unit thinned in certain areas and was included as a member of another unit or as an inconsequential bed within another unit. An example is the Mississippian Chainman Shale, which is a major shale confining unit in White Pine County but a generally inconsequential shale horizon included within other units in Clark County and southwestern Utah. During compilation of the geologic map, separate stratigraphic columns were used for different counties, along with a stratigraphic column for units in western Utah. Correlations between specific geologic units are commonly given in the literature. These correlations were used to associate units of the same or similar age in different parts of the map area. An example is the correlation between the Devonian Guilmette Formation and the Devils Gate Limestone.

The map includes 7 new digital geologic cross sections (Plate 3), most of which trend generally east-west. These cross sections are roughly evenly spaced across the map area at the same scale as the map, at locations chosen to best show specific geologic and structural relationships important to the interpretation of the exposed geology. A hydrogeologic map (Plate 4) and cross sections (Plate 5) were also constructed, where geologic units with similar hydrologic properties such as porosity and permeability were combined into hydrogeologic units, distinct from the geologic units that comprise them. Few of the reports and maps used to compile the geologic maps had associated geologic cross sections, so the cross sections for this report are based on interpretations of the county geologic maps along with all other available maps and reports of the map area. The other available maps include the geologic map by Terrascan Group, Inc (1987), with associated cross sections, which were referred to in making the cross sections for the map in this report.

All cross sections incorporated lithologic information from available oil- and water-well logs. Oil-well logs in Nevada are available online from the Nevada Bureau of Mines and Geology or through their publications. Garside et al. (1988) compiled geologic data from oil and gas wells drilled



Source Maps:
1. Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Workman, J.B., Mahan, S.A., Paces, J.B., Dixon, G.L., Rowley, P.D., Burchfiel, B.C., Bell, J.W., and Smith, E.I., 2005, Geologic and Geophysical maps of the Las Vegas 30' x 60' quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations map 2814, 1:100,000-scale.
2. Page, W.R., Dixon, G.L., Rowley, P.D., and Brickey, D.W., 2005, Geologic map of parts of the Colorado, White River, and Death Valley ground-water flow systems: Nevada Bureau of Mines & Geology Map 150, scale 1:250,000. Digital GIS data provided.
3. Workman, J.B., Menges, C.M., Page, W.R., Taylor, E.M., Ekren, E.B., Rowley, P.D., Dixon, G.L., Thompson, R.A., and Wright, L.A., 2003, Geologic map of the Death Valley ground water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies MF-2381-A, 1:250,000 scale. Digital GIS data provided.
4. Longwell, C.R., Pampeyan, E.H., Bowyer, Ben, and Roberts, R.J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines and Geology Bulletin 62, 218 p., scale 1:250,000.
5. Tschanz, C.M., and Pampeyan, E.H., 1970, Geology and Mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology Bulletin 73, 188 p.
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12. Hintze, L.F., and Davis, F.D., 2002b, Geologic map of the Tule Valley 30' x 60' quadrangle and parts of the Ely, Fish Springs, and Kern Mountains 30' x 60' quadrangles, northwest Millard County, Utah: Utah Geological Survey Map 186, scale 1:100,000.
13. Hintze, L.F., and Davis, F.D., 2002a, Geologic map of the Wah Wah Mountains North 30' x 60' quadrangle and part of the Garrison 30' x 60' quadrangle, southwest Millard County and part of Beaver County, Utah: Utah Geological Survey Map 182, scale 1:100,000.
14. Hintze, L.F., Willis, G.C., Laes, D.Y.M., Sprinkel, D.A., Brown, K.D., 2000, Digital Geologic Map of Utah, Utah Geological Survey Map 179DM, scale 1:500,000.
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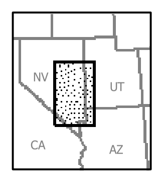

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Figure 3-1
Index Map of Previous Large-Scale Mapping Used in the Geologic Evaluations and to Create the Geologic and Hydrogeologic Maps of Plates 1 and 4

in Nevada from 1907 through 1988. This compilation was supplemented by Nevada Bureau of Mines and Geology Open-File Report 01-7 (Hess, 2001). This information was supplemented again in 2004 (Hess, 2004). Oil-well logs in Utah were obtained from the Utah Division of Oil, Gas, and Mining website (UDOGM, 2006). Water-well logs in Utah were obtained from the Utah Division of Water Rights website (UDWR, 2006).

Geophysical studies, notably gravity maps (Saltus, 1988a and b; Cook et al., 1989; Ponce, 1992; Saltus and Jachens, 1995; Ponce et al., 1996), aeromagnetic maps (Hildenbrand and Kucks, 1988a and b), and seismic sections (Allmendinger et al., 1983; Hauser et al., 1987) were used to aid in the interpretation of geologic cross sections. Gravity maps and electromagnetic profiles were contracted by the USGS and completed in preliminary form (E.A. Mankinen et al., USGS, unpub. data, 2005; McPhee et al., 2005 and in press; Scheirer, 2005). The gravity data were converted to depth-to-basement data and were used to aid in constructing the cross sections. Reports summarizing these newly obtained gravity and electromagnetic data are forthcoming.

4.0 CONCEPTUAL GEOLOGIC MODEL

4.1 Geology and Stratigraphy

4.1.1 Overview

The geology of the study area (Plates 1 and 3) is characterized by a thick stratigraphic sequence of rocks from Proterozoic to Holocene age that has been structurally deformed during several tectonic episodes. The thick sequence includes three major assemblages that are important aquifers:

- the carbonate aquifer of Paleozoic age
- volcanic rocks of Tertiary age
- basin-fill sediments of Tertiary to Quaternary age

Along with the aquifers are moderate to thick confining units or low-permeability units, including:

- Early to Late Proterozoic metamorphic and igneous rocks
- Late Proterozoic to Lower Cambrian quartzite and shale
- Shale, sandstone, and conglomerate of Mississippian age
- Triassic to Cretaceous shale, siltstone, and sandstone
- Mesozoic to Cenozoic plutons

Three tectonic episodes, plus an intervening episode of extensive volcanism, have affected the hydrogeology of the region. The oldest tectonic episode is the Antler deformation (Late Devonian to Late Mississippian). This episode included east-verging thrust sheets. The second tectonic episode was the Sevier deformation (Jurassic through early Cenozoic) that resulted in east-verging thrust sheets in which Paleozoic carbonate rocks were placed over each other and over younger rocks. The thrust faults of both episodes are capable of impeding flow across them.

In Eocene to Miocene time, volcanism resulted in the development of thick blankets of ash-flow tuff and related lava flows, including many scattered calderas that were the sources of the tuff. The caldera margins are interpreted to have formed new groundwater flowpaths and barriers.

The third tectonic episode is the middle Miocene to Holocene basin-range deformation that shaped the current topography of the Great Basin, including most of Nevada and parts of western Utah and southeastern California. Basin-range faulting produced horst and graben topography, resulting in deep basins and relatively high mountain ranges, generally oriented north-south. The mountain ranges provided areas of groundwater recharge, and accumulations of alluvial fill within the basins provided areas of aquifer storage and avenues of groundwater flow. Basin-range faults may provide hydrogeologic barriers to groundwater flow. Basin-range faults may provide conduits to groundwater flow, generally from north to south. These north-south conduits may double as barriers to east or west flow in certain flow systems such as the GSLDFS.

The age of the rocks in the study area is summarized in a Geologic Time Scale chart (Figure 4-1). The oldest rocks are Early and Late Proterozoic metamorphic and igneous units. These rocks are overlain by thick sequences of quartzite and subordinate shale, which are locally metamorphosed to slate and schist, of Late Proterozoic age. The Proterozoic rocks pass conformably upward into rocks of similar type and thickness, though less metamorphosed, that are Late Proterozoic to Early Cambrian in age. During Middle Cambrian time, carbonate deposition was initiated, and thick sequences of marine limestone and dolomite were deposited from the Middle Cambrian through the Permian Periods. These rocks make up the carbonate aquifer of Nevada and adjacent parts of Utah, and range in thickness between 5,000 and 30,000 ft throughout this area (Harrill and Prudic, 1998).

Locally, marine sandstone and shale are intertongued with the carbonates. These units generally do not form significant impediments to regional groundwater flow, with the exception of the Chainman Shale and related shale and sandstone of Late Mississippian age. This unit locally exceeds 2,000 ft in thickness, and in all but the southern part of the study area, this unit divides the carbonate aquifer into two distinct aquifers, the lower and upper carbonate aquifers. The Chainman Shale and related clastic units were derived from erosion of a structural highland, the Antler Highland, west of the study area. The highland, made up in large part of the Roberts Mountain allochthon, was produced by the Antler compressive deformational event.

Mesozoic rocks in the study area are largely clastic, nonmarine, and thin where deposited, but in most places they have been removed by erosion. They and older rocks were deformed during the Sevier deformational event. At this time, the study area was a highland, also known as a hinterland, and an episode of erosion of the area removed most Mesozoic rocks.

Plutons of Late Jurassic to Paleocene age were intruded during pulses during Sevier deformation. These plutons probably had associated extrusive volcanic units, but all of these units have been removed by erosion. Mesozoic plutons commonly led to significant mineralization in the study area.

Middle Tertiary (Eocene to Miocene) time marked the beginning of calc-alkaline intrusion and resulting volcanism, the terminal product of subduction beneath western North America that began in the Triassic Period (Atwater, 1970; Lipman et al., 1972; Hamilton, 1995). Above individual source plutons, vent deposits included andesitic and dacitic lava flows and volcanic mudflow breccia that locally exceeded several thousand feet of thickness. Caldera deposits consist of dacitic to rhyolitic ash-flow tuffs, which are similarly thick within individual calderas. Farther outward from the vents above the plutons, lava flows are sparse because they do not flow more than a few miles from their vents, but outflow ash-flow tuffs accumulated to aggregate thicknesses exceeding 1,000 ft in most of the study area.

Starting at about 20 million years (Ma) ago, subduction ceased and extensional deformation increased in the map area (Christiansen and Lipman, 1972; Christiansen and Yeats, 1992; Rowley and Dixon, 2001). Basin-range deformation, characterized by vertical (normal) faulting, began to form

ERA	PERIOD	EPOCH	TIME	PROCESSES AND ROCK TYPES
Cenozoic	Quaternary	Holocene Pleistocene	Present 1.8 Ma	Valley-Fill Alluvium
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	*5 Ma* *38 Ma* 65 Ma	Start Basin-Range Faulting (20 Ma) Volcanics and Older Sediments Emplacement of Calderas
Mesozoic	Cretaceous Jurassic Triassic		248 Ma	Sevier Orogeny, Intrusions Continental Sediments
Paleozoic	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian		543 Ma	Antler Orogeny, Intrusions Chainman Shale, Carbonates
Precambrian			4.5 Ga	Quartzite and shale

Source: Adapted from http://www.geosociety.org/science/timesscale/timescl.pdf

Figure 4-1
Geologic Time Scale, Including Rock Type and Tectonic Events

alternating mountain ranges and valley basins. The main pulse of this basin-range faulting began about 10 Ma ago, during which time the present topography formed. As valleys formed, they were filled by debris eroded from the adjacent mountain range, creating basin-fill deposits.

Individual rock units, structures, basins, and ranges are described in the chapters below. Thicknesses of most units are from the county reports of the area where the unit is exposed. The relationships between geologic units in the different areas of the map can be determined from Figures 4-2 to 4-5. These figures illustrate geologic columns for Lincoln County (Figure 4-2), White Pine County (Figure 4-3), and western Utah (Figure 4-4), and Clark County (Figure 4-5).

4.1.2 Proterozoic Rocks

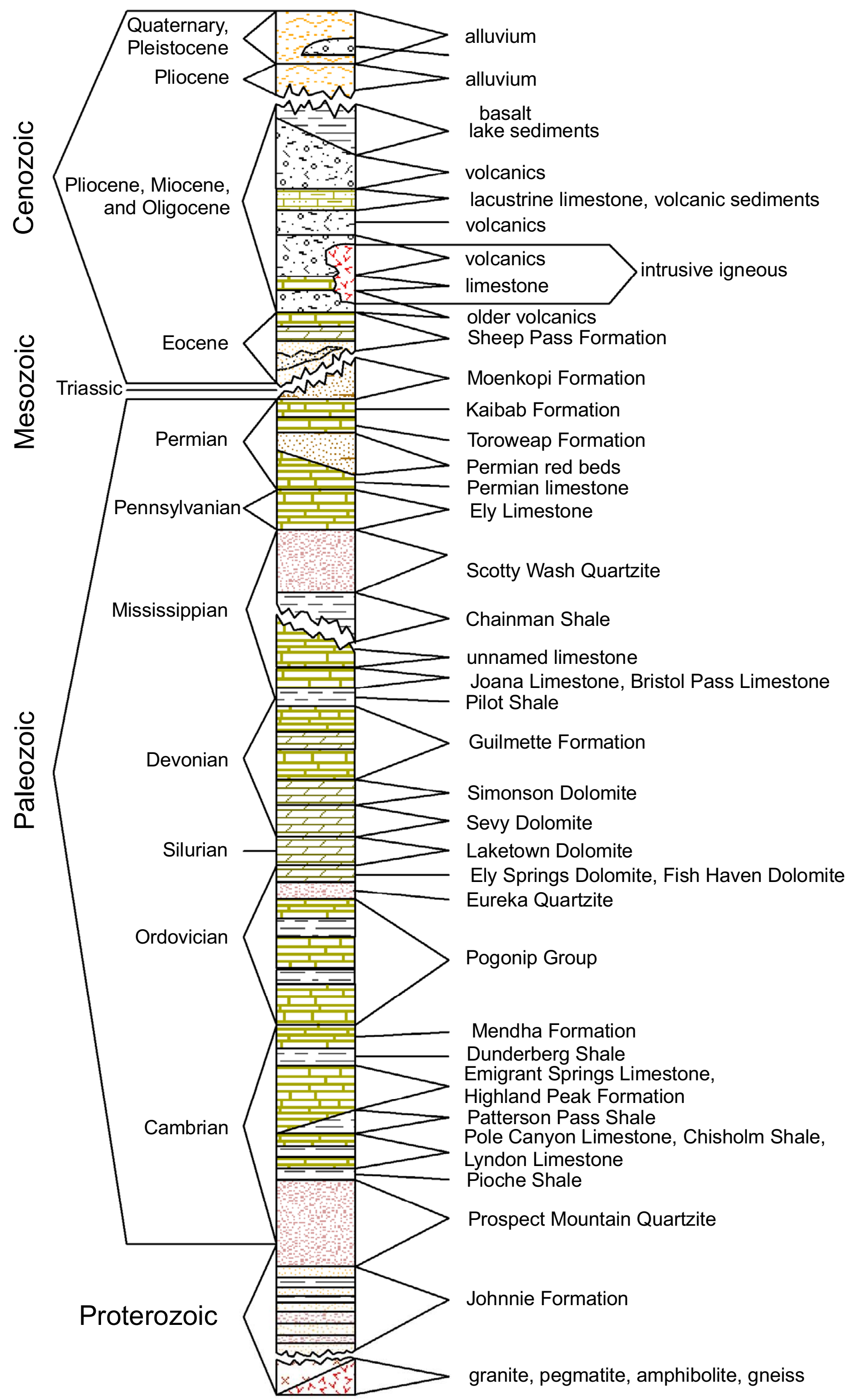
The oldest rocks in the map area are Late Proterozoic quartzite, which we have mapped as Precambrian rocks (p€). These rocks appear to be the initial deposits of the Cordilleran miogeocline, a western belt of offshore carbonate-shelf and intertidal deposits (Page et al., 2005a). These units were deposited in shallow marine waters along a passive continental margin of what is now western North America (Stewart and Poole, 1972; Stewart, 1976).

In White Pine County and adjacent Utah, the principal Late Proterozoic unit is the McCoy Creek Group. The assemblage consists of well-bedded, resistant feldspathic quartzite and subordinate slate and argillite more than 9,000 ft thick in the Schell Creek Range (Plate 1) and about 7,600 ft thick in the Deep Creek Range, Utah. The metamorphic grade of these units is low to moderate, locally producing schist. The unit is mapped in the Deep Creek Range with the underlying Trout Creek Group, also of Late Proterozoic age and similar in appearance. The Trout Creek Group is estimated at 11,600 ft thick (Hintze, 1988) and of higher metamorphic grade. Link et al. (1993) concluded that both of these sequences range in age from 780 to 560 Ma and that the upper part of the McCoy Creek Group may be correlative with the Johnnie Formation of southern Nevada, which is as much as 4,000 ft thick. In Lincoln County and at least in parts of White Pine County, the basal units of the overlying Prospect Mountain Quartzite are considered to be partly Proterozoic. The McCoy Creek and Trout Creek units are mapped in the study area as Precambrian rocks (p€).

4.1.3 Paleozoic Rocks

4.1.3.1 Cambrian Rocks

The Prospect Mountain Quartzite (Cambrian to Precambrian sedimentary rocks, €p€s) overlies the McCoy Creek Group in White Pine County. The Prospect Mountain consists of well-bedded, resistant quartzite and subordinate shale, commonly weakly metamorphosed. It has been generally considered to be Early Cambrian, although it is not well characterized by age or correlation from place to place, and at least south of the map area it is partly Late Proterozoic. In the map area, complete sections are uncommon, but the unit ranges from 3,000 to nearly 8,000 ft thick (Tschanz and Pampeyan, 1970). South of the map area, the Prospect Mountain Quartzite is correlated with three units mapped at the Nevada-California border: the Stirling Quartzite (Late Proterozoic and Early Cambrian), the Wood Canyon Formation (Early Cambrian), and the Zabriskie Quartzite (Early



Source: Tschantz and Pampeyan, 1970, NBMG Bulletin 73

Figure 4-2
Geologic Units of Lincoln County, Nevada

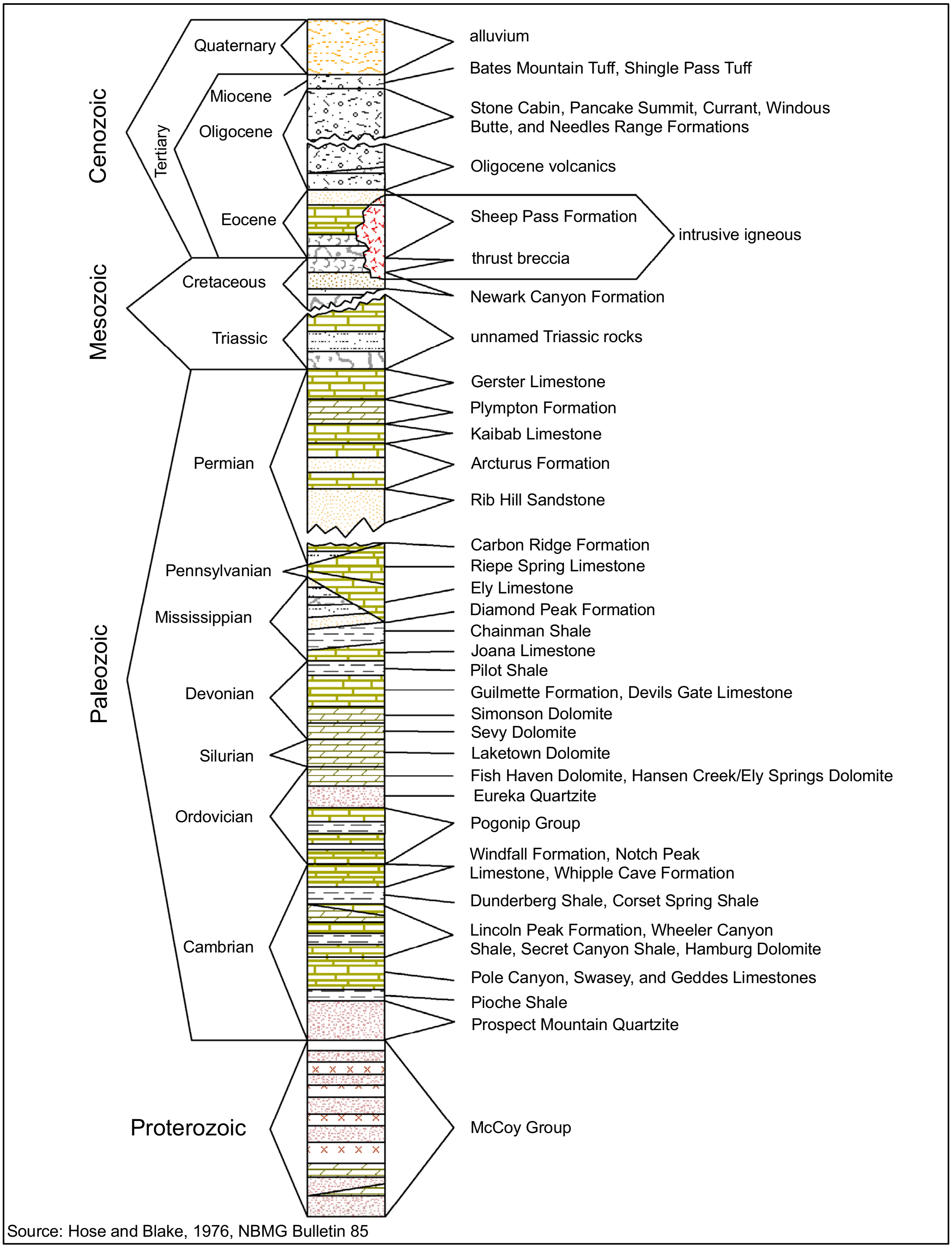


Figure 4-3
Geologic Units of White Pine County, Nevada

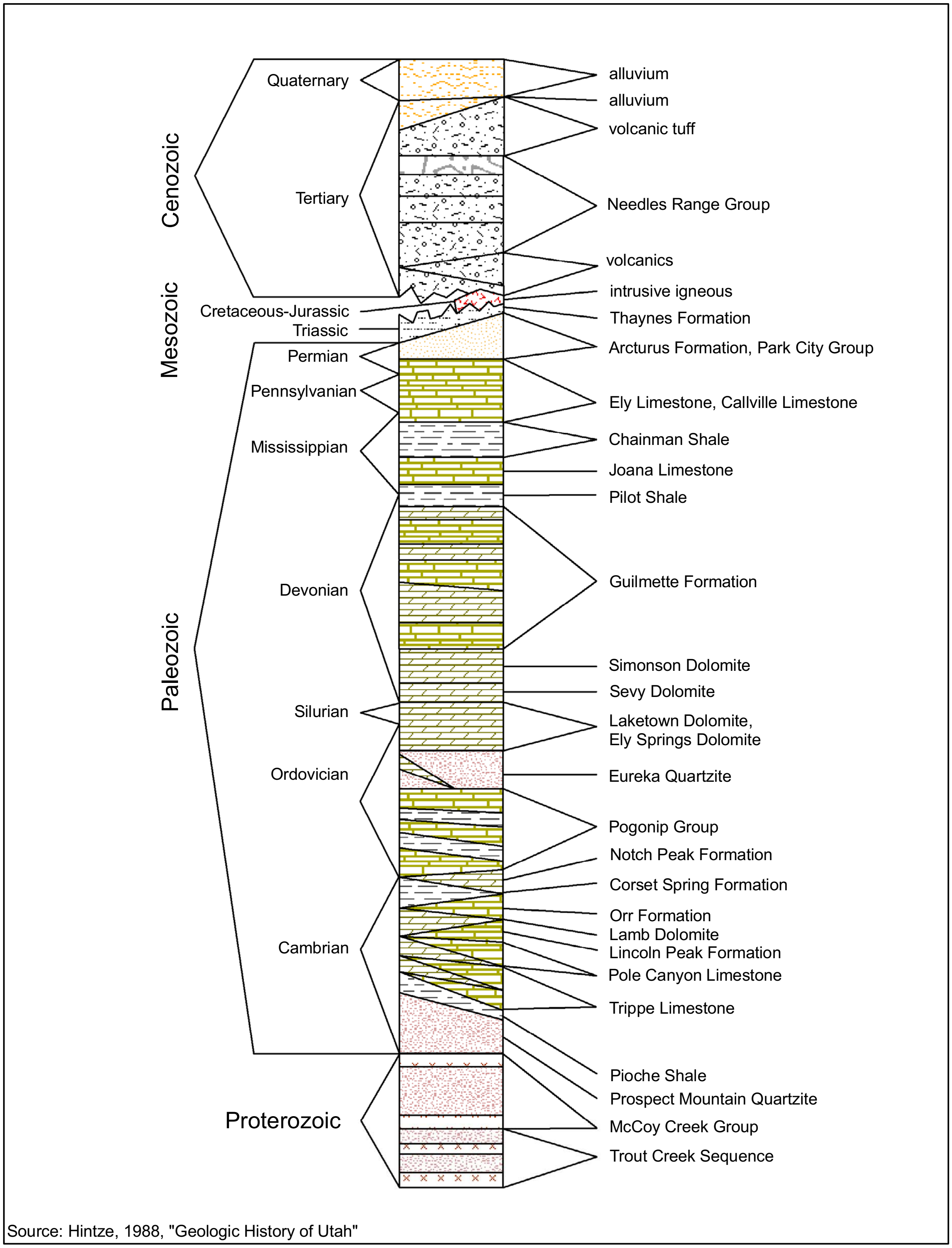
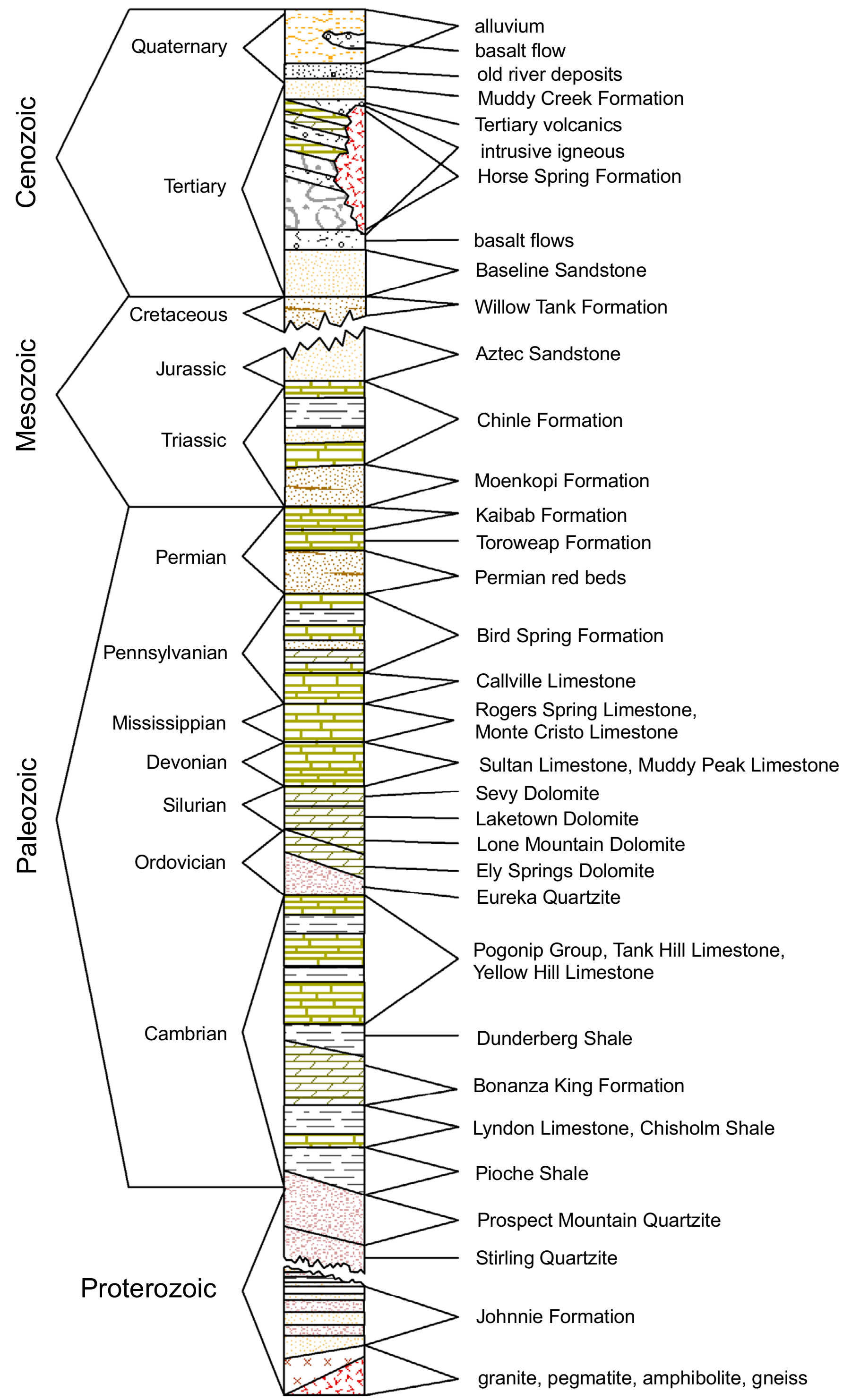


Figure 4-4
Geologic Units of Western Utah



Source: Longwell et al., 1965, NBMG Bulletin 62

Figure 4-5
Geologic Units of Clark County, Nevada

Cambrian; Stewart, 1970, 1974, and 1984; Rowley et al., 1994). Link et al. (1993) considered the Stirling Quartzite to postdate the Late Proterozoic McCoy Creek Group.

Above the Prospect Mountain Quartzite are, from base to top, the Pioche Shale (Lower and Middle Cambrian, 200 to 1,000 ft thick), Lyndon Limestone (Middle Cambrian, 150 to 400 ft thick), and Chisholm Shale (Middle Cambrian, 100 to 300 ft thick). These three units are combined in many places with the Prospect Mountain Quartzite, as Є pЄs in White Pine County. These rocks are partly correlative with the Carrara Formation at the Nevada Test Site (NTS) and in portions of Clark County.

Cambrian carbonate rocks range in thickness from about 3,000 to 5,000 ft in the map area. The map unit is shown as the middle part of Cambrian rocks (Cm). In and south of the map area, the most widespread and best studied of the Cambrian carbonate rocks is the Highland Peak Formation, consisting of Middle and Late Cambrian well-bedded limestone and dolomite (Tschanz and Pampeyan, 1970).

In the northern part of the map area, the Cambrian carbonate rocks consist of many named units of generally similar lithology, total thickness, and age (Hose and Blake, 1976). In the northwest, these were originally named, from base to top, the Eldorado Dolomite, the Geddes Limestone, the Secret Canyon Shale, and the Hamburg Dolomite. In the Snake Range, these are, from base to top, the Pole Canyon Limestone, the Lincoln Peak Formation, and the Johns Wash Limestone. These latter names are now preferred in the northwestern part of the map area and areas to the west. In the Cherry Creek Mountains of Nevada and in Utah, the units making up the entire sequence of Middle Cambrian carbonate rocks are, from base to top, the Dome Formation, Swasey Limestone, Wheeler Shale, Marjum Limestone, Weeks Limestone, Trippe Limestone, Wah Wah Summit Formation, Orr Formation, and others (Hose and Blake, 1976; Hintze and Davis, 2003). The overall Cm sequence is roughly equivalent to the Bonanza King Formation to the south (Longwell et al., 1965).

Above the Middle Cambrian carbonate section in Nevada is an Upper Cambrian to Lower Ordovician(?) sequence that includes a lower unit, the Dunderberg Shale, and an unnamed upper unit of limestone and dolomite (Tschanz and Pampeyan, 1970). The rocks are mapped as an upper part of the Cambrian section (Cu); in some cross sections, the map unit is combined with Cm as Cambrian carbonate rocks, undivided (Єc). In White Pine County and in Utah, the Cu limestone unit has been variously referred to as the Windfall Formation, Orr Formation, Notch Peak Limestone, and Whipple Cave Formation. In the southern part of the study area, the Cu limestone unit is the Nopah Limestone.

4.1.3.2 Ordovician to Devonian Rocks

The Ordovician to Silurian parts of the rock column in the map area are shown as a lower unit (Middle and Lower Ordovician, symbol Ol) and an upper unit (Silurian and Upper Ordovician, symbol SOu). The lower unit in the area consists in ascending order of the Pogonip Group and the Eureka Quartzite. The Pogonip Group consists of interbedded thick-bedded limestone, sandy to silty limestone, conglomerate, and shale, generally about 2,000 to 3,500 ft thick in the map area. The Eureka Quartzite is a distinctive white, resistant, brittle, vitreous, fine- to medium-grained quartzite that thins southward from 600 to 800 ft thick in the Confusion Range to 200 ft in southern Lincoln County (Hose and Blake, 1976; Tschanz and Pampeyan, 1970). The Eureka unit is a major marker bed throughout most of the map area (Plates 1 and 2). In the northwestern part of the map area, the lower unit includes the Vinini and Valmy Formations.

The upper unit (SOu) generally consists in ascending order of the Hansen Creek Formation, Ely Springs Dolomite, Fish Haven Dolomite, and Laketown Dolomite. The Ely Springs Dolomite is a mostly poorly resistant, gray to dark-gray carbonate unit that occurs over most of the area of Plate 1 in Lincoln County (Tschanz and Pampeyan, 1970). The Ely Springs Dolomite in Lincoln County overlaps into northern Nye and Eureka Counties, where it is locally called the Hansen Creek Formation, a dark dolomite and/or limestone unit that thins southward from 500 to 100 ft (Tschanz and Pampeyan, 1970; Kleinhampl and Ziony, 1985). In White Pine County, the Ely Springs Dolomite is called the Fish Haven Dolomite and ranges between 200 and 850 ft thick. The Silurian Laketown Dolomite is lithologically similar to the Ely Springs Dolomite and Fish Haven Dolomite and ranges between 600 and 1,850 ft thick.

In Eureka and Nye Counties, the Laketown Dolomite is underlain by, and partly age-equivalent, to the Lone Mountain Formation, a unit with limestone and dolomite that is not present farther east in Lincoln and White Pine Counties (Kleinhampl and Ziony, 1985). In Nye County, these units, particularly the Lone Mountain Formation, overlie and interfinger with the Roberts Mountain Formation. The Roberts Mountain is gradational to western facies deep-water sediments and is comprised of shaly limestone, dolomite, and shale with a thickness of 500 to 1,900 ft (Kleinhampl and Ziony, 1985). See Figures 4-2 to 4-5 for geologic sections in different areas of the map.

Devonian carbonate rocks over most of the study area consist of, in ascending order, the Sevy Dolomite, Simonson Dolomite, and Guilmette Formation. Where combined, they are mapped as Devonian rocks, undivided (Du). In the southern part of the study area, this map unit includes the Muddy Peak Limestone (Upper and Middle [?] Devonian). In most places, however, the three formations are mapped as the Simonson and Sevy Dolomites (Ds) and Guilmette Formation (Dg). The Sevy Dolomite is a resistant, gray dolomite, commonly argillaceous and with a sandstone unit near the top. This dolomite increases in thickness southward across the map area from about 450 ft in the Snake Range to 1,300 ft from the Limestone Hills southward (Tschanz and Pampeyan, 1970). The Simonson Dolomite is resistant, dark- and light-gray dolomite about 900 to 1,200 ft thick over most of the map area, but it thins to less than 700 ft in the southeastern part of the map area, continuing to decrease in thickness farther south. The Simonson Dolomite is about 500 ft thick in the Snake Range (Tschanz and Pampeyan, 1970), although both the Simonson and Sevy dolomites may be reduced in thickness by faulting.

The Guilmette Formation (Dg) is a mostly resistant, fossiliferous limestone and dolomite, with biostromes and bioherms, and commonly sandy with minor sandstone layers. The unit ranges in thickness from about 1,050 to 3,500 ft and appears to decrease in thickness in all directions from its thickest occurrences in north-central Lincoln County (Tschanz and Pampeyan, 1970; Hose and Blake, 1976). In Clark County, the Guilmette map unit includes the Sultan Limestone, which is made up of a lower dolomite unit and an upper limestone unit with a thickness of 1,800 ft (Longwell et al., 1965).

In Eureka County and northern Nye County, the rocks of the Sevy, Simonson, and lower Guilmette units are called the Nevada Formation (Dn), which is about 2,500 ft thick. This map unit locally includes the Cockalorum Wash Formation. In Eureka and northern Nye Counties, the upper Guilmette Formation is called the Devils Gate Limestone (Dd), which is about 2,000 ft thick (Roberts et al., 1967; Hose and Blake, 1976; Kleinhampl and Ziony, 1985).

4.1.3.3 Mississippian to Lower Permian Rocks

In White Pine County, a distinctive sequence of rocks consists, in ascending order, of the Pilot Shale, Joana Limestone, Chainman Shale (Mc), and Diamond Peak Formation (Md). In Lincoln County, only the Pilot Shale is recognized (Tschanz and Pampeyan, 1970). These map units represent products of the Antler deformation, which took place in Late Devonian to Late Mississippian time and which resulted in the Antler Highland located west of the map area. The basin of deposition of these units was to the east of the highland (Poole and Sandberg, 1977 and 1991; Larson and Langenheim, 1979, Figures 7, 8). Where these four units are thin, they are lumped on the map as Mississippian to Devonian rocks (MDd). But in most places, Chainman Shale and Diamond Peak Formation are mapped separately and Pilot Shale and Joana Limestone are combined as unit MD. The Pilot Shale, Late Devonian to Early Mississippian, is mostly a poorly resistant, gray, thin bedded dolomitic siltstone and limestone containing little shale. This unit is generally from 100 to 400 ft thick, but locally, in northern White Pine County and western Utah, it is 500 to 900 ft thick (Hose and Blake, 1976; Tschanz and Pampeyan, 1970; Hintze and Davis, 2002a and b). The Joana Limestone (Lower Mississippian) is a mostly resistant, bluish-gray limestone about 100 to 1,000 ft thick.

The Monte Cristo Group of southern Nevada, which is Upper and Lower Mississippian, is considered equivalent to the Joana Limestone. The Monte Cristo Group overlies the Sultan Limestone. The Monte Cristo is a dark-gray to light-gray limestone containing abundant chert and is about 750 ft thick. The general equivalent of the Chainman Shale at the southwestern edge of the study area and southwest of the area is the Eleana Formation (Mississippian and Upper Devonian), which is several thousand feet thick (Workman et al., 2003). In mapping, the Monte Cristo, Rogers Spring, and Eleana are included with the MD map unit. The map unit also includes local units Mercury Limestone and Bristol Pass Limestone (both mostly in White Pine County), Webb Formation (Elko County), and Ochre Mountain Limestone (Utah).

The Upper Mississippian Chainman Shale is a soft black impermeable shale that is between 200 and more than 2,000 ft thick. This unit is mapped (unit Mc) in the study area but is thin south of the study area and there is included within a sequence of permeable carbonate rocks. It is a regional aquitard (called the “upper aquitard”) separating the lower carbonate aquifer from the upper carbonate aquifer over all except the southern part of the study area. Paleotopography during deposition and post-depositional erosion resulted in substantial variations in Chainman thickness. The unit was mapped (Hintze and Davis, 2002b) in the Confusion Range as having thicknesses greater than 2,000 ft. A similar thickness is reported from an oil-well log in Lake Valley (Hess, 2004). Although these two locations are distal from the source area, they represent localized depositional basins.

West of the map area, the Upper Mississippian Diamond Peak Formation is mapped as unit Md above the Chainman Shale. The Diamond Peak Formation is a poorly resistant, gray siltstone, claystone, sandstone, and conglomerate that ranges in thickness from 600 to 2,500 ft (Hose and Blake, 1976; Kleinhampl and Ziony, 1985). The unit thins and pinches out eastward in north-central White Pine County. The Diamond Peak Formation is derived from erosion of the Antler Highland and is included in the upper aquitard with Chainman. The Diamond Peak is generally equivalent to the Scotty Wash Quartzite southwest of the map area. The Scotty Wash Quartzite is made up of interbedded sandstone, shale, and local limestone of limited extent. The Scotty Wash is included with the Md map unit.

Much of the study area is underlain by the Ely Limestone, which is mostly Pennsylvanian but includes Mississippian rocks at its base and Permian rocks at its top. The Ely Limestone is mapped as Pennsylvanian rocks (lP). In the Utah part of the map area, the Ely Limestone is 1,850 to 2,000 ft thick (Hintze and Davis, 2002a and b). The map unit is called the Wildcat Peak Formation in the northwestern part of the study area and the Callville Limestone in the southern and eastern part of the study area. The Ely Limestone is overlain by a Lower Permian limestone of similar lithology in northern White Pine County (Hose and Blake, 1976). All units are resistant, gray limestone sequences that collectively range in thickness from 1,900 to 3,000 ft thick. The overlying Lower Permian limestone is called the Riepe Spring Limestone. Where both Ely and Riepe Spring are mapped together in the northern part of the mapped area, they are shown as Permian and Pennsylvanian rocks, undivided (PlP). The rocks in the PlP unit are unnamed in Lincoln County and range from 3,500 ft to more than 5,000 ft thick (Tschanz and Pampeyan, 1970). The Ely and Riepe Spring Limestones are overlain by, and partly equivalent to, the Carbon Ridge Formation, a Lower Permian, nonresistant, thin-bedded limestone and shale that is 1,400 to 2,300 ft thick. The Carbon Ridge is locally mapped separately in the northwestern part of the study area as Pc, or where thinner is included within the PlP map unit.

The Bird Spring Formation is an Upper Mississippian to Lower Permian limestone south of the study area that is roughly time equivalent to the combined Ely Limestone, Riepe Spring Limestone, and Carbon Ridge Formation of White Pine County (Longwell et al., 1965; Tschanz and Pampeyan, 1970). The Bird Spring is included in the PlP map unit, as is the Brock Canyon Formation northwest of the map area, and the Oquirrh Group (Lower Permian and Pennsylvanian) northeast of the study area.

The Lower Permian Rib Hill Sandstone (Pr) overlies the Carbon Ridge Formation northwest of the map area (Hose and Blake, 1976). The Rib Hill is a nonresistant sandstone and dolomite 500 to 1,400 ft thick. In northern White Pine County and adjacent parts of Utah, the Lower Permian Arcturus Formation (Pa) is named for a sequence of poorly resistant, gray limestone, sandstone, and siltstone that is 2,700 to 3,400 ft thick (Hose and Blake, 1976). Northwest of the map area, the Arcturus Formation overlies the Rib Hill Sandstone. Where the two are combined in the mapping, they are shown as unit Par. In Elko County, this map unit includes the Pequop Formation.

4.1.3.4 Park City Group

The Park City Group (Pp) is a distinctive, resistant, light-gray Lower Permian limestone and dolomite sequence that is exposed only locally. The scattered nature of the outcrops suggest that the unit was originally fairly extensive in the study area but has been partly removed by erosion over most its original extent. In White Pine County and adjacent western Utah, the group is made up, from base to top, of the Kaibab Limestone, Plympton Formation, and Gerster Limestone. The Kaibab Limestone is 50 to 600 ft thick, the Plympton is 700 to 900 ft thick, and the Gerster is as thick as 1,100 ft (Hose and Blake, 1976). These rocks are not found in Eureka or Nye Counties.

In Lincoln County, and east of the map area in Utah, the east platform part of the sequence consists of the Toroweap Formation, the Kaibab Limestone, and locally the Plympton Formation (Tschanz and Pampeyan, 1970). In Lincoln County, these units have a combined thickness of between 250 and 450 ft. The Toroweap is a cherty, thin-bedded shaly limestone, and the Kaibab limestone is a cherty, sandy light-gray limestone.

4.1.4 Mesozoic Rocks

Mesozoic rocks were deposited locally or have been largely removed by erosion in the map area. However, they are exposed in some ranges and are widespread east and south of the map area. Most of these rocks are continental clastic rocks deposited in fluvial, lacustrine, eolian, and marginal marine environments. The Thaynes Formation (Lower Triassic) is a soft, gray, thin-bedded claystone and limestone that is locally about 1,900 ft thick in western Utah in the northeast part of the map area (Hintze and Davis, 2002b). The overlying Moenkopi Formation (Lower Triassic) is a mostly soft, red and gray, thin-bedded siltstone, limestone, sandstone, and shale, commonly gypsiferous, and locally about 2,000 ft thick in western Utah. The Thaynes and Moenkopi Formations are thin in the Nevada portion of Plate 1 and are not separated on this map. All Triassic rocks in the map area have been lumped as Triassic sedimentary rocks (TRs).

Cretaceous synorogenic sedimentary rocks (Ks) are present but uncommon in the map area. Most of this area was a highland undergoing erosion at that time. The Lower Cretaceous Newark Canyon Formation is present just northwest of the map area as a poorly exposed, reddish-brown to gray, fresh-water limestone, siltstone, conglomerate, and sandstone from 1,400 to 1,800 ft thick (Hose and Blake, 1976). Upper Cretaceous sedimentary rocks, shed east from erosion of Sevier highlands in and north of the map area, are thin and patchy in the map area but extensive and thick east and south of the map area.

Plutonic rocks related to the Middle Jurassic through Paleocene Sevier deformational event are exposed locally throughout the study area (Maldonado et al., 1988). Of these, Jurassic diabase has been identified in the Burbank Hills of Utah (Hintze and Davis, 2002b). Other plutons of quartz monzonite to granodiorite and of mostly Middle Jurassic age form a north-trending belt along the eastern edge of White Pine County, extending into the Clifton Hills of Utah. A north-trending plutonic belt of Cretaceous age is exposed in eastern White Pine County, extending into the Deep Creek Range and including the main mass of the large Kern Mountains granite pluton of apparent

Cretaceous and Eocene age (Best et al., 1974; Miller et al., 1999). An east-trending string of small Lower Cretaceous plutons extends from Eureka through Ely, Nevada.

4.1.5 Cenozoic Rocks

Cenozoic rocks in the map area belong to three main sequences: (1) locally exposed, mostly thin, older continental sedimentary rocks, (2) generally voluminous, calc-alkaline volcanic rocks and their source plutons, and (3) rocks that formed during regional basin-range extension, namely thin bimodal-composition (basalt and high-silica rhyolite) lava flows and locally thick, basin-fill sediments. On the geologic map, most of these rocks are separated into several rock types based on age, following the mapping strategy of Ekren et al. (1977). The basalts and basin-fill sedimentary rocks, including surficial sediments, of sequence #3, however, are mapped respectively as Quaternary to Late Tertiary basaltic rocks (QTb) and Quaternary to late Tertiary alluvium (QTa).

4.1.5.1 Eocene to Miocene Sedimentary Rocks

The oldest Cenozoic sedimentary rocks (Ts1) are thin and poorly exposed in the study area but are more common in eastern Clark County and southwestern Utah. These units are unconformably deposited on rocks deposited and deformed during the Sevier deformational event. In eastern Nevada, the principal unit is the Sheep Pass Formation of Eocene to Oligocene age (Hose and Blake, 1976). The Sheep Pass Formation occupied a basin of about 15,000 square miles over an area that extended south from present Ely and Eureka, Nevada to well southwest of the map area (Fouch et al., 1991). The unit is mostly nonresistant, gray conglomerate, sandstone, mudstone, and limestone, with a thickness of 600 to 3,000 ft in the map area.

Similar sedimentary rocks (Ts2, Ts3, Ts4) of various names and ages, from Oligocene to Miocene, are exposed in and adjacent to the study area. These include the Gilmore Gulch Formation of about 30 Ma (Ts2), exposed just northwest of the map area. The Horse Spring Formation, about 12 to 20 Ma, is mapped as Ts4 just south of the map area.

4.1.5.2 Tertiary Volcanic Rocks

Volcanic rocks make up the primary Cenozoic rock type in the study area. The older (Eocene to Miocene) sequence of calc-alkaline rocks consists of andesite to low-silica rhyolite that are mapped as different units separated by rock type and age. Tertiary plutonic rocks, which are the sources for the volcanic rocks, are mapped as unit Ti whether of calc-alkaline or bimodal origin.

The calc-alkaline sequence is made up largely of regional ash-flow tuff sheets derived from widely scattered calderas. The oldest tuffs are mapped as Tt1 (Eocene and Oligocene) that predate the Needles Range Group (about 32 Ma). The next younger group of tuffs, consisting mostly of the Needles Range Group, is mapped as Tt2 (Oligocene), from about 32 Ma to 27 Ma, the latter the age of the Isom Formation. The next younger tuffs are mapped as Tt3 (Oligocene and Miocene), ranging in age from that of the Shingle Pass Tuff (about 27 Ma) to the youngest calc-alkaline tuffs (about 18 Ma). Individual calderas are filled with thick intracaldera ash-flow tuffs that are at least several thousand feet thick. Their outflow sheets are generally thin, generally less than 1,000 ft, but the aggregate thickness of all of these tuffs is considerable in most places.

The outflow tuffs are interspersed with locally distributed but thick central stratovolcano deposits made up of lava flows and volcanic mudflow breccia generally deposited above their source plutons. Where these calc-alkaline flows and breccia are largely andesite, they are mapped as Ta1, Ta2, Ta3, and Ta4 based on ages that correspond to those of the ash-flow tuffs. Unit Ta4 is made up of andesitic (calc-alkaline) flows of post-18 Ma that are exposed in the southern part of the map area. Where calc-alkaline flows and breccia are largely low-silica rhyolite, they are mapped as Tr1, Tr2, and Tr3 based on ages that correspond to those of the tuffs.

The tectonic environment during calc-alkaline magmatism was generally one of east-west extension in the map area. The direction of principal maximum compressive stress was generally north-south, creating an environment of strike-slip and oblique-slip faults. The orientation and size of mountains during this time are poorly known, but the outpouring of large volumes of volcanic ash-flow tuff probably resulted in a subdued landscape with topographic variations caused by the uneven distribution of these units.

In the Great Basin, vents—notably calderas—for Tertiary calc-alkaline volcanic rocks occur in generally east-west igneous belts that become younger from north to south (Ekren et al., 1976 and 1977; Stewart and Carlson, 1976; Stewart et al., 1977; Rowley, 1998; Rowley and Dixon, 2001). These igneous belts are partly controlled by transverse zones of faulting and underlain by batholiths whose cupolas provide the main vent areas for the volcanic rocks. The oldest volcanic rocks in the map area belong to the Ely-Tintic igneous belt (belt names from Rowley, 1998), in the northern part of the map area. The ages of vents in this belt are about 38 Ma and locally older (Eocene) along the northern margin of the map area and 36 Ma farther south (Rowley, 1998). An east-west gap in vent areas, about 30 to 60 miles wide, occurs south of Ely and Preston, Nevada, although a volcanic plain of thin outflow tuffs underlies the gap. To the south, the Pioche-Marysvale igneous belt crosses near Pioche, Nevada. The volcanic centers here are about 32 to 31 Ma on the northern side of the belt and about 28 to 27 Ma along the southern part. About 12 miles south of the Pioche-Marysvale belt is the Delamar-Iron Springs igneous belt, of about 24 Ma along its northern side and 16 Ma along its southern side. Its southern edge is just south of the latitude of Pahranagat Valley, Nevada.

In the Ely-Tintic igneous belt, the most voluminous volcanic unit is the Kalamazoo Tuff (35 Ma), an ash-flow tuff sequence deposited over an east-west elongated area 90 miles long and 25 miles wide. Its caldera has not been found but may underlie the Red Hills or adjacent northern Spring Valley (Gans et al., 1989), near the center of deposition. Other ash-flow tuffs and lava flows underlie and overlie the Kalamazoo Tuff, and the overall thickness of the volcanic rocks in the igneous belt is about 500 to 1,500 ft. Plutons of 30 to 45 Ma age range are scattered throughout the belt; most of these represent source areas of volcanic rocks that have been since been removed by erosion. One of these plutons, which is roughly 45 to 30 Ma in age (Best et al., 1974), is at the eastern end of the composite-age Kern Mountains pluton.

In the Pioche-Marysvale belt, volcanic rocks are thicker and more widespread than in the Ely-Tintic belt because calderas are more abundant and larger and the volcanic rocks are somewhat younger and thus less eroded. Most volcanic rocks are regional ash-flow tuffs from calderas, but lava flows and mudflow breccia erupted from volcanoes in and along the margins of calderas or from isolated volcanoes. The largest vent area in the belt is the Indian Peak caldera complex (Best et al., 1989a) in the southeastern part of the area. It erupted ash-flow tuffs and related rocks of the Needles Range Group (Oligocene, about 32 to 28 Ma) and the Isom Formation (27 to 26 Ma). This may be the largest caldera complex in the world; ash-flow tuffs from this complex are spread over an area of about 200 miles east-west by 150 miles north-south.

A cluster of smaller calderas west of the Indian Peak caldera complex, just southwest of the map area, also belongs to the Pioche-Marysvale igneous belt. These calderas produced, from oldest to youngest and generally from north to south, regional ash-flow tuffs known as the Stone Cabin Formation (35.3 Ma), Pancake Summit Tuff (34.8 Ma), Windous Butte Formation (31.3 Ma), tuff of Hot Creek Canyon (29.7 Ma), Monotony Tuff (27.3 Ma), tuff of Orange Lichen Creek (26.8 Ma), Shingle Pass Tuff (26.7 to 26 Ma), tuff of Lunar Cuesta (25.4 Ma), tuff of Goblin Knobs (25.4 Ma), tuff of Big Ten Peak (25 Ma), Pahranagat Tuff (22.6 Ma), and Fraction Tuff (18.3 Ma) (Best et al., 1989b and 1993). Most of this cluster of calderas was referred to as the “central Nevada caldera complex” (Best et al., 1993; Scott et al., 1995). However, the feature is not a classic caldera complex because all of it has not subsided following tuff eruptions, but instead individual calderas (subsided areas) are locally separated by pre-caldera Phanerozoic sedimentary rocks that are currently exposed outside the margins of individual calderas. Within calderas in the map area, intracaldera ash-flow tuffs and subordinate lava flows and mudflow breccia are several thousand feet thick and are underlain by intracaldera source plutons. Outside the calderas, the thickness of volcanic rocks in the belt in the map area is about 1,500 to 3,000 ft, but locally more. A few plutons of the same age range, likely representing sources for volcanic rocks that have been removed by erosion, occur in the Grant Range and many other parts of the study area.

The bimodal sequence is made up of small basalt lava flows and cinder cones as well as small high-silica rhyolite volcanic domes, lava flows, ash-flow tuffs, and airfall tuffs. The basalts are lumped on the geologic map as unit QTb, rhyolite domes and flows as Tr4, and tuffs as Tt4. The tectonic environment during bimodal magmatism was east-west extension, with the direction of principal maximum compressive stress generally oriented vertically, creating and environment of north-south normal faults. Bimodal magmatism coincided with basin-range deformation, in which the present topography was created and previous tectonic features and topography were deformed and obscured.

4.1.5.3 Miocene to Holocene Sediments

With the start of basin-range deformation at about 20 Ma, north-striking normal faults created the present ranges and basins. Erosion of the ranges, as they were faulted up, resulted in basin-fill sediments that accumulated to thicknesses of locally more than 10,000 ft in down-faulted basins. In most places, the basin-fill sediments are unnamed. These units are referred to as Holocene through Miocene alluvium (QTa) and are considered to be aquifers where fractured by faulting.

The bimodal volcanic rocks that were deposited at the same time were either high-silica rhyolite lava flows and tuffs or basalt lava flows and tuffs. Their distribution in the map area is spotty and their thickness is rarely more than several hundred feet, except for their source volcanic domes or cinder cones. Where thin, they are combined in the cross sections with the older, much thicker calc-alkaline volcanic rocks or with thick interbedded basin-fill sediments.

The basin-fill sediments (QTa) were largely deposited by streams in closed basins. In general, coarse-grained materials accumulated around the edges of the mountain fronts, whereas finer materials accumulated toward the center of the basins. In some basin interiors, fine-grained sediments accumulated in ephemeral playa lakes. The largest playa lakes are Plio-Pleistocene in age, including the latest Pleistocene Bonneville and Lahontan lakes that had water depths of as much as 1,000 ft, resulting in deposition of clay and saline sediments in many basins (Mifflin and Wheat, 1979). Data from drill holes in Snake Valley report several hundred feet of evaporates within the deepest part of the basin. These lakes, however, were short lived and produced fine-grained materials that rarely exceeded a few tens of feet in thickness. Because of the vagaries of the sizes of storms, of climate changes, of integration of some basins, and of timing of the deformation of basin-bounding versus within-basin faults, the stratigraphy of basin-fill sediments is characterized by a complex intertonguing of beds of all lithologies. Within-basin faults commonly produced horsts (hills) of soft basin-range sediments that were then eroded away by streams and redeposited as younger basin-fill sediments. As with the older basin-fill sediments, Quaternary deposits are dominated by stream alluvium but also include the deposits from landslides, playas, and springs that are not individually separated in this report or on the maps due to their limited extent.

4.2 Hydrogeologic Units

Hydrogeologic units, as given on Plates 4 and 5, and listed in Table 4-1, are a set of geologic formations that are grouped based on physical properties of the units. This grouping is based on lithologic properties rather than more traditional geologic groups based on genetic sequences. The hydrogeologic units described in this report are considered useful for hydrogeologic studies. The geologic and hydrogeologic maps and cross sections were developed concurrently in preparation of this report.

4.2.1 Precambrian Metamorphic Rocks

Precambrian rock units (p€m) primarily consist of moderately to intensely metamorphosed Precambrian “basement” rocks. The largest exposure in the map area, on Plate 4, is on the eastern side of the Schell Creek Range, north of US 50 and on the western side of the Snake Range, north and south of US 50. This unit includes the Proterozoic rock units up through the McCoy Group. The permeability of the unit is low, except in areas where fractured or weathered.

4.2.2 Cambrian to Precambrian Siliciclastic Rocks

The Cambrian to Precambrian clastic rock unit (€p€s) is non-metamorphosed to moderately metamorphosed siliciclastic rock deposited in the Late Proterozoic and Early Cambrian. The unit is

Table 4-1
Brief Summary of Hydrogeologic Units

QTb	Quaternary and Tertiary basalt - Quaternary and late Tertiary mafic volcanic rocks that are too thin to show on cross sections. These rocks are significant as a separate unit only where they are divided from the older volcanic rocks (Tv) by alluvium.
QTs	Quaternary and Tertiary sediments - Includes sediments younger than the volcanic section, but may include older sediments where volcanic rocks are minor or nonexistent. Also includes playa deposits.
Tv	Tertiary volcanic rocks - Miocene to Eocene volcanic rocks.
Tos	Older Tertiary sediments - Primarily created for the cross sections; includes the older Tertiary alluvial section below the volcanic section.
TJi	Tertiary to Jurassic intrusive rocks - includes all plutons.
KTRs	Cretaceous to Triassic siliciclastic rocks - Thicker where near the Colorado Plateau, and generally of low permeability. These units are more abundant in the southern part of the study area.
PlPc	Permian and Pennsylvanian carbonate rocks - Includes Ely Limestone, Bird Spring Formation, the Park City Group and other units. Includes Triassic carbonate rocks in the Butte Mountains, where these rocks are of limited extent. Also includes Permian red beds, undifferentiated.
Ms	Mississippian siliciclastic rocks - Includes Chainman Shale, Scotty Wash Quartzite, Diamond Peak Formation, Eleana Formation, and others. The Chainman Shale and Scotty Wash Quartzite are not differentiated in Lincoln County, except in the Egan and Schell Creek Ranges.
MOc	Mississippian to Ordovician carbonate rocks - Joana Limestone (Monte Cristo Formation) to Pogonip Group, also includes Chainman Shale in most of Lincoln and Clark County. The Pilot Shale and Eureka Quartzite are also included. Also included are the Guilmette Formation, Simonson Dolomite, Sevy Dolomite, and the Laketown Dolomite.
Єc	Cambrian carbonate rocks - Includes the Bonanza King, Highland Peak, Lincoln Peak, and Pole Canyon Formations, and several units in western Utah.
ЄpЄs	Cambrian and Precambrian siliciclastic rocks - Includes the Wood Canyon Formation and the Prospect Mountain and Stirling Quartzites, and the Chisholm Shale, Lyndon Limestone, and Pioche Shale.
pЄm	Precambrian metamorphic rocks - Precambrian X, Y, and Z high-grade metamorphic rocks, generally Late Proterozoic. It also includes the Johnnie Formation in the southern map area, and the weakly metamorphosed McCoy Creek and Trout Creek Groups in Schell Creek, Deep Creek, and Snake Ranges.

quartzite with a substantial thickness of shale also present. The unit is thickest in the southwest where it is estimated to exceed 10,000 ft, and it is thinnest in the north and southeast, where it is estimated to be about 5,000 ft thick or locally less. The thickness of the unit is approximate because the base is rarely exposed, but the estimate is consistent with the amount of section that is exposed. In most places, the youngest formation within this unit is the Pioche Shale. The permeability of the unit is low except in areas where fractured or weathered. The difference in permeability between pЄm and ЄpЄs in exposed sections is considered minor. The ЄpЄs unit is expected to be slightly more permeable than the older pЄm (Belcher and Elliott, 2001).

4.2.3 Cambrian Carbonate Rocks

The Cambrian carbonate unit (Єc) consists of Middle and Late Cambrian carbonate rocks, notably the Bonanza King, Highland Peak, and Pole Canyon Formations. The units are interpreted to be thicker in the south (~8,000 ft) and thinner (~5,000 ft) in the north. This unit is mostly carbonate with a limited thickness of clastic sections. In the southern part the map area, the unit constitutes about half of the Paleozoic section. The rocks are generally very permeable, especially where faulted. The Cambrian carbonate aquifer includes a thin, spatially limited aquitard, the Dunderberg Shale. This unit is of limited extent and is too thin to be considered capable of limiting flow on a regional basis.

4.2.4 Mississippian to Ordovician Carbonate Rocks

The Mississippian to Ordovician carbonate rock unit (MOc) consists of the middle part of the Paleozoic carbonate section. The unit can exceed 12,000 ft but has a wide variation in thickness, as on Cross Section N-N', due to paleotopographic influences during deposition and post-depositional erosion. The unit includes the section from the Mississippian Joana or Monte Cristo Limestone to the Ordovician Pogonip Group or Antelope Valley Formation and therefore includes the Pilot Shale and Eureka Quartzite. This unit is characterized as carbonate with limited clastic rocks. It is generally very permeable, especially when faulted.

The Mississippian to Ordovician carbonate aquifer includes the Ordovician Eureka Quartzite and Pilot Shale, confining units. Neither of these formations is considered a significant aquitard at the scale of Plates 4 through 5, and the Eureka Quartzite, where fractured, can be an aquifer nearly as permeable as the carbonates. This section of rocks also includes the Guilmette, Sultan, Sevy, and Simonson Formations of Devonian Age and the Lone Mountain Dolomite of Silurian age. These rocks are predominately dolomite.

4.2.5 Mississippian Siliciclastic Rocks

The Mississippian clastic rock unit (Ms) includes the Diamond Peak Formation, Chainman Shale, Scotty Wash Quartzite, and equivalent siliciclastic rock units. The first two formations listed are not differentiated in this report in Lincoln County, except in the Egan and Schell Creek Ranges, and are not differentiated in Clark County because the are thin. The clastic rock unit is derived from erosion of highlands in north-central Nevada associated with the Antler upland. The permeability of the unit is low and the unit is an important confining layer in the Paleozoic section north of the North Pahroc Range (about 38° north latitude). In the Snake Range, the rock unit is too thin to comprise an aquitard.

4.2.6 Permian and Pennsylvanian Carbonate Rocks

The Permian and Pennsylvanian carbonate unit (PlPc) includes the Ely Limestone and Bird Spring Formation. It is nominally equivalent to the upper carbonate aquifer of Winograd and Thordarson (1975) at the NTS. In the northern part of the map area, these rocks are continuous with the Arcturus and Park City Groups, which are predominantly carbonate rocks. The unit is thickest near Robinson Summit in the Egan Range with a thickness of ~10,000 ft at Cross Section W-W'. This unit is mostly carbonate, with a minimal thickness of clastic rocks. It is generally very permeable on a regional scale, especially where faulted. It is hydrologically similar to the lower carbonate section but separated from it by the Mississippian confining unit, unit Ms. The unit includes Permian carbonate and red beds in the southern part of the area.

4.2.7 Cretaceous to Triassic Siliciclastic Rocks

The Cretaceous to Triassic clastic unit (KTRs) consists of Mesozoic rocks in eastern Lincoln and Clark Counties. These units are locally below thrust faults with overlying older Paleozoic carbonates thrust from the west during Sevier deformation, and this unit may be 10,000 ft thick or more. The rocks of this unit are generally much less permeable than the carbonate aquifers.

4.2.8 Tertiary to Jurassic Intrusive Rocks

The Tertiary to Jurassic intrusive unit (TJi) includes all plutons in the study area. Mesozoic plutons form either a significant part of, or the bulk of, several large ranges in the northeastern part of the map area, including the Snake, Schell Creek, Egan, and Kern ranges. In addition, extensive Tertiary plutons exist beneath all calderas. The permeability of the unit is low in areas except where fractured or weathered, but generally more permeable than units pЄm or ЄpЄs.

4.2.9 Older Tertiary Sedimentary Rocks

The older Tertiary sedimentary unit (Tos) consists mostly of older Tertiary clastic sedimentary rocks (Eocene to Oligocene age) below the volcanic section. The unit reaches a maximum thickness of 4,000 ft in Railroad Valley, just west of the map area.

4.2.10 Tertiary Volcanic Rocks

The Tertiary volcanic unit (Tv) include large volumes of middle Tertiary (Eocene to middle Miocene), mostly intermediate to felsic volcanic rocks. It also includes thin sedimentary rocks and local tuffaceous sediments that are interbedded with the volcanic units. Outflow rocks are generally less than 3,000 ft thick, but intracaldera rocks may locally be more than 10,000 ft thick.

The Tertiary volcanics consist of a number of units of variable permeabilities. In general, the permeability is considered moderate, but where faulted, the unit may be more permeable and, in some places, it may be an important aquifer.

4.2.11 Quaternary and Tertiary Sediments

The Quaternary and Tertiary sedimentary (QTs) consists mostly of basin-fill sediments younger than the volcanic section. This unit may include older Tertiary sediments where the volcanic rocks are thin or nonexistent and these older units are too thin or too localized to separate out. In some cases, these older units consist of sands and gravels that are difficult to distinguish from the younger alluvial sediments, and these units are, therefore, lumped together.

The QTs unit is interpreted to be thicker than 10,000 ft in some down-faulted grabens (valleys). The unit is composed of conglomerate, fresh water limestone, sand, silt, gravel, and clay, and therefore it has a large range of permeability. Also included in this unit are playa deposits that are too thin to show on cross sections but are an obvious feature throughout the Great Basin.

4.2.12 Quaternary and Tertiary Basalt

The Quaternary and Tertiary basalt unit (QTb) resulted from Quaternary and late Tertiary mafic volcanism. The deposits are too thin to show on cross sections but locally cover large areas. The unit is of possible hydrologic significance as a separate unit only where divided from the older volcanic rocks by alluvium. It is separated from the alluvium largely because it is a distinct rock type.

4.3 Structural Geology

This section discusses the structural framework of the study area. This presentation is followed by an analysis of the effect of specific structures on the hydrogeology of the region. This analysis covers structures as both groundwater flow conduits and flow barriers, in other words how they guide flow along and across a general flow path.

4.3.1 Evolution of the Regional Structure

Three main structural events affected the map area: (1) Late Devonian to Late Mississippian Antler compressive deformation, (2) Late Jurassic to early Tertiary Sevier compressive deformation, and (3) Cenozoic basin-range extensional deformation. In addition to these events, middle Cenozoic time was characterized by mild extension (Rowley, 1998; Miller et al., 1999; Rowley and Dixon, 2001) and voluminous calc-alkaline volcanism that profoundly affected the topography and hydrology of the study area.

The Late Devonian to Late Mississippian Antler compressive deformation affected the northwestern part of the map area, creating a north-trending highland (Larson and Langenheim, 1979; Carpenter et al., 1994; Poole and Sandberg, 1977 and 1991). This event formed folds and thrusts of the Roberts Mountain allochthon, which was at least 8,000 ft thick and passed through the western side of Eureka, Nevada (Carpenter et al., 1994; Saucier, 1997). The thrusts transported deeper-water sedimentary rocks eastward as much as 100 miles. Coarse synorogenic siliceous clastic detritus was shed from the highland into the foreland basin to the east, transitioning to shale farther east. The main synorogenic rock units that resulted were the Chainman Shale and Diamond Peak Formation and farther south, the Scotty Wash Quartzite.

The second structural event, the Middle Jurassic to early Tertiary Sevier compressive deformation, resulted in generally north- to north-northeast-striking, east-verging folds and thrust faults. Scattered Middle Jurassic to lower Tertiary plutons were emplaced in many ranges of the study area. Eastward-directed overthrusts emplaced Late Proterozoic to middle Paleozoic rocks over Late Proterozoic to Mesozoic rocks (Armstrong, 1968). At least a half dozen large thrusts are well exposed in the Las Vegas area, each with displacements ranging from several to 20 miles (Page et al., 2005b). Tectonic shortening caused by thrusting in southern Nevada is at least 22 to 45 miles (Stewart, 1980; Burchfiel et al., 1974). Most of the study area has been considered to be the western hinterland of the deformation. In other words, the leading edges of most major thrusts are east of the map area, and the deformation created highlands within the hinterland of the map area that in turn shed clastic material primarily to the east. Some of the thrusts, including the Gass Peak, however, have been projected northward into the hinterland in the central and northern part of the study area, (Vandervoot and Schmitt, 1990; Dobbs et al., 1994; Taylor et al., 2000). Sevier-type deformation is shown schematically on Figure 4-6, and the Sevier-age Glendale/Muddy Mountains thrust in the Muddy Mountains (east of Las Vegas) is shown on Figure 4-7.

East-striking faults and folds, alignments of plutons and volcanic vents, alignments of geophysical anomalies, local alignments of basins and ranges, hot springs, hydrothermally altered rocks, and mineral deposits have been noted in the Great Basin for years, primarily by geologists of the mining industry. Ekren et al. (1976 and 1977), Rowley et al. (1978), and Stewart et al. (1977) called these alignments “lineaments” with an origin similar to transform faults in the ocean basins. Ekren et al. (1976) also suggested that the lineaments began to form in the Cretaceous, if not earlier, and continued to be active throughout both Tertiary calc-alkaline magmatism and basin-range deformation. Like transform faults, these lineaments seem to represent boundaries between areas to the north and south that had different amounts, rates, and types of structural deformation. Rowley (1998) and Rowley and Dixon (2001) referred to them as transverse zones, and we follow their terminology here. They are poorly known and have been mapped in detail only locally, so they are projected with limited evidence between areas where they are known.

Transverse zones bound parts of most igneous belts in the Great Basin. Transverse zones may both provide barriers to the southward flow of groundwater and act as conduits to east or westward flow of groundwater (Prudic et al., 1995; Rowley, 1998; Rowley et al., 2001).

The third structural event, the basin-range episode of extensional deformation, began at about 20 Ma and continues today. It is characterized by east-west extension and resulted primarily in north-striking normal faults. Over some parts of the Great Basin, early phases of this deformation produced north-striking basins and ranges due partly to gentle folding. Sediments were deposited in basins formed by these early faults and broad warps, but these basins were not necessarily in the same locations as they are today. The present topography was produced later during the main pulse of basin-range deformation, which began after 10 Ma for most parts of the Great Basin. The axes of basins and ranges since 10 Ma were commonly different from those created during the early phase of deformation. Some parts of the older basins were uplifted as part of the new ranges and some parts of the older ranges were downthrown as part of the new basins.

The dominant fault type since major deformation began (about 10 Ma) continued to be north-striking normal faults, but locally strike-slip and oblique-slip faults accommodated the east-west extension. East-striking transverse faults continued to be active at the same time, segmenting the Great Basin into broad east-trending corridors of different types and amounts of east-west pulling apart.

In some parts of the map area, low-angle faults were previously mapped as thrust faults. These faults, however, place younger rocks on older rocks. In some places, the direction of movement of the upper plates of these faults is westward rather than eastward. We consider that most of these faults are much younger, Tertiary in age, expressions of structural extension and that most formed during the

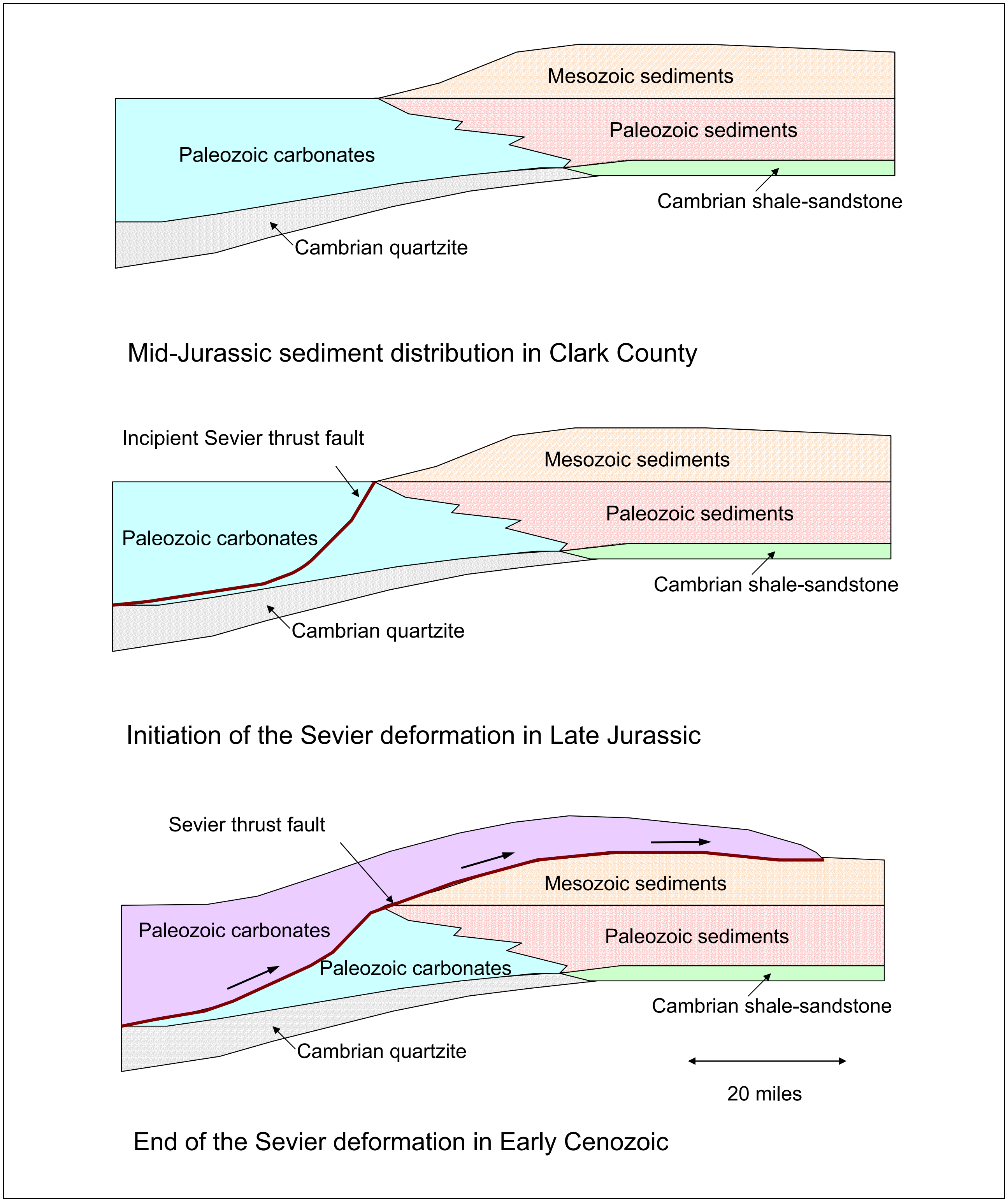


Figure 4-6
Schematic Diagram of Sevier Thrust Sheets, Illustrating the Movement of Paleozoic Carbonates Over Cratonic Sediments

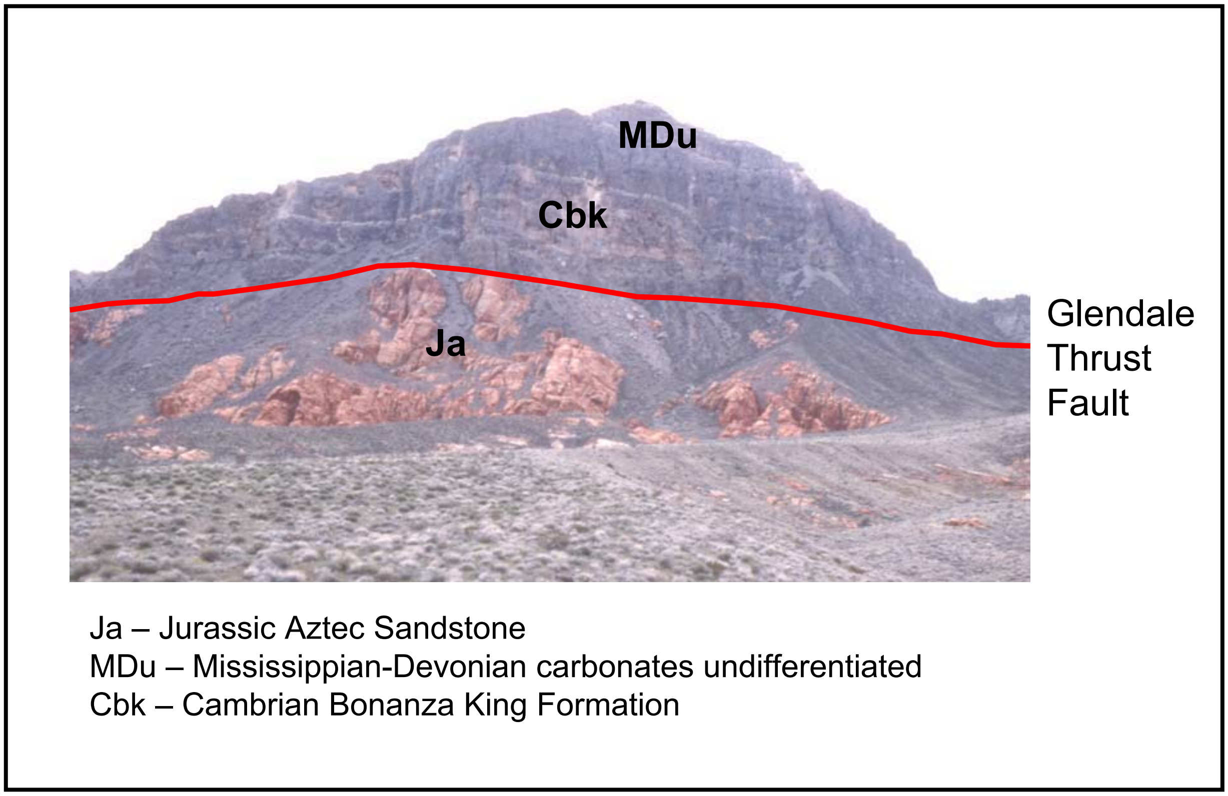


Figure 4-7
Paleozoic Carbonates Thrust Over Jurassic Aztec Sandstone in the Muddy Mountains Near Muddy Peak

basin-range deformational event. We interpret the faults to be detachment faults, although the general synonyms attenuation or denudation faults that were used by some early workers who first recognized them (Moores et al., 1968; Armstrong, 1972) are more appropriate in places where many subhorizontal faults are present, notably the Eureka area. In these areas, rapid uplift of ranges resulted in their tops being structurally stripped (or attenuated or denuded) by low-angle faults that verged into the adjacent low areas, much like large gravity slides.

One major fault to which the name detachment fault is appropriate is the well-known Snake Range decollement. Although originally considered to be a thrust fault that placed Middle Cambrian and younger rocks over Middle Cambrian and older rocks (e.g., Nelson, 1966), the fault was later mapped in greater detail and reinterpreted as an Eocene to middle Miocene low-angle fault caused by stretching and thinning during uplift of a metamorphic core complex (Miller et al., 1983; Gans et al., 1985 and 1989). This detachment may represent the ductile/brittle transition zone uplifted by the core complex (Miller et al., 1983; Gans et al., 1985 and 2000b; see Figure 4-8). Rocks have been thinned by the elimination of strata due to the faulting. Later work indicated that, while the decollement had an older (late Eocene and early Oligocene) history, most displacement on it was middle Miocene and later, coinciding with basin-range deformation (Miller et al., 1999). The core-complex uplift that formed the decollement included the Kern Mountains and southern Deep Creek Range (Miller et al.,

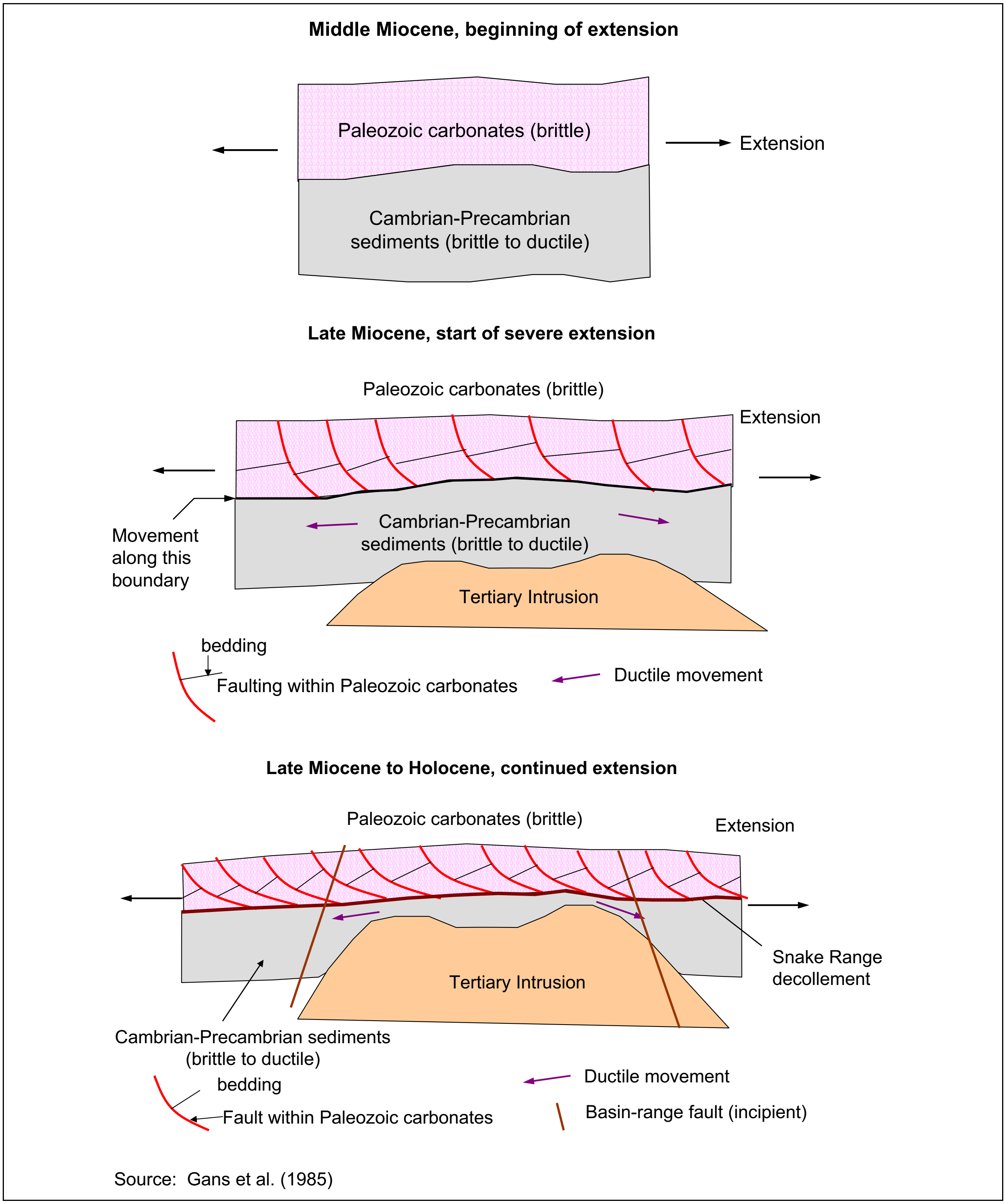


Figure 4-8
One Scenario for Development of the
Snake Range Decollement During Late Cenozoic Extension

1999). Finally, Miller et al. (1999, p. 902) suggested that the Snake Range decollement may not be a normal fault at all but instead a "highly complex structural boundary developed above a rising and extending mass of hot crystalline rocks."

4.3.2 Effect of Structures on Groundwater Flow

This section evaluates the effect of the four episodes of structural deformation and volcanism on the groundwater flow in the study area.

4.3.2.1 The Antler Deformation

The Antler episode of compressive deformation probably had the least structural effect of any structural event on the hydrogeology of the region. Most of the thrust faults associated with this tectonic event are west and northwest of the study area. Instead, the deformational event had more of an effect on the types of sediment deposited than on any structural controls on groundwater flow. The deformation created a highland west of the map region and sandstone and shale, including the Chainman Shale, were deposited within the study area, forming a lithologic aquitard. Most of the tectonic features developed during this event were themselves deformed and changed in subsequent tectonic episodes.

4.3.2.2 The Sevier Deformation

The Sevier episode of compressive deformation had a stronger effect on the hydrogeology of the region than the Antler event. The Sevier event resulted in major thrust faults, especially north and west of Las Vegas, south of the map area. Gouge and mylonitic zones along these thrusts created barriers to groundwater flow, particularly south of the map area. Furthermore, these thrust faults brought western-assemblage carbonate rocks over eastern-assemblage cratonic clastic sedimentary rocks of Triassic through Cretaceous age. These cratonic aquitard units generally are flow barriers. Some of these geologic barriers to flow are several thousand feet thick. In other places, thrust faults brought Precambrian and Cambrian siliciclastic rocks over the carbonate units, as along the Gas Peak and Delamar thrusts south of the map area.

4.3.2.3 The Eocene-Miocene Episode of Calc-Alkaline Volcanism

The third episode of landscape change was during the Eocene, Oligocene, and Miocene epochs, when the area was drastically affected by voluminous calc-alkaline volcanism, mild extension, and high-angle strike-slip faults and high- to low-angle normal faults. The topography became dominated by calderas, which capped mountainous areas formed by uplift and inflation of the crust due to the rise of underlying source batholiths and stocks. Ash-flow tuffs that erupted from the calderas blanketed and subdued the topography. Stratovolcanoes and other volcano edifices fed lava flows and mudflows. The geometry, extent, strike, size, and type of structure that formed during this time are poorly known but likely included strike-slip and normal faults, including detachment faults. The region was characterized by mild extension and wrench tectonics. Strike-slip faults probably had northeast and northwest strikes. The caldera complexes and their associated ring faults and other margin structures provided mostly barriers to groundwater flow. Perhaps more important than the caldera margins are the intracaldera intrusions that invariably underlie the calderas, along with the hydrothermal clay formed by heating and convective overturn of ancient groundwater as well as contact metamorphism of intracaldera ash-flow tuff by the intrusions. Faults and associated joints that postdate and cut the calderas may provide conduits for groundwater flow through the calderas.

4.3.2.4 The Miocene-Quaternary Basin-Range Episode of Extension

The basin-range episode of extensional faulting began in the Miocene and is continuing today. The faults that formed during this episode are generally moderate to steeply dipping normal faults that are generally north trending. They formed most of the topography we see today. High-angle oblique-slip and local strike-slip faults that formed as accommodation zones during the same east-west extension also were important. The high-angle faults and resultant fractures generally provided conduits to groundwater flow rather than flow barriers. In areas where groundwater flow is directly across these fault zones, such as between Spring and Hamlin Valleys, groundwater flow may be limited by gouge in the core zones of the faults but not prevented by these structures (Figure 4-9). Along the WRFS where flow is from north to south, parallel to these structures, flow is enhanced in the north-south direction by these faults (Figure 4-9). The hydrologic effect produced by faults largely results from joints that the faults cause, with larger-displacement faults resulting in more joints and thus greater fracture flow. However, for brittle rocks such as carbonates, ash-flow tuff, and basalt flows, even small faults—which are many times more abundant in the Great Basin than the large faults we have mapped—will create rock fractures, acting like a hammer on a plate of glass. Brittle rocks in the Great Basin cannot help but be fractured throughout, creating important aquifers.

Some normal faults are low-angle, that is detachment or attenuation faults. Their effect on groundwater flow is much less important than that from high-angle faults. These detachment zones may be either from brittle or plastic deformation, resulting respectively in gouge or mylonitic zones along the faults. Gouge and mylonite may provide barriers to groundwater flow. An example is the Snake Range decollement that formed as the Snake and Schell Creek Ranges were uplifted and intruded. The detachment faults of the Snake Range decollement locally prevent groundwater recharge from penetrating the range. But a more profound effect on groundwater recharge is caused by the underlying Proterozoic and Cambrian metamorphic rocks and quartzite, which also provide barriers to east or west flow through the ranges.

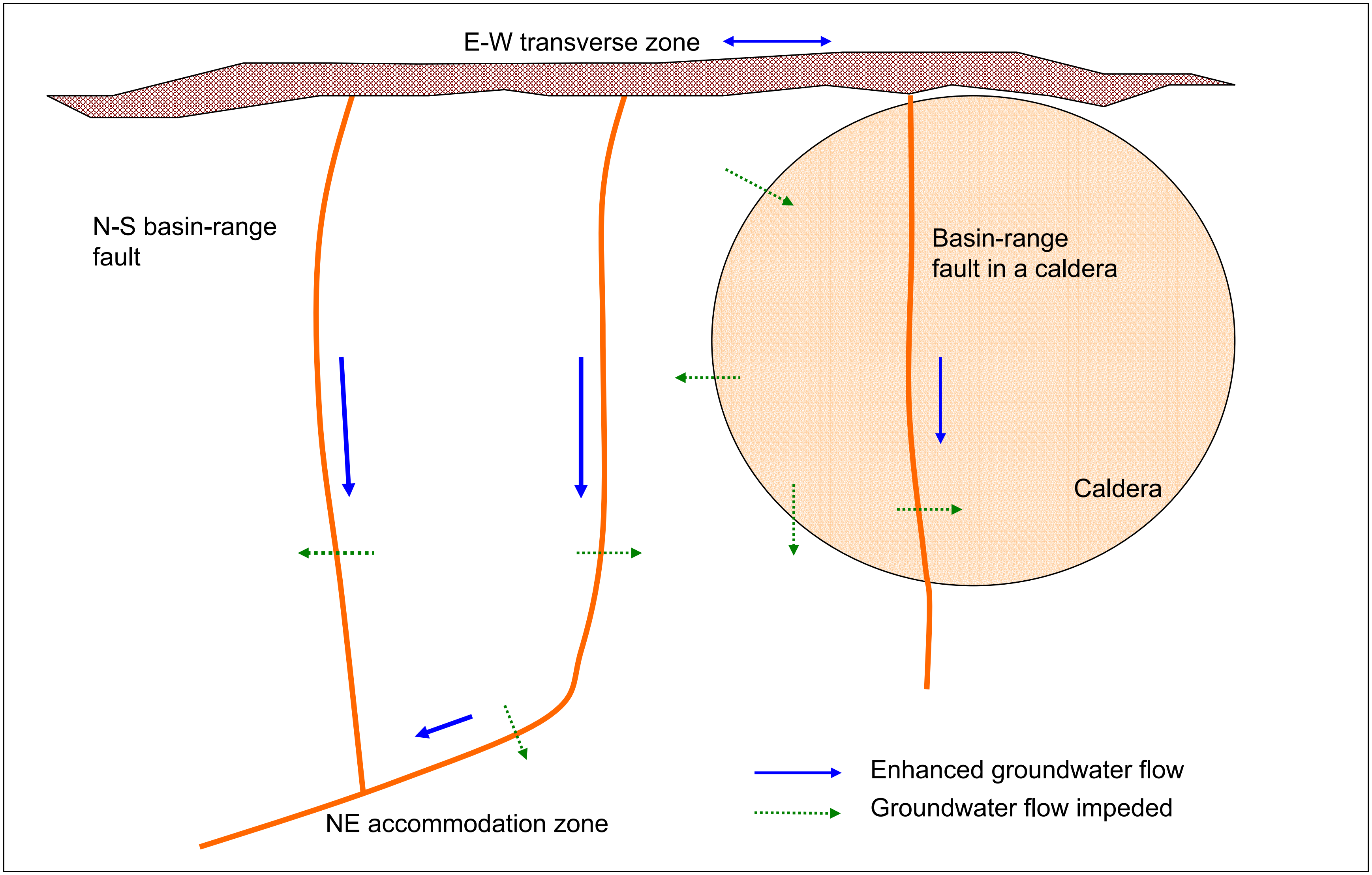


Figure 4-9
Diagrammatic Map Showing Enhancement or Impedance of Groundwater Flow Along or Across Faults, Transverse Zones, and Calderas

5.0 SPRING VALLEY

5.1 Northern and Central Schell Creek Range

The Schell Creek Range is a high, narrow horst, with the main bounding fault on the eastern side of the range. The northern part of the range is made up of steeply west-dipping Proterozoic through Permian rocks (Lumsden et al., 2002), with overlying Tertiary volcanic rocks along the faulted western flank of the range (Cross Section X-X', Plates 1 and 3). The volcanic rocks, which are dominated by Eocene and Oligocene andesitic to dacitic lava flows, are at least 4,000 ft thick in the range (Gans et al., 1989). The source of the Eocene Kalamazoo Tuff, which is the largest ash-flow sheet in this area, may be in the northern Schell Creek Range (Gans et al., 1989). A major structure within the range is the Snake Range decollement, a low-angle detachment fault exposed along the crest of the range. The Snake Range decollement commonly separates the Cambrian Pioche Shale below from the younger Paleozoic rocks above. This detachment transported Middle Cambrian and younger rocks eastward over Lower Cambrian and Proterozoic rocks. The Paleozoic rocks in the upper plate of the decollement are typically attenuated and complexly faulted. Despite its academic importance, the decollement appears to have little hydrologic significance.

About 10 miles north of Ely, two north-northeast-striking faults form a graben, Duck Creek Valley, within the range (Cross Section W-W', Plates 1 and 3). The faults continue through the eastern side of the range into Spring Valley. Farther south, greater uplift along the range has exposed a significant sequence of west-dipping Proterozoic through Lower Cambrian quartzite (Cross Section W-W', Plates 1 and 3). The Proterozoic rocks consist mostly of the McCoy Creek Group, consisting of about 9,000 ft of quartzite and argillite, with schist at the base. These rocks are overlain by the Prospect Mountain Quartzite, not measured but presumably about 4,000 ft thick, and the overlying thin Pioche Shale. Small Tertiary intrusions are exposed locally along the range. Farther south, at Connors Summit, the range has undergone less uplift and most rocks consist of highly faulted, upper Paleozoic carbonate rocks (Cross Section V-V', Plates 1 and 3). The Snake Range decollement is also exposed along this part of the crest of the Schell Creek Range, and has transported Middle Cambrian and younger rocks eastward over Lower Cambrian and Proterozoic rocks.

About 20 miles south of Connors Summit, a thin, low, northeast-dipping, northwest-trending cuesta of Permian and Pennsylvanian carbonate rocks connects the Schell Creek Range with the northern end of the Fortification Range. This cuesta separates Spring Valley from Lake Valley to the south. The Schell Creek Range continues farther south; its geology is described in Section 10.1.

5.2 Fortification Range

The Fortification Range is a narrow, locally high, complexly faulted horst. It is made up of middle to upper Paleozoic rocks in the northern half and east-dipping volcanic rocks in the southern half. The northern half is low and is characterized by faulted sections, including the Chainman Shale, which is more than 1,000 ft thick (Cross Section U-U', Plates 1 and 3). The southern half of the range is much higher, with crests generally above 8,000 ft, because of more resistant volcanic rocks (Loucks et al., 1989). Part of this section of volcanic rocks includes local tuffs at least 5,000 ft thick yet with no base exposed, that we interpret to be intracaldera rocks of the Indian Peak caldera complex (Cross Section R-R').

The Fortification Range is a groundwater barrier between the GSLDFS (Spring Valley) to the east and the WRFS (Lake Valley) to the west. Part of the reason for the barrier is the presence of the Chainman Shale and the Scotty Wash Quartzite units in the fault blocks. In addition, the caldera, in large part because of its underlying intracaldera intrusions and its rim margins, restricts groundwater flow through the range. Furthermore, the low northwest-trending cuesta of upper Paleozoic carbonate rocks that connects the northern end of the range with the Schell Creek Range is underlain by the Chainman Shale and the Scott Wash Quartzite and appears to be cut by only small north-trending faults, so it appears to be mostly a groundwater divide between Spring and Lake Valleys.

5.3 Antelope Range

The Antelope Range is a low horst of faulted, mostly Tertiary volcanic rocks that unconformably overlie west-dipping Silurian to Permian sedimentary rocks, dominantly carbonate rocks (Cross Sections X-X', Y-Y'). The range appears to be a barrier to groundwater flow because it is bounded by north-trending faults. Water-level data indicate that groundwater is flowing south in Spring Valley, to the west, and flowing north in Tippett (Antelope) Valley, to the east. However, groundwater in both valleys is part of the GSLDFS.

5.4 Snake Range

The Snake Range is a high, internally complexly faulted horst, bounded on both sides by high-angle normal faults (Cross Sections U-U', V-V', W-W', Plates 1 and 3). Most of the Snake Range is cored by Late Proterozoic to Cambrian quartzite, intruded by a massive batholith (Cross Section V-V', Plates 1 and 3) of apparent Jurassic age (Whitebread, 1970; Miller et al., 1994 and 1995; Gans et al., 1999a and b; Lee et al., 1999a, b, and c; Miller and Gans, 1999; Miller et al., 1999). The range is a metamorphic core complex, which rose rapidly and formed the Snake Range decollement. Some studies of the decollement considered it to be the brittle-ductile transition zone separating brittle extension in the upper plate from ductile stretching of the lower plate although alternatively it could represent not so much a normal fault as a "highly complex structural boundary developed above a rising and extending mass of hot crustal rocks" (Miller et al., 1983; Gans et al., 1985). Later studies concluded that, at least in places, it is a detachment fault (Miller et al., 1999). This low-angle Tertiary detachment formed over an extended period as the range uplifted and stretched the roof apart although most of its development was synchronous with basin-range extension (Miller et al., 1999; Gans, 2000a). The fault placed complexly faulted Middle Cambrian carbonate and younger rocks over a lower plate of Middle Cambrian carbonate rocks, Lower Cambrian clastic rocks, and older rocks. The decollement is exposed on the top and eastern side of the northern half of the range (Cross Section W-W', Plates 1 and 3). East of the range, the decollement has been imaged by seismic profiles (Allmendinger et al., 1983; Miller et al., 1999) as it passes eastward beneath the surface of Snake Valley.

The central part of the Snake Range is narrower and lower. Here, where US 6/US 50 passes over Sacramento Pass, north-striking, east-dipping listric normal faults drop down thick Tertiary volcanic rocks and basin-fill sediments to the east (Gans et al., 1989; Miller et al., 1994, 1995, and 1999). The southern end of the range is a low series of tilt-block cuestas of Devonian and Mississippian sedimentary rocks faulted against Tertiary volcanic rocks (Cross Section U-U', Plates 1 and 3). The Snake Range is a barrier to flow through it because of the thick Proterozoic to Lower Cambrian quartzite and the Jurassic intrusion. However, at Sacramento Pass, some east-striking faults appear to pass through the range, possibly providing conduits for groundwater through the range to the east. Nonetheless, such flow would appear to be minimal because the pass rises at least 1,500 ft above the water table in Spring Valley, so the pass might just as well be a groundwater divide.

5.5 Limestone Hills

The western end of the tilt-block carbonate cuestas of the southern Snake Range continue southward to become the Limestone Hills (Plate 1). The Hills are mostly east-dipping Devonian carbonate rocks bounded by north-striking normal faults on their western and eastern sides (Cross Section U-U', Plates 1 and 3). The southern end of the Limestone Hills is the northern margin of the Indian Peak caldera complex (Tschanz and Pampeyan, 1970; Willis et al., 1987; Best et al, 1989c). The Atlanta silver-gold mining district is in Silurian to Ordovician carbonate rocks along the east-striking caldera margin. Local northwest-striking faults cut across the Hills at the northern and southern ends. Therefore the geology of the Limestone Hills allows an interpretation that groundwater flows through them, from west to east along these cross faults and through fractured carbonate rocks. Hood and Rush (1965) estimated a west to east flow of 4,000 acre-feet per year through the Limestone Hills into Hamlin Valley, presumably along the carbonates and cross faults.

5.6 Spring Valley

Spring Valley is a broad, deep graben containing at least 6,000 ft of basin-fill sediments (Cross Sections U-U', V-V', W-W', X-X', Plates 1 and 2). Oil-well test data (Yelland no. 1, TD=6,500 ft; Bastian Creek no. 1, TD=4,761 ft) in Spring Valley north of US 6/US 50 suggest that basin-fill sediments extend from 3,600 to 4,100 ft below the surface, underlain by 400 to 1,200 ft of Tertiary volcanic rocks (Hess, 2004). Cross Section V-V' is closely constrained by a seismic profile close to the line of section, as well as the Yelland no. 1 well (Gans et al., 1985) south of it. These data indicate more than 6,000 ft of basin-fill sediments and 2,500 ft of underlying Tertiary volcanic rocks.

The graben of Spring Valley is defined by many normal faults, with vertical displacements on some of them locally exceeding 10,000 ft (Cross Sections [U-U', V-V', W-W', X-X', Plates 1 and 3). Gans et al. (1985) suggested that the Schell Creek fault may have total offset in excess of 30,000 ft. Water-level data indicate that groundwater flows south in Spring Valley, and we conclude that it is along basin-range faults and related fractures.

6.0 HAMLIN VALLEY

6.1 Southern Snake Range and Limestone Hills

The geology of the Snake Range and Limestone Hills is discussed in Sections 5.4 and 5.5.

6.2 White Rock Mountains

The White Rock Mountains, along the Nevada-Utah state line, consists entirely of Tertiary intracaldera volcanic rocks, probably floored by an intracaldera (resurgent) intrusion (Cross Section Q-Q'). All of these rocks belong to the Indian Peak caldera complex (Willis et al., 1987; Best et al., 1989c). Because of its underlying intracaldera intrusion, the Indian Peak caldera complex may be a low-permeability unit with limited groundwater flow through it. The White Rock Mountains, however, is a horst bounded on both sides by major north-striking normal faults. These north-striking basin-range faults probably provide the primary conduits for groundwater flow.

6.3 Needle Range

The Needle Range, just east of the Nevada-Utah state line, forms the eastern side of Hamlin Valley. The range consists of two sub-ranges, the Mountain Home Range to the north and the Indian Peak Range to the south. The northern part of the Needle Range consists of folded, middle to upper Paleozoic rocks (Hintze and Davis, 2002a). Locally lower Paleozoic carbonate rocks are thrusted over upper Paleozoic carbonate rocks (Best et al., 1987a and b). Most of the Needle Range, however, consists of east-dipping outflow ash-flow tuffs, derived primarily from the Indian Peak caldera complex. The eastern caldera margin passes through much of the southern part of the range (Williams et al., 1997). The Needle Range is a faulted horst, with the main basin-range fault on the western side, where it separates Hamlin Valley from the Needle Range (Cross Sections Q-Q', U-U').

6.4 Hamlin Valley

Hamlin Valley is a moderately deep graben bounded by normal faults (Cross Sections Q-Q', U-U'). The Valley contains at least 4,000 ft of basin-fill sediments. Oil-well test data from east of the Limestone Hills (Hamlin Wash no. 18-1, TD=3,990 ft; Hamlin Wash no. 19-1, TD=6,980 ft; Fletcher no. 1, TD=7,481 ft) indicate basin-fill sediments from 2,600 to 6,000 ft thick here, underlain by 500 to at least 1,500 ft of volcanic rocks (Hess, 2004). Several miles south of these wells, the buried northern margin of the Indian Peak caldera complex is projected across Hamlin Valley, so the southern half of Hamlin Valley contains a presumed similar thickness of basin-fill sediments, underlain by intracaldera volcanic and intrusive rocks. Water-level data, the northward flow of surface water, and the general northward lowering of topography in Hamlin Valley indicate northward groundwater flow, with much of the recharge being derived from the Indian Peak caldera complex. However, water-level data indicate that some groundwater enters northern Hamlin Valley from the west, through the Limestone Hills.

7.0 SNAKE VALLEY

7.1 Kern Mountains

The Kern Mountains is an east-trending range made up mostly of granitic, biotite-bearing plutonic rocks (Plate 1). These plutons are of three main ages of 75 to 35 Ma (Best et al., 1974; Ahlborn, 1977; Miller et al., 1999). A separate, shallow Tertiary pluton that erupted lava flows occurs on the southeastern side of the range (Gans et al., 1989). The batholith that underlies the Kern Mountains is considered by Miller et al. (1999) to represent the underlying part of the core complex that formed the Snake Range and its detachment faults to the south and the Deep Creek Range and its detachments to the north. The unusual eastern trend of the Kern Mountains results because it is defined by east-striking faults north and south of it. These are part of the Sand Pass transverse zone (Rowley, 1998; Rowley and Dixon, 2001). Narrow, east-trending Pleasant Valley underlies the fault on the north side. This valley may have as much as 3,000 ft of valley fill (Cross Section X-X', Plates 1 and 3). The valley south of the Kern Mountains, in contrast, appears to be shallow. The Kern Mountains are within the GSLDFS, which also includes Spring Valley west of the range and Snake Valley east of the range. Water-level data indicate that the main groundwater flow in Spring Valley is southward, whereas the main flow in Snake Valley is northward. Based on the presence of east-striking faults and fractured volcanic and carbonate rocks on the northern side of the Kern Mountains, limited eastward groundwater flow here is possible.

7.2 Snake Range and Limestone Hills

The geology of the Snake Range and Limestone Hills is discussed in Sections 5.4 and 5.5.

7.3 Confusion Range, Conger Range, and Burbank Hills

The Confusion Range and small, low adjacent ranges of the same rocks north and south of it form the entire eastern (Utah) side of Snake Valley (Plate 1). These include the Confusion Range; the Conger Range forming a southwest-diverging fork in the southern Confusion Range; and the Burbank Hills south of the Conger Range and southeast of the towns of Baker and Garrison. All of these ranges consist almost entirely of north-striking, folded, thrusted, and attenuated, middle to upper Paleozoic rocks that together form a synclinorium, that is a combination of synclines and anticlines that overall appear as a broad syncline (Hose, 1977; Hintze and Davis, 2002a and b, and 2003; Cross Sections V-V', W-W', Plates 1 and 3). The Mississippian Chainman Shale, 1,000 to 2,000 ft thick in the area, is exposed on both sides of all these ranges (Hintze and Davis, 2002a and b, and 2003). Tertiary regional ash-flow tuffs formerly covered most of the area, except paleotopographic high points, to a thickness of as much as 500 ft. However, erosion has left only patches of these tuffs, notably those of the Oligocene Needles Range Group that were derived from the Indian Peak caldera complex

(Best et al., 1989a and b). Basin-range faults cut all these ranges and hills, but most are of small magnitude, so individual stratigraphic units are remarkably coherent and continuous over this large area. The most significant basin-range fault zone is the one that defines the eastern side of Snake Valley. Basin-range faults that separate the Confusion Range from Tule Valley have moderate vertical offset.

The Confusion Range and adjacent ranges and valleys are within the GSLDFS. The Chainman Shale, despite its prominence in the area, may not be a significant barrier to eastward or westward groundwater flow, partly because of carbonate rocks beneath the folded Shale. Nonetheless, the available water-level data suggest that most groundwater flow is northward, probably along the north-striking faults and north-striking beds.

7.4 Northern Mountain Home Range

The Mountain Home Range, which is the northern part of the Needle Range, merges with the Burbank Hills to the north. The geology of the Needle Range is discussed in Section 6.3. Therefore the geology of the northern Mountain Home Range is similar to that of the Confusion Range and its adjacent ranges. The exception is that the Mountain Home Range is more heavily broken by normal faults than in the Confusion Range.

7.5 Snake Valley

Snake Valley is a major graben, bounded by high-angle normal faults, as is typical of other grabens in the project area (Plate 1). Snake Valley contains about 5,000 ft of basin-fill sediments, but local holes in the basin contain thicker deposits than this (Allmendinger et al., 1983; Saltus and Jachens, 1995; Davis, 2005; Kirby and Hurlow, 2005; Cross Sections U-U’, V-V’, W-W’, X-X’, Plate 3). Oil-well test data from a dry hole near Baker (Baker Creek no. 12-1, TD=4,787 ft) indicated that basin-fill sediments and presumed Tertiary volcanic rocks extend to 4,600 ft depth here (Hess, 2004). Farther north, three dry holes drilled in the middle of Snake Valley, Utah, were described in detail as part of a field trip (Herring et al., 1998). The northern of these (Balcron no. 12-36 Cobra State, TD=3,765 ft) penetrated 1,845 ft of basin-fill sediments, then 800 ft of basal Tertiary sedimentary rocks, then Ordovician to Silurian carbonate rocks (Herring, 1998b). Farther south, the EREC no. 31-22 Mamba Federal hole (TD=3,258 ft) penetrated 2,800 ft of basin-fill sediments, underlain by Chainman Shale (Herring, 1998a). The southern well (Amerada-Hess, TD=7,782 ft) penetrated at least 1,000 ft of basin-fill sediments (Schalla, 1998). We (Cross Section W-W’, Plates 1 and 3) and Miller et al. (1999, Figure 10) show the Snake Range decollement being dropped down by the main frontal faults of the Snake Range and from there passing beneath Snake Valley and at least the western part of the Confusion Range. However, Allmendinger et al. (1983) suggested that the west-bounding fault of the Snake Valley graben is the Snake Range decollement. Kirby and Hurlow (2005) adopted this model, and further suggested that this fault acted as a barrier to groundwater moving from the major recharge area of the high Snake Range into Snake Valley. They thus implied that somehow the recharge volumes for Snake Valley were less than previously estimated. We find no basis for their hypothesis.

Groundwater in Snake Valley receives input from Hamlin Valley groundwater, including groundwater from southern Spring Valley that passes through the Limestone Hills into Hamlin Valley. It combines with local recharge, mostly from the Snake Range, and according to water-level data travels northward along the faults and fractured rock of the Snake Valley graben, on its way to the Great Salt Lake Desert. Gates (1987 and 2004), Schaefer and Harrill (1995), Nichols (2000), and Katzer and Donovan (2003) discussed the water budget of Snake Valley.

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8.0 TIPPETT (ANTELOPE) VALLEY

8.1 Antelope Range

The geology of the Antelope Range is discussed in Section 5.3.

8.2 Unnamed Hills East of Tippett Valley

A series of low, unnamed hills lines the eastern side of Tippett Valley. They consist mostly of Eocene andesitic lava flows less than 2,000 ft thick that unconformably overlie upper Paleozoic carbonate rocks. The hills are continuous only on the northern and southern side, and they are faulted in most places. A log of oil-well test REMKIN Federal no. 1 (TD=3,500 ft), spudded at the southeastern edge of Tippett Valley, penetrated 1,100 ft of lava flows, 1,200 ft of Permian and/or Pennsylvanian carbonate rocks, 200 ft of Chainman Shale, then Joana Limestone and Guilmette Formation extending to the total depth of the well. These faults and the carbonate rocks that are locally exposed and widely underlie the volcanic rocks at shallow depth appear to allow groundwater through them and northeastward toward the groundwater sink of the Great Salt Lake Desert.

8.3 Kern Mountains

The geology of the Kern Mountains is discussed in Section 7.1.

8.4 Tippett (Antelope) Valley

Tippett Valley appears to be relatively shallow, containing perhaps 1,000 ft of basin-fill sediments at the northern and southern ends (Cross Sections X-X') and perhaps somewhat greater thicknesses in the central part. Recharge to the valley largely comes from the Antelope Range, perhaps from Spring Valley through the heavily faulted southern end of Tippett Valley, and perhaps from the western Kern Mountains.

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9.0 STEPTOE VALLEY

9.1 Cherry Creek Mountains

The Cherry Creek Mountains is a large horst of gently west-dipping Precambrian through Permian sedimentary rocks. Basin-range faults separate the range from Butte Valley on the west and from Steptoe Valley on the east; the bigger fault is on the east (Cross Section Y-Y'). At the southern end of the range, a Tertiary intrusion localized the Cherry Creek mining district, which produced gold, silver, and base metals.

9.2 Northern and Central Egan Range

Like the Cherry Creek Mountains just north of it, the Egan Range is a high, north-trending horst of Precambrian through Permian rocks. Tertiary volcanic rocks unconformably overlie the Paleozoic rocks. The major basin-range fault zone that uplifted the Egan Range is along the eastern side. The vertical displacement along this fault is as much as 20,000 ft. The range continues southward for 70 miles in White Pine County, then another 40 miles in Lincoln County. At the northern end of the range, the rocks dip westward and are intruded by Tertiary stocks. A thin sliver of bedrock cored by a Tertiary intrusion connects with the Cherry Creek Mountains. A northeast-striking oblique-slip fault that is left-lateral and down-to-the-west cuts through the southern end of this sliver. This fault may provide an avenue for some groundwater to flow between Butte Valley South and Steptoe Valley. However, the pluton in this sliver, along with Late Proterozoic to Lower Cambrian quartzite into which it intruded, forms a barrier to groundwater flow north of the oblique-slip fault.

The Snake Range decollement is present in the Egan Range as a thin skin of Paleozoic rocks at the crest of the range and along its western slope (Cross Sections W-W', X-X'). The decollement is a Tertiary detachment fault that transported rocks as old as Middle Cambrian eastward and placed them on top of older rocks.

About 20 miles south of the northern end of the Egan Range, the range becomes considerably wider and lower as the Butte Mountains joins it from the west and Butte Valley terminates. Here the range is broken into a series of horsts and grabens (Cross Section W-W'). The downthrown areas on the western side of the Egan Range are underlain by Tertiary volcanic rocks. The town of Ruth, Nevada, is in this broad, low, heavily faulted part of the Egan Range. A major mining district, the Robinson district, was developed on a series of east-trending ore deposits of copper, lead, zinc, silver, and gold, which are associated with a Cretaceous pluton. Barren Tertiary plutons also are present in the Ruth area and extend east to Ely, on the eastern side of the Egan Range in Steptoe Valley (Brokaw and Shawe, 1965; Brokaw and Heidrich, 1966; Brokaw and Barosh, 1968; Brokaw, 1973; Brokaw et al., 1973; Jones, 1996).

South of the Robinson mining district, the Egan Range continues southward for almost 30 miles as a single, high horst of east-dipping Cambrian through Permian rocks that together are more than 30,000 ft thick (Kellogg, 1963 and 1964; Taylor et al., 1991; Cross Section V-V'). Patches of volcanic rocks overlie the Paleozoic rocks on the eastern edge of the range. Several small Tertiary plutons also are exposed. Although the Egan Range continues farther south of this point, Steptoe Valley terminates where a thin sliver of Paleozoic rocks connects the Egan Range to the Schell Creek Range.

9.3 Northern and Central Schell Creek Range

The geology of the northern and central Schell Creek Range is discussed in Section 5.1.

9.4 Steptoe Valley

Steptoe Valley is a deep graben with as much as 8,000 ft of basin-fill sediments in it (Cross Sections V-V', W-W', X-X', Y-Y'). Thus it is one of the deepest grabens in the central Great Basin. Oil-test wells supply additional information on the valley. In the center of the northern part of the valley, east of the northern end of the septum of rocks that connect the Cherry Creek Mountains and the Egan Range, two adjacent wells, Steptoe Unit no. 1 (TD=8,406 ft) and Steptoe Federal no. 17-14 (TD=11,700 ft), revealed 2,600 to 3,100 ft of basin-fill deposits, underlain by 3,900 to 4,300 ft of volcanic rocks. Two wells (Steptoe Federal no. 1-24, TD=6,075 ft; Federal no. 54X-36, TD=7,810 ft) drilled in the center of the valley several miles northwest of McGill, Nevada (Cross Section W-W'), showed the following rocks, respectively: (1) 2,100 ft of basin-fill sediments, 2,200 ft of volcanic rocks, and Permian to Pennsylvanian carbonate rocks to total depth; and (2) 5,600 ft of combined basin-fill sediments and volcanic rocks, underlain by Ely Limestone, Chainman Shale, Joana Limestone, and Guilmette Formation to total depth. Test-well Nevada-Federal O no. 2 (TD=3,253 ft), drilled in the middle of the valley several miles southeast of Ely, recorded 2,200 ft of basin-fill sediments, 400 ft of volcanic rocks, 400 ft of Simonson Dolomite, then plutonic rock to total depth. In the center of the southern end of Steptoe Valley (Cross Section V-V'), oil-test well Titan Federal no. 1-9 (TD=7,460 ft) showed 1,700 ft of basin-fill sediments, 1,400 ft of volcanic rocks, Ely Limestone, Diamond Peak Formation, Chainman Shale, Joana Limestone, Pilot Shale, and Guilmette Formation to total depth.

Surface water flows north in the part of the valley that is in the project area. Likewise, according to water-level data, groundwater also flows northward, and it continues well north of the project area.

10.0 LAKE VALLEY

10.1 Southern Schell Creek Range

Lake Valley, as we define it here, is south of the thin, low, northeast-dipping, northwest-trending cuesta of Permian and Pennsylvanian carbonate rocks that connects the eastern side of the Schell Creek Range with the northern end of the Fortification Range. The geology of the northern and central Schell Creek Range, north of this cuesta, is discussed in Section 5.1. The southern Schell Creek Range, described here, is that part of the range south of this cuesta. The southern Schell Creek Range consists of a heavily faulted sequence of Proterozoic through Tertiary rocks that dips west. Like the rest of the Schell Creek Range, the southern part also is a horst but, unlike the rest of the range, the dominant basin-range fault appears to be the one on the western side of the range. Most faults within the southern Schell Creek Range strike northeast.

In the vicinity of the cuesta, the rocks are upper to middle Paleozoic in age. But farther south along the range, these rocks are faulted against Proterozoic to Lower Cambrian quartzite (Cross Section U-U'), which there dominate the range. The quartzite is as thick as 5,000 ft (Taylor et al., 1991) and, being resistant, underlies peaks as high as 11,000 ft west of the Geyser Ranch. The resistant quartzite is cut by east-striking, down-to-the-south faults at Patterson Pass, exposing lower Paleozoic rocks south of Patterson Pass that are less resistant to erosion. From Patterson Pass, heading south, the Schell Creek Range is narrow and low, and it consists of alternating northeast-trending slivers of lower Paleozoic carbonate rocks (Cross Section R-R') faulted against upper Paleozoic rocks, then against Tertiary volcanic rocks.

The southern tip of the Schell Creek Range is west of northern Dry Lake (Muleshoe) Valley, rather than Lake Valley, but it is discussed here. This part of the Schell Creek Range consists of Tertiary volcanic rocks displaced along northeast-striking faults against lower Paleozoic carbonate rocks. Just to the south of this, the Schell Creek Range joins the Egan Range to the west along a complex hash of northwest- and northeast-striking faults. Here a Tertiary pluton and adjacent dikes have produced copper-lead-silver deposits in adjacent lower Paleozoic carbonate rocks at the Silver King Mine (Cross Section Q-Q').

10.2 Fairview Range

The Fairview Range is a horst made up of Devonian to Pennsylvanian rocks at both the northern and southern ends of the range. The central part of the range consists of the western lobe of the Indian Peak caldera complex (Best et al., 1998; Cross Section Q-Q'). A low pass between the Fairview Range and the Bristol Range to the south is cut by numerous east-striking faults of the Blue Ribbon transverse zone, which crosses the entire Great Basin at about this latitude (Bartley, 1989; Hurtubise, 1994; Ekren and Page, 1995; Page and Ekren, 1995; Prudic et al., 1995; Overtoom and Bartley, 1996; Best et al, 1998; Rowley, 1998; Rowley and Dixon, 2001). The transverse zone provides a conduit for groundwater to flow between Lake Valley and Dry Lake Valley (Rowley, 1998; Rowley and Dixon, 2001). Other possible conduits to flow from Lake to Dry Lake Valleys are in the northern Fairview Range, along cross faults and carbonate rocks.

10.3 Fortification Range

The geology of the Fortification Range is discussed in Section 5.2.

10.4 Lake Valley

Lake Valley, as defined here, contains at least 2,000 ft of basin-fill sediments throughout its 60-mile length, but locally the sediments may be much thicker (Scheirer, 2005; Cross Sections Q-Q', R-R', U-U'). Logs of two oil-well tests (Dutch John Unit no. 1, TD=12,750 ft; Apache Frontier Exploration Federal no. 22-13, TD=6,115 ft) in the center of Lake Valley, east of the northern Fairview Range, give the following information, respectively, on rocks penetrated: (1) 2,200 ft of basin-fill sediments, 2,700 ft of volcanic rocks, Pennsylvanian rocks, Diamond Peak Formation, Chainman Shale, Joana Limestone, Pilot Shale, and Guilmette Formation; and (2) 1,000 ft of basin-fill sediments, Ely Limestone, Diamond Peak Formation, Chainman Shale, Ordovician rocks, and plutonic rocks. Just south of the location of these wells, the buried east-trending northern margin of the Indian Peak caldera complex passes across the valley, so south of this margin, basin-fill sediments of presumed similar thickness to these sediments in the two wells would be underlain by intracaldera volcanic and intrusive rocks.

Lake Valley, as well as Patterson Valley (southern Lake Valley), is part of the MVFS, a subsystem of the WRFS. Water-level data indicates that groundwater flows southward in Lake Valley. At the thin bedrock ridge between the Fortification Range and the Schell Creek Range, the combination of thick carbonate rocks here and north-south faults cutting these rocks creates the potential for limited groundwater flow between southern Spring and Lake Valley. However, the Chainman Shale and Scotty Wash Quartzite outcrops just below the limestone units at the surface. Therefore, while geologically permissible, passage of water out of the valley at this point, is more speculative or appears to be minor.

11.0 CAVE VALLEY

11.1 Southern Egan Range

The southern Egan Range is a horst uplifted along normal faults, the largest of which is the one on the western side of the range. Where adjacent to Cave Valley, the range consists of east-dipping Cambrian to Permian rocks of mostly carbonate lithology. The Chainman Shale, the principal source rock for the Railroad Valley oil field (Taylor et al., 1991), is a substantial aquitard in the range. Paleozoic rocks are unconformably overlain by Tertiary volcanic rocks. The lower part of the Tertiary rock column, mostly adjacent to Cave Valley, includes the Sheep Pass Formation, which is as much as 3,000 ft thick (Kellogg, 1964). The Sheep Pass Formation contains huge exotic blocks of Mississippian and Permian units that slid into the Sheep Pass basin from adjacent mountains during deposition of the formation (Kellogg, 1964). Just north of the latitude of Lund, the range is high (about 10,000 ft elevation) and contains a section of Paleozoic strata about 30,000 ft thick (Kellogg, 1963 and 1964; Taylor et al., 1991).

The Egan Range south of the latitude of Lund is complexly faulted (Cross Section U-U') and thus declines in elevation to a low pass, Shingle Pass (Cross Section R-R'). Shingle Pass, at about 7,000 ft elevation, provides a road exit from Cave Valley to White River Valley to the west. Within the range, most faults strike northeast. The most prominent of these is an oblique-slip (left lateral, down-to-the-northwest normal) fault that underlies Shingle Pass and cuts entirely across the range (Cross Section R-R'). East-dipping volcanic rocks on the northern side of the fault zone are juxtaposed against southeast-dipping lower Paleozoic carbonate rocks to the southeast. Water-level data in Cave Valley suggest north to south groundwater flow. The fault at Shingle Pass provides a conduit for groundwater flow from northern Cave Valley into White River Valley. But it also creates a partial barrier for groundwater flow between northern and southern Cave Valley because Chainman Shale is capping the southeast-dipping strike ridge of carbonate rocks southeast of the fault zone. The strike ridge passes northeast across central Cave Valley and abuts against the Schell Creek range-front fault on the eastern side of the valley.

Continuing south from Shingle Pass, the range climbs back to more than 9,000 ft but it is narrow. It continues as an east-tilted horst, then bends southeast to join the southern end of the Schell Creek Range. The southern Egan Range consists of a hash of low fault blocks bounded by faults of different strikes, mostly north-northwest, north-northeast, and east-west (Cross Section Q-Q'). These faults juxtapose mostly gently-dipping Tertiary volcanic rocks against each other and against Paleozoic rocks. The faults and the badly fractured rocks may allow groundwater to pass southwestward into White River Valley.

11.2 Southern Schell Creek Range

The geology of the southern Schell Creek Range is discussed in Section 10.1.

11.3 Cave Valley

Northern Cave Valley is a narrow graben that contains mostly east-dipping Cambrian rocks at shallow depth and relatively thin basin-fill sediments (Cross Section U-U'). Gravity data (Scheirer, 2005) and oil-test-well logs (Federal no. 1, TD=5,016 ft; Hess, 2004) indicate that the base of the combined basin-fill sediments and underlying volcanic rocks is at or less than about 3,000 ft below the valley floor.

Southern Cave Valley is a tilt block containing the same east-dipping Cambrian through Tertiary sequence of the Egan Range passing beneath the valley (Cross Section R-R'). The tilt block terminates eastward against the north-striking range-front fault of the Schell Creek Range (Cross Section R-R'). This fault probably provides the main conduit for groundwater from northern to southern Cave Valley. Gravity data suggest that, although some of the southern part of Cave Valley contains less than 3,000 ft of basin-fill sediments and volcanic rocks, other parts contain as much as 6,000 ft of these rocks, and that a narrow graben containing still more of these rocks may underlie the central axis of the valley. Oil-well-test data (Foreland Federal no. 1-28, TD=3,909 ft; Cave Valley Federal no. 13-10, TD=5,600 ft; Cave Valley Unit Federal no. 1, TD=7,024 ft; Flat Top Federal no. 27-15, TD=5,320 ft; Flat Top Federal no. 27-16, TD=6,090 ft; Sidehill Pass Federal no. 18-13, TD=6,802 ft) from southern Cave Valley suggest that basin-fill deposits are 1,700 to 6,200 ft thick and are underlain by 400 to 1,400 ft of volcanic rocks, then in turn by 700 ft (recognized in one hole) of Sheep Pass Formation before hitting Paleozoic rocks.

12.0 NORTHERN DRY LAKE (MULESHOE) VALLEY

12.1 Southern Schell Creek Range

Only the southern tip of the southern Schell Creek Range bounds northern Dry Lake (Muleshoe) Valley. The geology of this part of the range is discussed in Section 10.1.

12.2 Fairview Range

The geology of the Fairview Range is discussed in Section 10.2.

12.3 Northern Dry Lake (Muleshoe) Valley

Northern Dry Lake (Muleshoe) Valley is a complex graben that contains at least several thousand feet of basin-fill sediments (E.A. Mankinen et al., unpub. data, 2005; Scheirer, 2005; Cross Section Q-Q'). Because the ranges that surround Dry Lake Valley are relatively low, it is unlikely that they provide all the groundwater in the valley. Probably significant conduits to flow from Lake Valley to northern Dry Lake Valley are provided by the north-striking faults that define both sides of Dry Lake Valley. Both fault zones pass through Muleshoe Pass, between the northern end of the Fairview Range and the Schell Creek Range. Other entrances of groundwater to northern Dry Lake Valley may be along cross faults and through carbonate rocks in the northern Fairview Range. According to water-level data, movement of groundwater from northern Dry Lake Valley is generally to the south.

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13.0 GEOPHYSICS

13.1 Gravity

Analysis of gravity anomalies in Spring and Snake Valleys (Figure 13-1) in east-central Nevada defines the overall shape of their basins, provides estimates of the depth to pre-Cenozoic basement rocks, and identifies buried structures beneath the sedimentary cover.

The USGS collected gravity observations at 545 new sites (Figure 13-2) to supplement about 5,000 previous stations in this area (Snyder et al., 1981; Bol et al., 1983; Snyder et al., 1984; Ponce, 1992 and 1997; Scheirer, 2005). At gravity stations on bedrock, samples were collected for density and magnetic susceptibility properties.

Values of observed gravity were calculated at the new stations by accounting for fluctuations related to tidal accelerations and for instrument drift constrained at the beginning and end of each day. New gravity stations were collected within coverage gaps of the prior data, especially in the ranges adjacent to the basins of concern. Gravity observations were processed to account for the predictable effects of latitude, elevation, and terrain variations, yielding isostatic gravity observations that primarily reflect density variations in the upper and middle crust.

Gridded isostatic gravity anomaly data were used to guide the gravity analysis in two modes: to detect significant lateral density interfaces in the subsurface using a maximum horizontal gradient technique (Blakely and Simpson, 1986) and to create models of the depth to pre-Cenozoic basement using the anomaly separation technique of Jachens and Moring (1990). The magnitude of the gradient is a function of the depth to the density boundary and the size of the density contrast.

The depth-to-basement technique involves two steps: (1) to separate contributions to the isostatic gravity anomaly that arise from Cenozoic sedimentary and volcanic deposits and those from pre-Cenozoic rocks and (2) to convert the contributions from the lower density deposits into a model of basin depth (Jachens and Moring, 1990).

Because available gravity data for the study area were made by many different observers at different times, the data set was examined to remove duplicate entries. Major station elevations were compared with elevations interpolated from 10- and 30-meter (m) digital elevation models. Large elevation differences indicate possible errors in station location or elevation, and each station so identified was examined individually to confirm the discrepancy before omitting it from the data set. The revised data set, including all new gravity observations, was gridded at a spacing of 0.5 kilometers (km) using a minimum curvature algorithm (Webring, 1985). The resulting isostatic gravity field (Figure 13-3) emphasizes features that reflect local density variations in the middle and

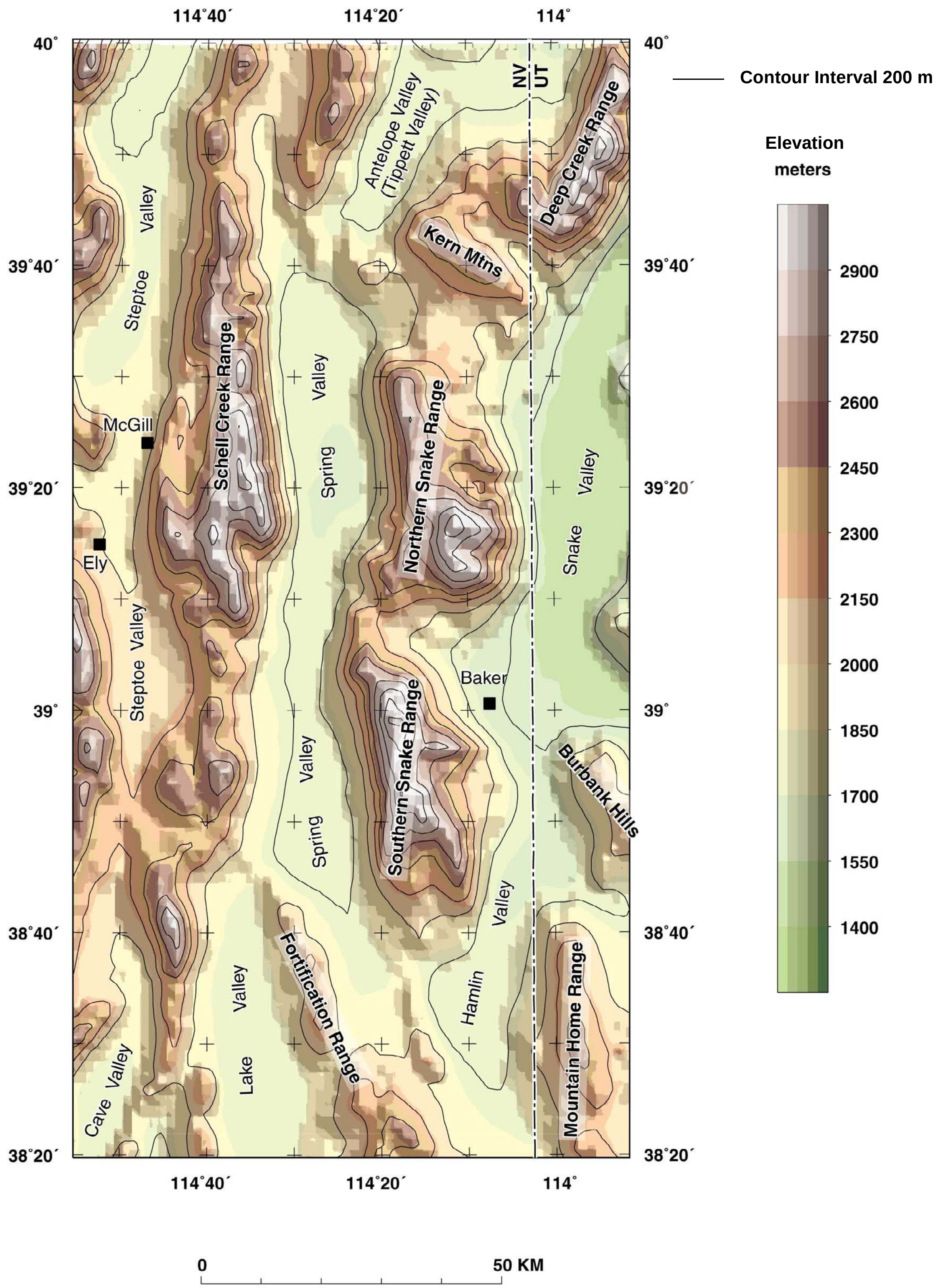


Figure 13-1
Index Map to the Spring Valley Study Area

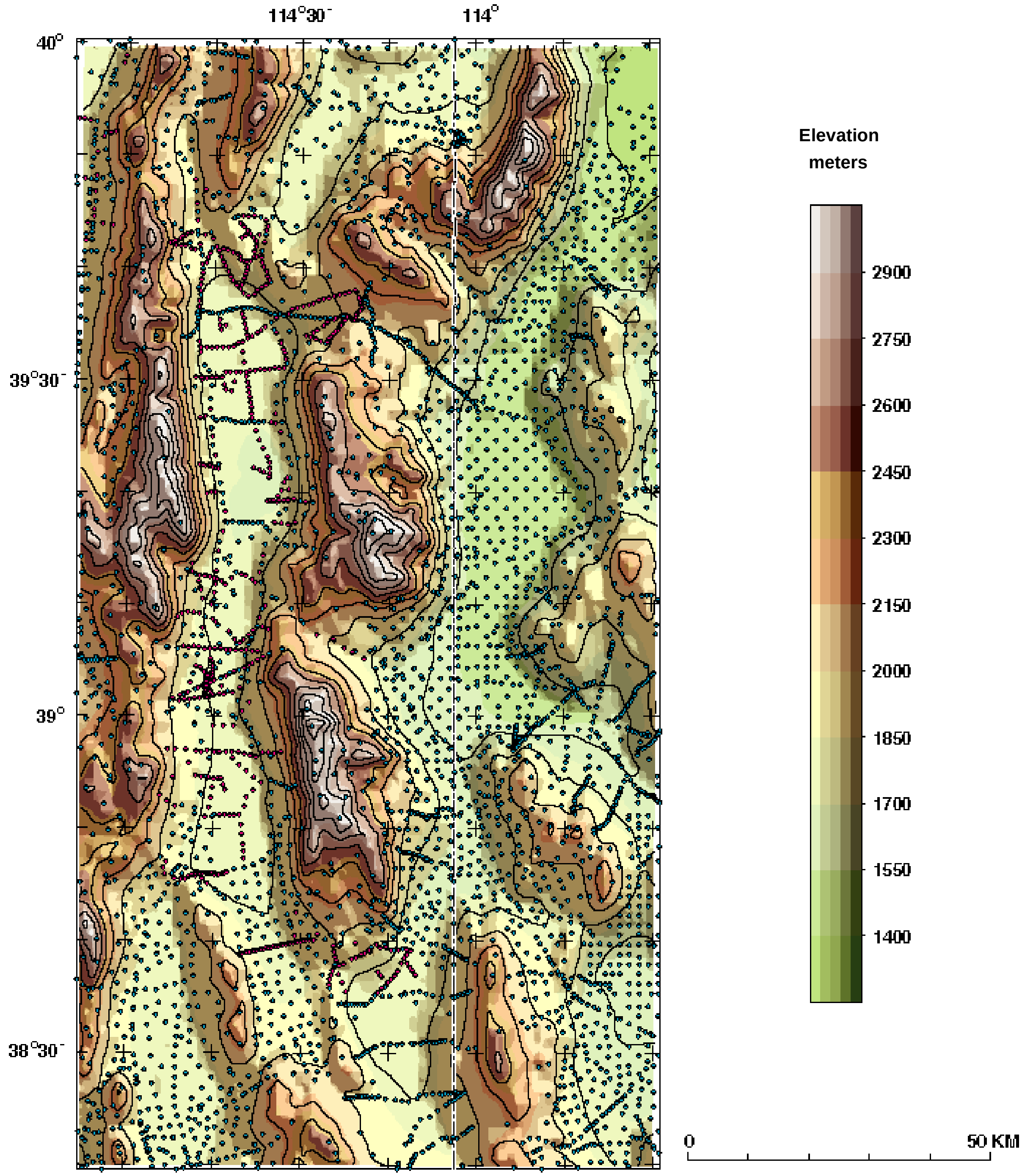


Figure 13-2
Previously Available Gravity Stations (green dots) and Gravity Stations Established During the 2004/2005 Field Seasons (red dots)

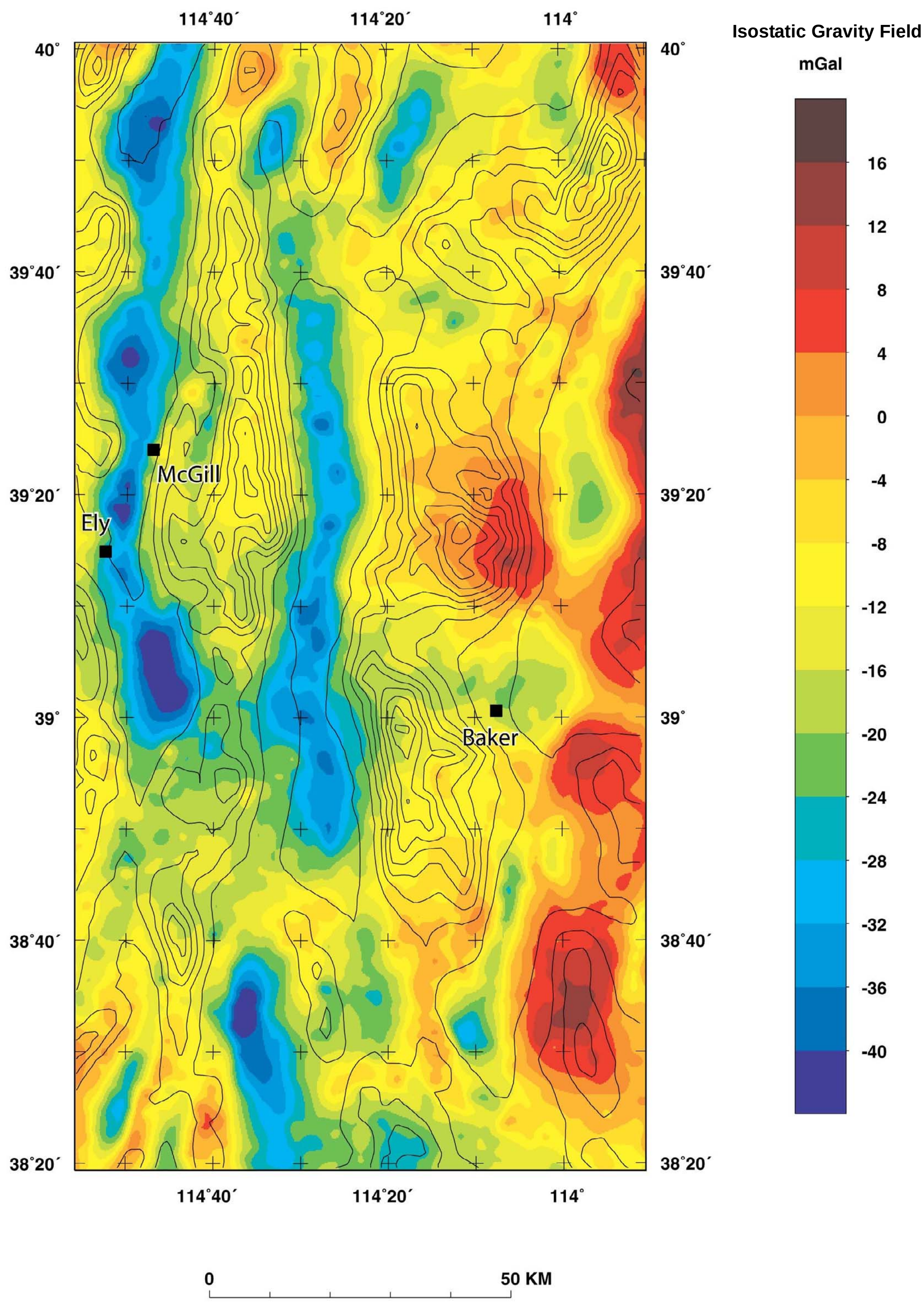


Figure 13-3
Isostatic Residual Gravity Field

upper crust. Gravity lows (cool colors) generally indicate low-density sedimentary and volcanic rocks in basin fill; gravity highs (warm colors) generally reflect pre-Cenozoic basement rocks in the basin.

The isostatic residual gravity field (Figure 13-3) reflects a pronounced contrast between dense pre-Cenozoic rocks and significantly less dense overlying strata. Because of this relationship, the gravity inversion method (Jachens and Moring, 1990) can be used to separate the isostatic residual anomaly into pre-Cenozoic "basement" and younger "basin" fields, thus allowing an estimate of thickness of Cenozoic alluvial fill and underlying Tertiary volcanic rocks within the area. The accuracy of thickness estimates derived by the gravity inversion technique is dependent on the assumed density-depth relation of the Cenozoic valley fill, and on the initial density assigned to the basement rocks. Density of basement rocks is generally assumed to be 2.67 milligrams per cubic meter and this value is considered appropriate in this area where major exposures consist of Late Precambrian through upper Paleozoic marine carbonate and siliciclastic sedimentary rocks. Subvolcanic Cenozoic intrusions are included here as part of the basement because their physical properties are similar to most of the older rocks, and they differ strongly from those of the eruptive and basin-fill sequences. The density-depth function used here is the same as used in an earlier basin-depth analysis of the Basin and Range province (Saltus and Jachens, 1995).

The gravity inversion method also allows the input of basement depths determined from deep drill-holes and seismic data. Figure 13-4 shows the constraints within the study area that were used for this gravity inversion and were gridded at a spacing of 1.0 km using a minimum curvature algorithm. The results are shown in Figure 13-5.

In general, the gravity inversion method indicates that the maximum thickness of basin fill (alluvium and volcanics) in all the valleys of the study area (Figure 13-5) is generally 2 km or more. Note, however, that the deepest areas of Spring and Hamlin Valleys are much narrower than both Steptoe and Snake Valleys. Maximum depths to pre-Cenozoic basement in Spring, Steptoe, and Hamlin Valleys are between 3 and 3.5 km. The northern-most areas of Steptoe and Spring Valleys (39°45' to 40°N) have maximum depths near 4 km. The approximately 4-km of fill in these areas are comparable to the deepest parts of Snake Valley. Maximum depths in Duck Creek Valley northeast of McGill range from approximately 1.5 to 2.0 km. There appears to be a particularly deep basin beneath Tippett Valley where depths are generally greater than 3 km, and in some areas these extend to between 5 and 5.5 km.

13.2 Audiomagnetotellurics Studies

In conjunction with the gravity studies of Scheirer (2005) and Mankinen et al. (in press), the audiomagnetotellurics (AMT) method was tested to see if it is a feasible approach to map the structure and contribute to the regional hydrological model in a typical Basin and Range setting. In particular, faults and stratigraphy within the valleys, as well as estimates of depth to basement are valuable targets. The AMT method is used to detect variations in shallow, subsurface electrical resistivity, which is largely dependent on the fluid content, porosity, fracturing, and conductive

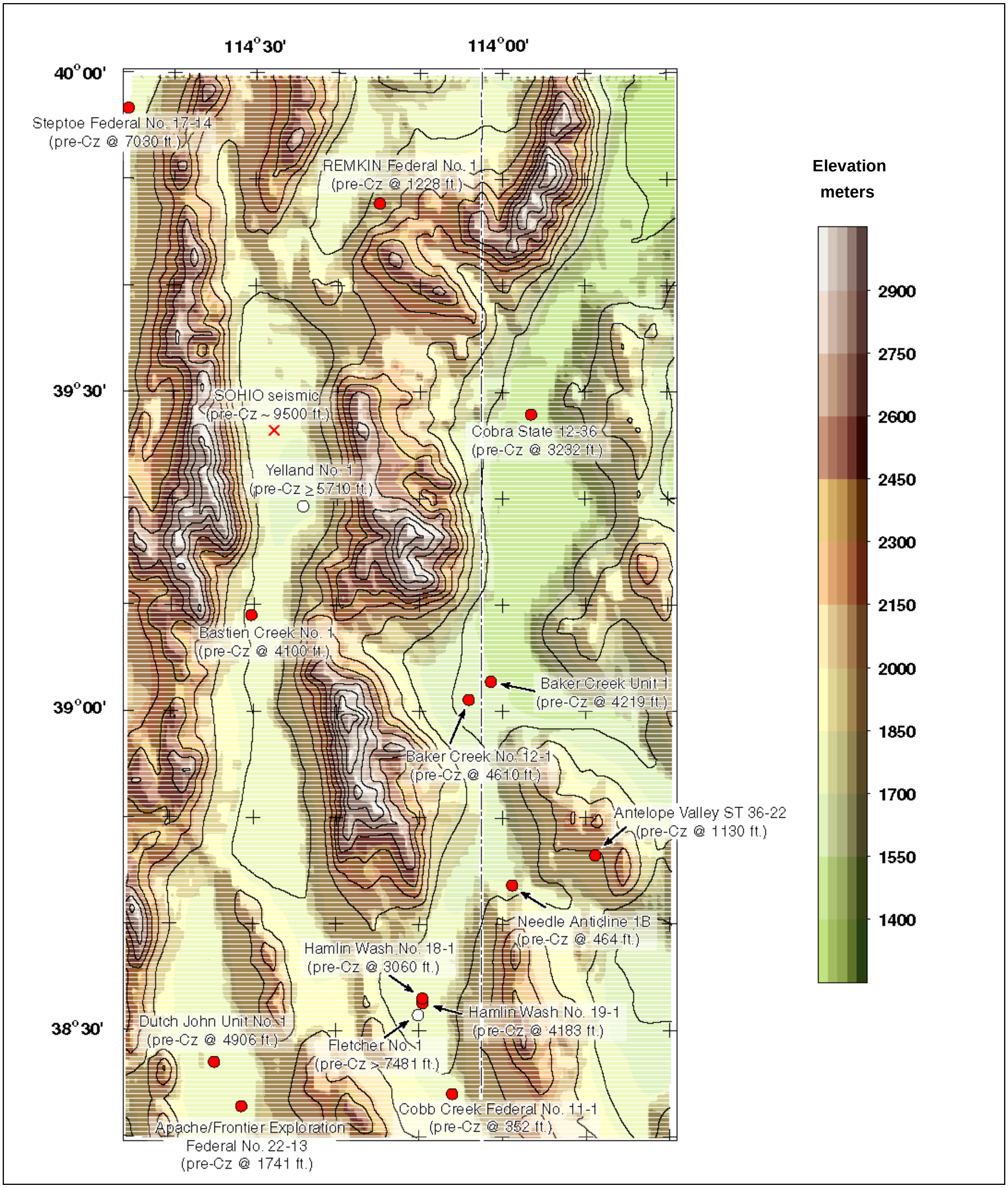


Figure 13-4
Red Dots are Drill Holes That Encountered Pre-Cenozoic Basement; White Dots are Less-Firm Constraints on Alluvial Thickness; Red Cross is Basement Pick From Seismic Interpretation

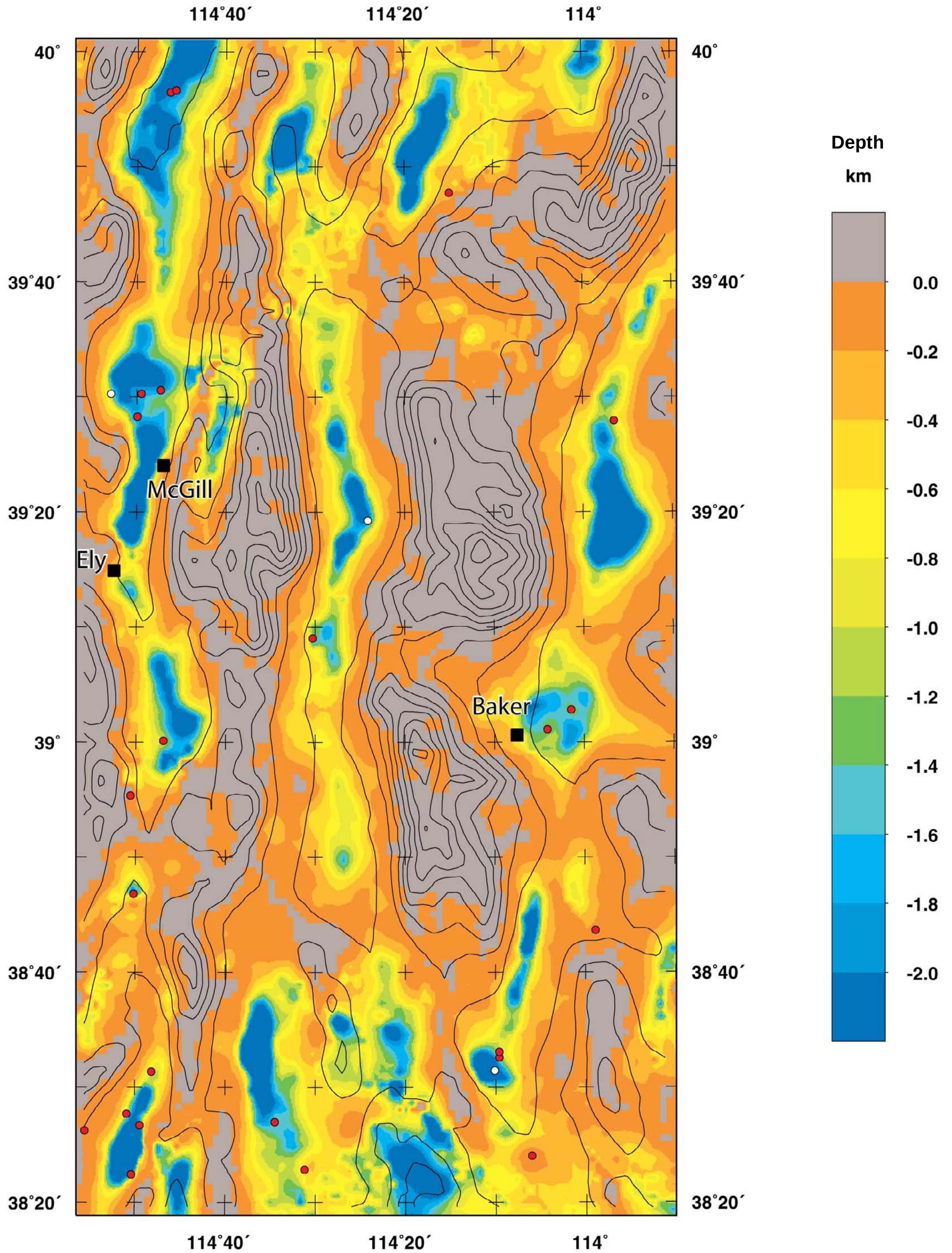


Figure 13-5
Depth to Pre-Cenozoic Basement in the Spring Valley Study Area

mineral content of the subsurface geology. We concluded that it may serve as a valuable tool for mapping subsurface faults and lithology at shallow levels of basins (~1,000 m).

The AMT data were collected along a profile in Spring Valley by McPhee et al. (2005) and shown on Figure 13-6. The model along Profile A in Spring Valley (Figure 13-7) shows detailed structure revealed by the inversion model results within the alluvial basin. A clear transition between unsaturated (200-500 ohm-m) and saturated alluvium/volcanic rocks (20-50 ohm-m) is present at roughly 300 ft (100 m) depth. High-resistive (greater than 1,000 ohm-m) carbonate rocks are clearly defined at the eastern end of Profile A under the Limestone Hills, and the locations and dips of several range-front and inter-basin faults, which lack surface expressions, are delineated throughout the upper 1 km of section.

McPhee et al. (2005 and in press) provided information on faults on the eastern side of the southern part of Cave Valley, based on AMT profiles (Figures 13-6 and 13-9). The data collected along this Profile E (Figure 13-9) were noisier than those collected along Profiles A and B in Spring Valley. The upper several hundred meters of the valley shows more conductive alluvial fill (3-20 ohm-m) than was observed in Spring Valley, perhaps due to the additional presence of clays in the valley. Clearly delineated structure within the basin shows other inter-basin faults as well.

An abrupt contract between the resistive limestones on the east side of Cave Valley in the Sidehill Pass area and the more conductive valley fill agrees with the sharp gravity gradient observed by (Scheirer, 2005), who calculated a steep eastern basin margin which is likely bounded by a range-front fault. The depth to basement beyond the eastern margin of Profile E extends deeper than the resolution of our model (Scheirer, 2005).

When compared to the basement-surface derived estimates from the inversion of the gravity data (Scheirer, 2005, and Mankinen, et al., in press), AMT proves successful at estimating the depth to bedrock, and the combination of AMT and gravity enhances confidence in this depth estimate.

13.3 Seismic Studies

An additional view into the subsurface structure of southern Cave Valley and Northern Dry Lake Valley (Muleshoe) is provided by a portion of the industry-shot ECN-01 seismic reflection line (Figure 13-10a). The seismic line crosses near the maximum depth position of Cave Valley (Figure 13-10a). The seismic reflection image illustrates the asymmetric character of Cave Valley, with a steeper eastern side where the range-front fault of the Schell Creek Range lies and a less-steep western floor leading up to the dip-slope of the Egan Range. Strong reflectors mark the base of Cave Valley, and a discordant and more horizontal packet of reflectors characterizes much of the deeper valley fill. Weaker subhorizontal reflectors are present in the upper valley fill. The reflectors in the shallow portions of Muleshoe Valley are weak or absent, but in its deeper section they exhibit characteristics similar to those of the Cave Valley reflectors. These seismic data are displayed in travel-time, so a quantitative appraisal of seismic depths to basement is not possible. Nevertheless, the inferred basin structure from gravity analysis (Figure 13-10b) shares a number of similarities with the seismic image: Cave Valley is asymmetric and reminiscent of a half-graben. The overall shapes

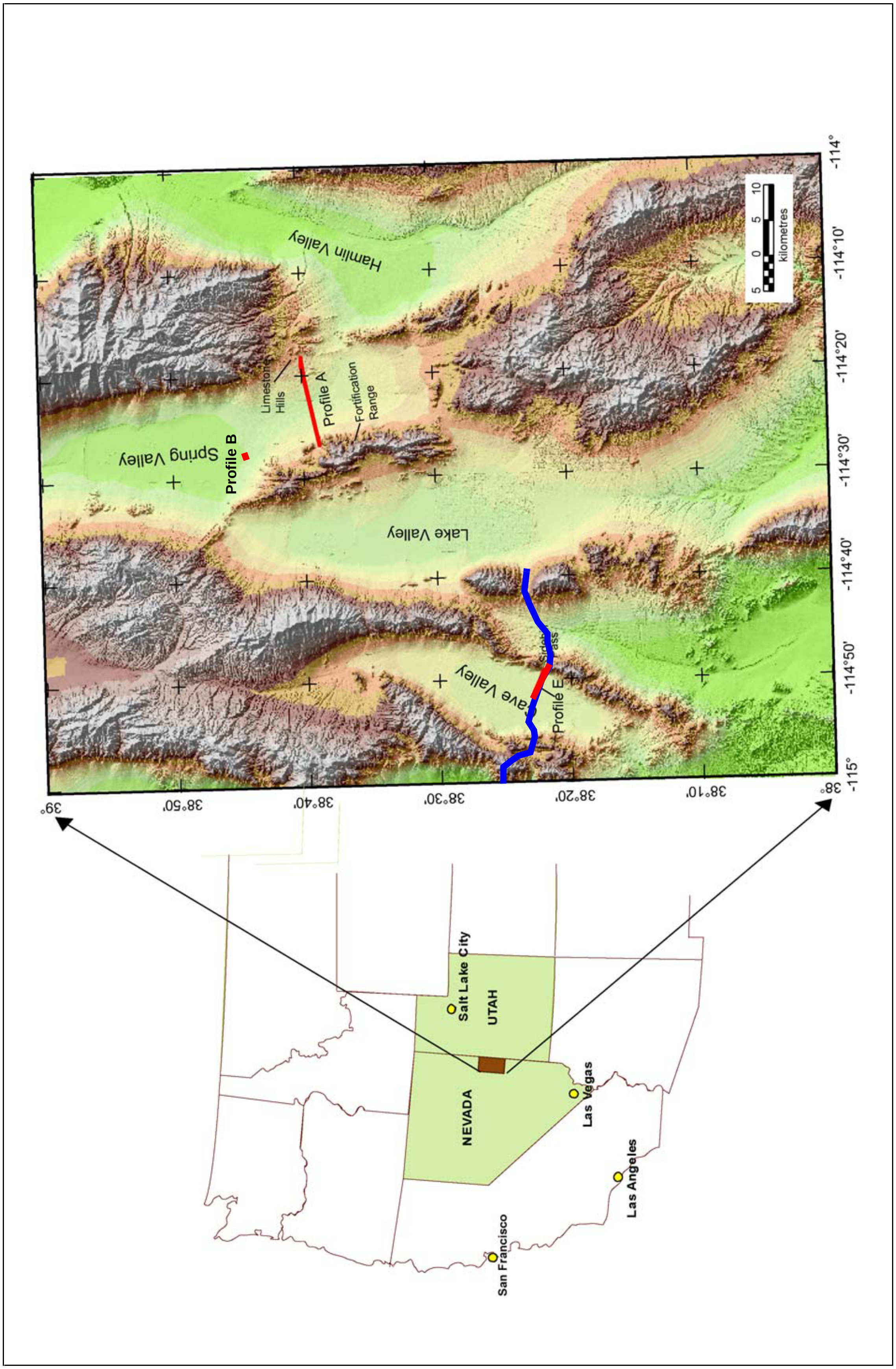
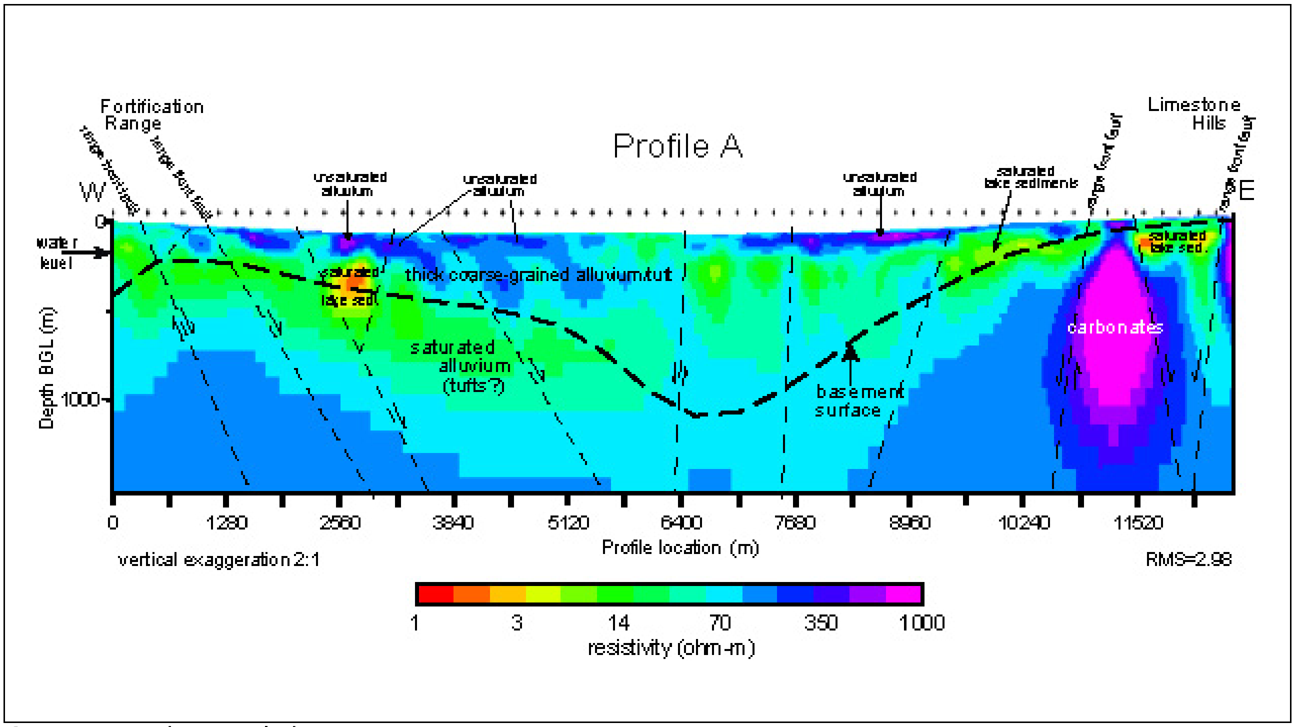


Figure 13-6
Location Map of the Study Area With AMT Profiles (red) and ECN-01 Seismic Line (blue)



Source: McPhee et al., in press

Figure 13-7
AMT Model Along Profile A Across Southern Spring Valley

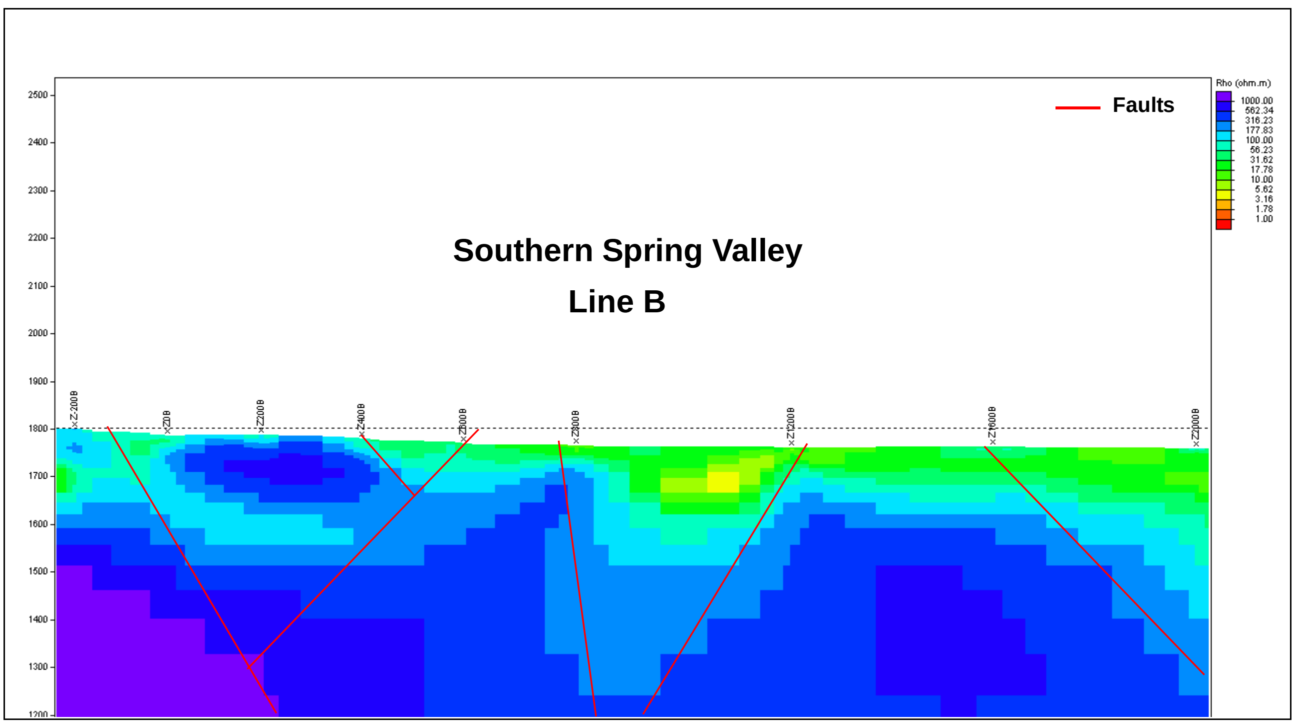


Figure 13-8
AMT Model Along Profile B Across Southern Spring Valley

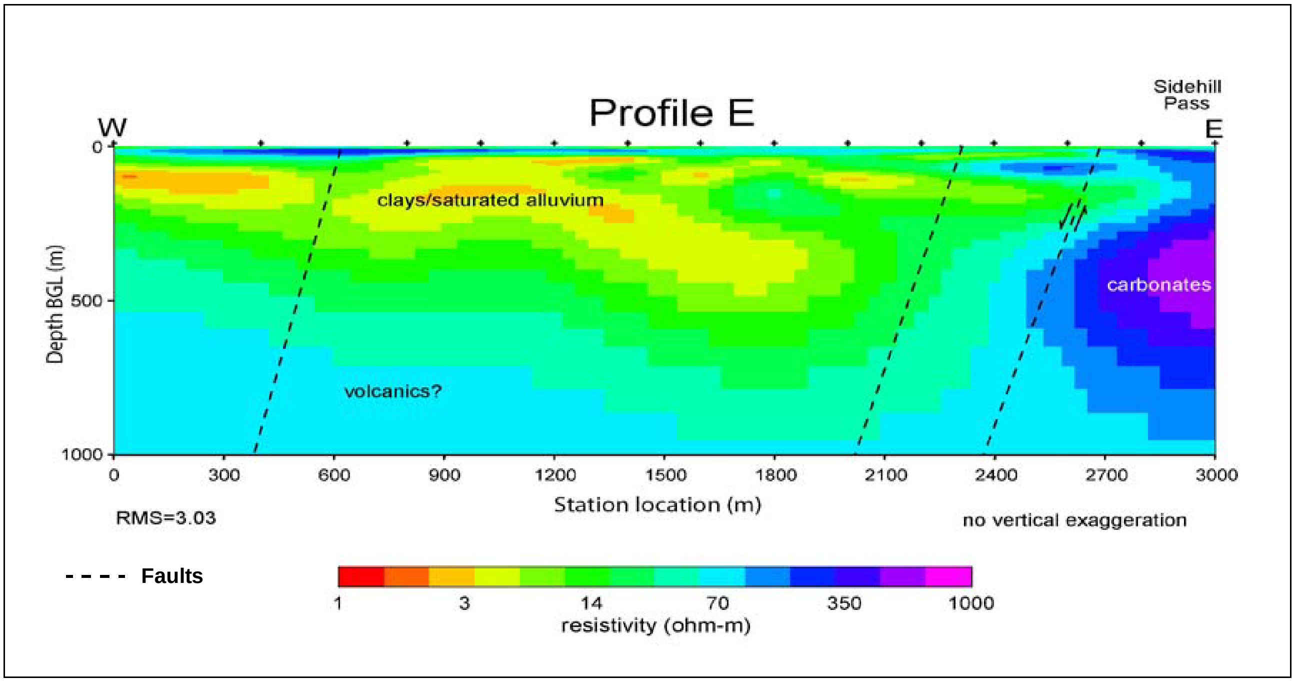
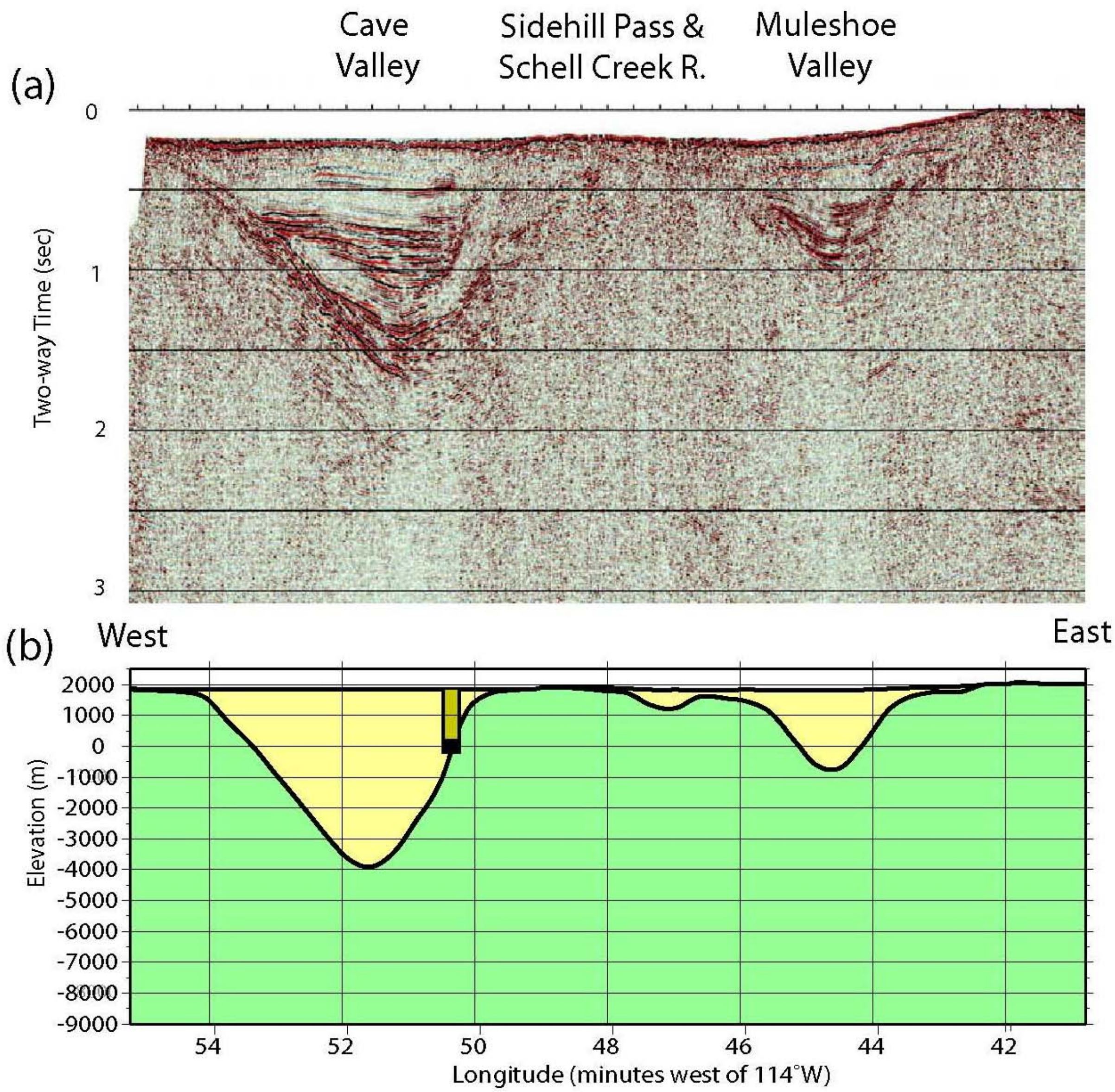


Figure 13-9
AMT Model Along Profile E Across Central Cave Valley

of Cave vs. Muleshoe, in deeper portions, look similar between the seismic and gravity models. American Petroleum Institute (API) well 27-017-05221 is superimposed schematically on Figure 13-10b to illustrate its general agreement with the gravity depth-to-basement estimate and to show its position with respect to the seismic structures.



(a) Cross section of southern Cave and northern Muleshoe Valleys ECN-01 seismic reflection section displayed in time. (b) Results of gravity depth-to-basement inversion with low density basin-fill in yellow; vertical exaggeration = 1.5 API well 27-017-05221 is displayed on the section, and its alluvial interval is shown in dark yellow.

Figure 13-10
(a) ECN-01 Seismic Reflection Section Displayed in Time
(b) Results of Gravity Depth-to-Basement

14.0 REFERENCES

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Plates

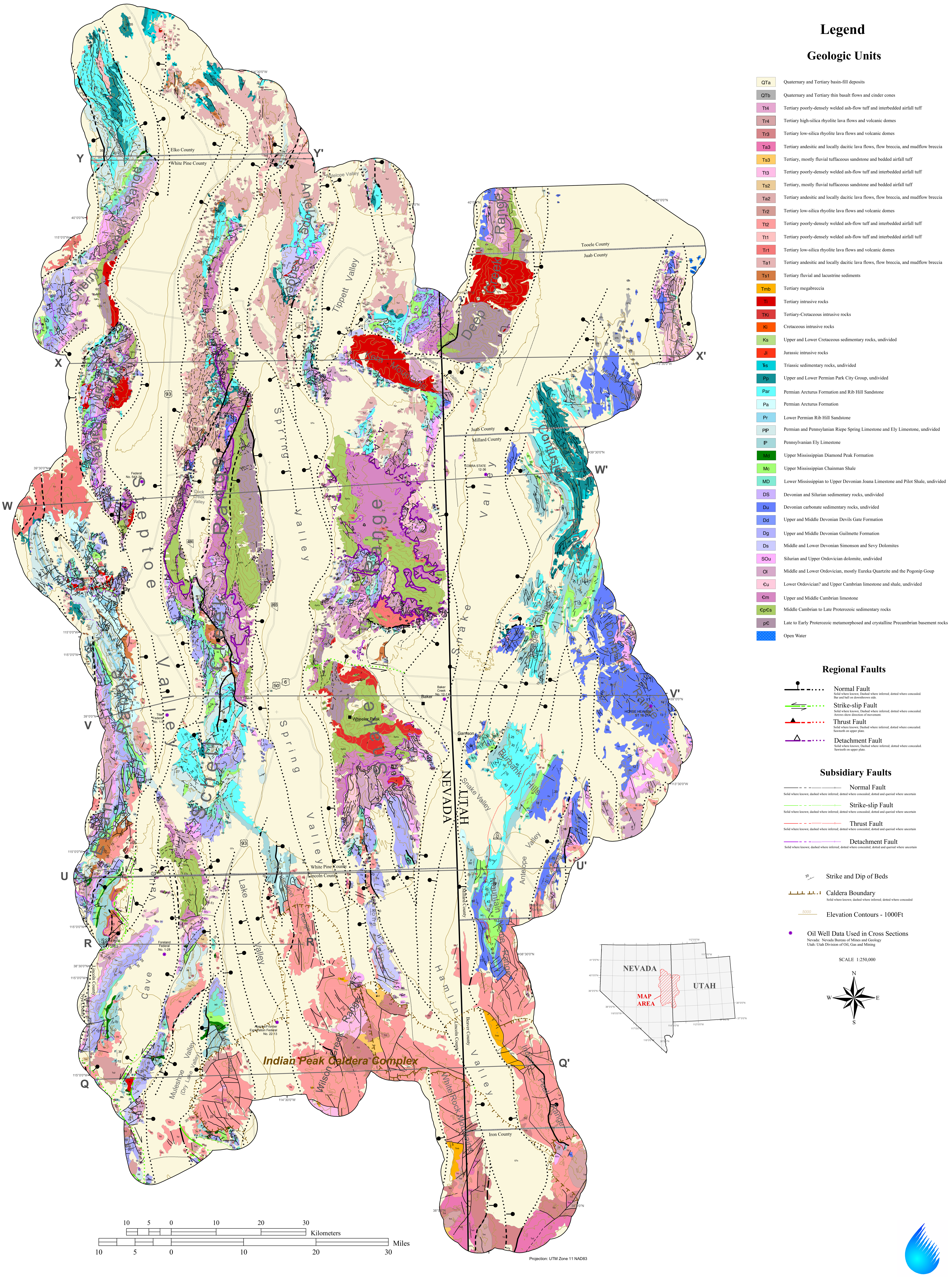
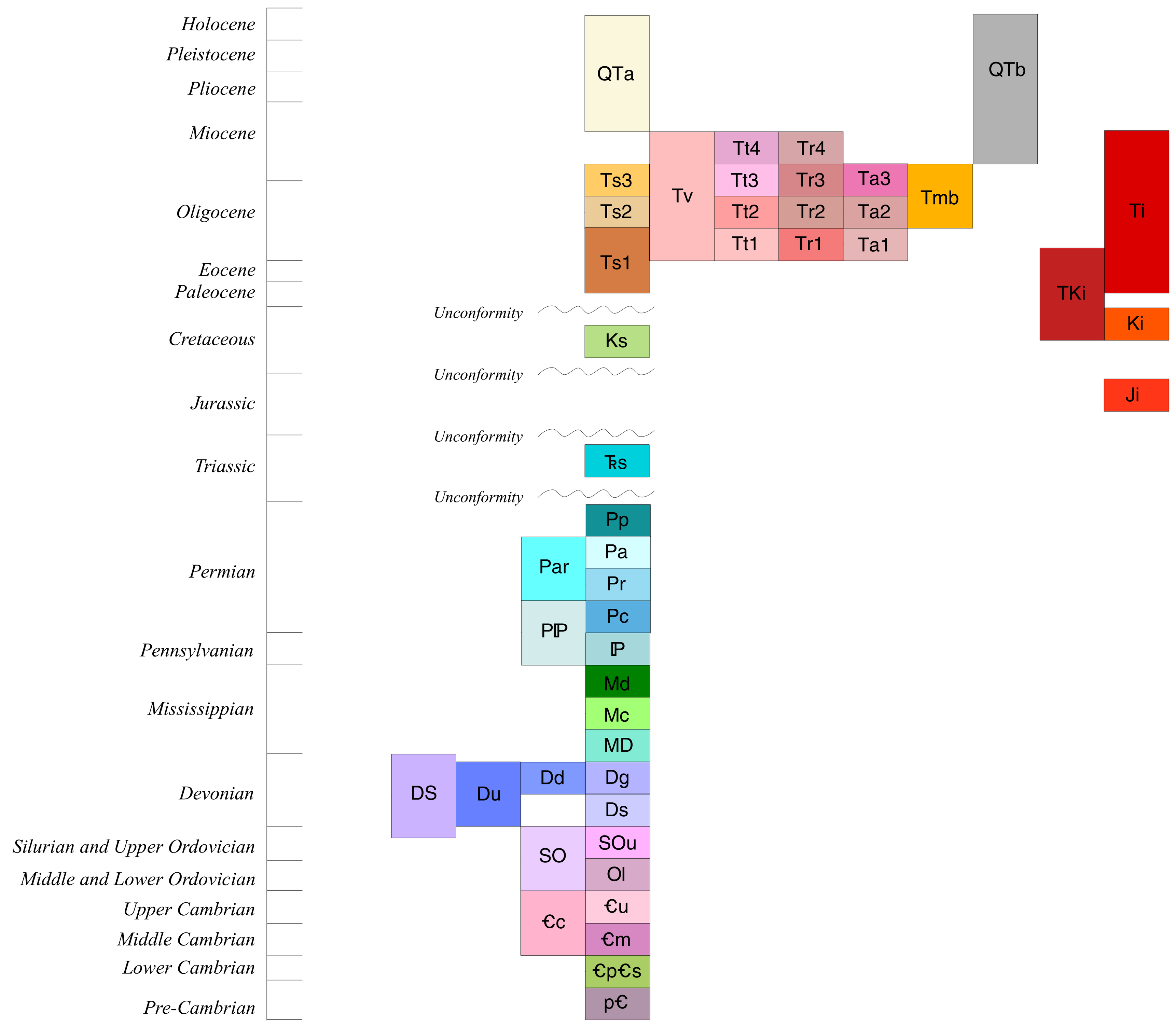


PLATE 1. GEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH



QTa Surficial and basin-fill deposits (Holocene to upper Miocene)—Unconsolidated to moderately consolidated, locally tuffaceous beds of sand, gravel, silt, and minor limestone deposited mostly by streams and small playa lakes. Generally thin but, where unit fills basin-range-fault-bounded basins, may be many thousands of feet thick and forms the upper valley-fill aquifer. Some basin-fill deposits bear local names, including the Muddy Creek Formation (south of the map area), Panaca Formation (south of the map area), Horse Camp Formation (northwest part of the area), and Salt Lake Formation (northeast part of the area).

QTb Basalt lava flows (Holocene to upper Miocene)—Resistant thin basalt lava flows and cinder cones. The mafic end of the bimodal volcanic sequence that is synchronous with basin-range extensional faulting.

Ts3 Sedimentary rocks, unit 3 (Miocene and Oligocene)—Moderately to well consolidated, thin, mostly fluvial, tuffaceous sandstone and bedded airfall tuff

Ts2 Sedimentary rocks, unit 2 (Oligocene)—Moderately to well consolidated, thin, mostly fluvial, tuffaceous sandstone and conglomerate. Includes the Gilmore Gulch Formation, with an age of about 30 Ma, in the western part of the area.

Ts1 Sedimentary rocks, unit 1 (Oligocene to Upper Cretaceous?)—Moderately to well consolidated, mostly fluvial sandstone, conglomerate, and minor lacustrine limestone. Primarily the Sheep Pass Formation, but south of the map area, includes the Paleocene(?) and Upper Cretaceous(?) Grapevine Wash Formation and the Eocene and Paleocene Claron Formation. Includes the Fowkes Formation and White Sage Formation in the northeastern part of the area. Unit in most places underlies all volcanic rocks.

Tv Volcanic rocks (Miocene and Oligocene)—Unit shown only in cross sections and on the hydrostratigraphic map, where it is referred to as the volcanic aquifer. May be several thousand feet thick in many places, and in calderas and near other source vents, may be many thousands of feet thick. On the geologic map, unit is separated into several rock types based on age, following the mapping strategy of Ekren and others (1977).

Tt4 Ash-flow tuff and interbedded airfall tuff, unit 4 (Miocene)—Poorly to densely welded, bimodal high-silica rhyolite and locally peralkaline ash-flow tuff and related airfall tuffs. Includes the Ox Valley Tuff (13.5 Ma), tuff of Etna (14.0 Ma), tuff of Rainbow Canyon (15.6 Ma), tuff of Acklin Canyon (17.1 Ma), and tuff of Dow Mountain (17.4 Ma), derived from the Caliente caldera complex. Includes the Kane Wash Tuff (14.4 to 14.7 Ma), the tuff of Boulder Canyon (15.1 Ma), and the tuff of Narrow Canyon (15.8 Ma), derived from the Kane Springs Wash caldera complex.

Tt3 Ash-flow tuff and interbedded airfall tuff, unit 3 (Miocene and Oligocene)—Poorly to densely welded, calc-alkaline, low-silica rhyolite to dacite ash-flow tuff and related airfall tuffs. Includes the tuff of Teepee Rocks (17.8 Ma), Hiko Tuff (18.3 Ma), Racer Canyon Tuff (18.7 Ma), and both Bauers Tuff Member (22.8 Ma) and Swett Tuff Member (23.7 Ma) of the Condor Canyon Formation, all derived from the Caliente caldera complex. Also includes the Harmony Hills Tuff (22.0 Ma), probably derived from the eastern Bull Valley Mountains; the Leach Canyon Formation (23.8 Ma), probably derived from the Caliente caldera complex; the Bates Mountain Tuff (22.8 Ma), derived from Lander County; and the tuff of Saulsbury Wash (21.6 Ma), the Pahranagat Formation (22.6 Ma), tuff of White Blotch Spring (24 to 25 Ma), the tuff of Kiln Canyon (24.1 to 25.1 Ma), the tuff of Lunar Cuesta (24.6 Ma), the tuff of the Quinn Canyon Range, and the Shingle Pass Tuff (26.4), all derived from the central Nevada caldera complex; and the tuff of Bald Mountain (about 25 Ma), derived from the Bald Mountain caldera in the Groom Range.

Tt2 Ash-flow tuff and interbedded airfall tuff, unit 2 (Oligocene)—Poorly to densely welded, calc-alkaline, low-silica rhyolite to dacite and trachydacite ash-flow tuff and related airfall tuffs. Includes the Isom Formation (about 27 Ma), probably derived from the Indian Peak caldera complex; the outflow Monotony Tuff (27.3 Ma), the intracaldera tuff of Goblin Knobs (27.3 Ma), and the tuff of Hot Creek Canyon (30.0 Ma), all derived from the central Nevada caldera complex; the outflow Windous Butte Formation (31.4 Ma) and intracaldera tuff of Williams Ridge and Morey Peak (31.3 Ma), derived from the Williams Ridge caldera of the central Nevada caldera complex; and the Needles Range Group (29 to 32 Ma), derived from the Indian Peak caldera complex.

Tt1 Ash-flow tuff and interbedded airfall tuff, unit 1 (Eocene and Oligocene)—Poorly to densely welded, calc-alkaline, low-silica rhyolite to dacite and trachydacite ash-flow tuff and related airfall tuffs. Deposited in the northern part of the map area. Includes the Pancake Summit Tuff (33.7 Ma), derived from the Broken Back caldera west of Eureka; the Stone Cabin Formation (35.4 Ma), derived from an unknown caldera in or near northern Railroad Valley; and the Kalamazoo Tuff (35 Ma), derived from an unknown source probably in the northern Schell Creek Range or beneath adjacent northern Spring Valley.

Tr4 Rhyolite lava flows, unit 4 (Miocene)—High-silica rhyolite lava flows and volcanic domes, mostly in and near the Caliente and Kane Springs Wash caldera complexes.

Tr3 Rhyolite lava flows, unit 3 (Miocene and Oligocene)—Low-silica rhyolite lava flows and volcanic domes, mostly in and near the Indian Peak, Caliente, and central Nevada caldera complexes.

Tr2 Rhyolite lava flows, unit 2 (Oligocene)—Low-silica rhyolite lava flows and volcanic domes, mostly in and near the central Nevada and Indian Peak caldera complexes.

Tr1 Rhyolite lava flows, unit 1 (Oligocene)—Low-silica rhyolite lava flows and volcanic domes, exposed in the northern part of the map area, including the White River caldera.

Ta3 Intermediate-composition lava flows, unit 3 (Miocene and Oligocene)—Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia. Includes andesite between the Racer Canyon Tuff and Condor Canyon Formation in the southeast part of the map area, between the Caliente and Kane Springs Wash caldera complexes, and in and near the Indian Peak and central Nevada caldera complexes.

Ta2 Intermediate-composition lava flows, unit 2 (Oligocene)—Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia. Includes andesite in and near the Indian Peak caldera complex and in the southern Egan Range.

Ta1 Intermediate-composition lava flows, unit 1 (Oligocene)—Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia. Exposed in the northern part of the map area. In the northeastern part of the area includes thin ash-flow tuffs, notably the Kalamazoo Tuff.

Tmb Megabreccia (Miocene and Oligocene)—Masses of mostly Paleozoic sedimentary rocks and intertongued volcanic breccia deposited within calderas from landsliding of the oversteepened caldera margins following caldera subsidence as a result of rapid eruptions of ash-flow tuff. Includes rocks in the Indian Peak caldera complex, Caliente caldera complex and central Nevada caldera complex. Includes gravity slides west of the Sheep Range and Beaver Dam Mountains.

Ti Intrusive rocks (Miocene and Oligocene)—Mostly silicic, calc-alkaline plutons.

TKi Intrusive rocks (Miocene to Cretaceous)—Mostly silicic, calc-alkaline plutons.

Ki Intrusive rocks (Upper Cretaceous)—Mostly silicic, calc-alkaline plutons that accompanied Sevier deformation.

Ks Sedimentary rocks, undivided (Upper and Lower Cretaceous)—Sevier-age, mostly thin, fluvial synorogenic clastic deposits, including the Baseline Sandstone (Upper and Lower Cretaceous) and Willow Tank Formation (Upper Cretaceous) in the southern part of the area, and the Iron Springs Formation (Upper Cretaceous), Cedar Mountain Formation (Upper Cretaceous), and Dakota Sandstone (Upper Cretaceous) in the southeastern part of the area; and the Newark Canyon Formation (Paleocene? to Lower Cretaceous?) in the northern part of the area.

Ji Intrusive rocks (Jurassic)—Mostly silicic, calc-alkaline plutons that accompanied Sevier deformation.

T̄s Sedimentary rocks, undivided (Triassic)—Includes, in the southeastern part of the area, the mostly fluvial Chinle Formation (Upper Triassic) and mostly fluvial Moenkopi Formation (Middle? and Lower Triassic). Includes the Luning Formation (Upper Triassic) in the northwestern part of the area. In the northeastern part of the area, includes the Thaynes Formation (Lower Triassic). The rocks are mostly clastic.

Pp Park City Group, undivided (Upper and Lower Permian)—From top to base, consists of the Gerster Limestone (Upper Permian), Plympton Formation (Upper and Lower Permian), Kaibab Limestone (Lower Permian), and Toroweap Formation (Lower Permian). These make up the top of the upper carbonate aquifer.

Par Arcturus Formation and Rib Hill Sandstone, undivided (Lower Permian)—Included within the upper carbonate aquifer. Includes the Pequop Formation in Elko County, a redbed unit in the southern part of the area, and the Queantoweap Sandstone south of the map area.

Pa Arcturus Formation (Lower Permian)—Mostly in the northern part of the area, thickening eastward.

Pr Rib Hill Sandstone (Lower Permian) —Only in the northwestern part of the area.

PP Riepe Spring Limestone and Ely Limestone, undivided (Lower Permian and Pennsylvanian)— Mapped only in the northern part of the map area. The Riepe Spring Limestone (Lower Permian) is exposed in the northwestern part of the area. Includes the Brock Canyon Formation (Permian and/or Pennsylvanian) in the northwestern part of the area; the Oquirrh Group (Lower Permian and Pennsylvanian) in the northeastern part of the area; and the Bird Spring Formation (Lower Permian to Upper Mississippian) in Clark County.

P Ely Limestone (Pennsylvanian)—May include Missippian rocks at its base. Mapped mostly in the central and northern part of the area, thickening eastward. Includes the Wildcat Peak Formation in the northwestern part of the area and the Callville Limestone in the southern and eastern part of the area.

MDd Diamond Peak Formation, Chainman Shale, Joana Limestone, and Pilot Shale, undivided (Upper Mississippian to Upper Devonian)

Md Diamond Peak Formation (Upper Mississippian)—Only in the northwestern part of the area. This is a clastic unit derived from erosion of the Antler highland, including the Roberts Mountain thrust formed during the Antler deformational event. Includes the Scotty Wash Quartzite in the southwestern part of the area.

Mc Chainman Shale (Upper Mississippian)—A clastic confining unit that has a similar origin to the Diamond Peak Formation. The two make up the upper aquitard in the northern half of the map area. Thus for this part of the map area, it separates the upper from the lower carbonate aquifer; in the southern part of the map area, the Chainman is thin and does not constitute a significant regional aquitard.

MD Joana Limestone and Pilot Shale, undivided (Lower Mississippian to Upper Devonian)—The Joana Limestone (Lower Mississippian) and Pilot Shale (Lower Mississippian and Upper Devonian) make up the top of the lower carbonate aquifer in the northern half of the map area. Includes local Lower Mississippian units Mercury Limestone and Bristol Pass Limestone. Includes the Rogers Spring Limestone (Lower Mississippian) and Monte Cristo Limestone (Upper and Lower Mississippian) in the southern part of the area; the Eleana Formation (Mississippian and Upper Devonian) in the western part of the area; the Webb Formation (Lower Mississippian) in Elko County; and the Ochre Mountain Limestone (Lower Mississippian) in the eastern part of the area. May include, at the top, thin deposits of the Chainman Shale.

DS Devonian and Silurian sedimentary rocks, undivided—Only shown on some cross sections.

Du Devonian carbonate sedimentary rocks, undivided—Includes the Woodruff Formation (Upper and Middle Devonian) in Elko County; and the Muddy Peak Limestone (Upper and Middle? Devonian) in the southern part of the area.

Dd Devils Gate Formation (Upper and Middle Devonian)—The western equivalent of the Guilmette Formation.

Dg Guilmette Formation (Upper and Middle Devonian)—Mapped throughout, except in the western part of the map area. Includes the Sultan Limestone in Clark County.

Ds Simonson Dolomite (Middle and Lower Devonian) and Sevy Dolomite, undivided (Lower Devonian)—Mapped in all but the western part of the map area.

SO Silurian and Ordovician sedimentary rocks, undivided—Shown on some cross sections.

SOu Upper part (Silurian and Upper Ordovician)--Includes the Laketown Dolomite (Silurian), Fish Haven Dolomite (Upper Ordovician), Ely Springs Dolomite (Upper Ordovician), and Hanson Creek Formation (Upper Ordovician). Includes the Roberts Mountains Formation and the Lone Mountain Dolomite in the northwestern part of the map area.

Ol Lower part (Middle and Lower Ordovician)—Mostly the Eureka Quartzite (Middle Ordovician) and the Pogonip Group (Middle and Lower Ordovician). Includes the Vinini Formation and Valmy Formation in the northwestern part of the area.

€c Cambrian carbonate sedimentary rocks, undivided —Shown only on some cross sections.

€u Upper part (Lower Ordovician? and Upper Cambrian)—Includes the Notch Peak Limestone, Orr Formation, Windfall Formation, Nopah Limestone, Dunderberg Shale, and Corset Spring Shale. In the extreme southwestern part of the map area, includes the Emigrant Formation (Upper and Middle Cambrian).

€m Middle part (Upper and Middle Cambrian)—Mostly the Highland Peak Formation and its southwestern equivalent, the Bonanza King Formation. Includes local units known as the Pole Canyon Limestone, Lincoln Peak Formation, Patterson Pass Shale, Hamburg Formation, Secret Canyon Shale, Geddes Limestone and Eldorado Formation. This unit is a thick limestone sequence that marks the base of the lower carbonate aquifer.

€p€s Lower part (Middle Cambrian to Late Proterozoic)—Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), Pioche Shale (Middle and Lower Cambrian), Carrara Formation (Middle and Lower Cambrian), Stella Lake Quartzite (Lower Cambrian), Prospect Mountain Quartzite (Lower Cambrian and Late Proterozoic), and Johnnie Formation (Late Proterozoic). The Prospect Mountain, in turn, has been subdivided into the Zabriskie Quartzite (Lower Cambrian), Wood Canyon Formation (Lower Cambrian), and Sterling Quartzite (Lower Cambrian and Late Proterozoic). Locally includes the Reed Dolomite (Lower Cambrian) and underlying Wyman Formation (Lower Cambrian?) south of the map area.

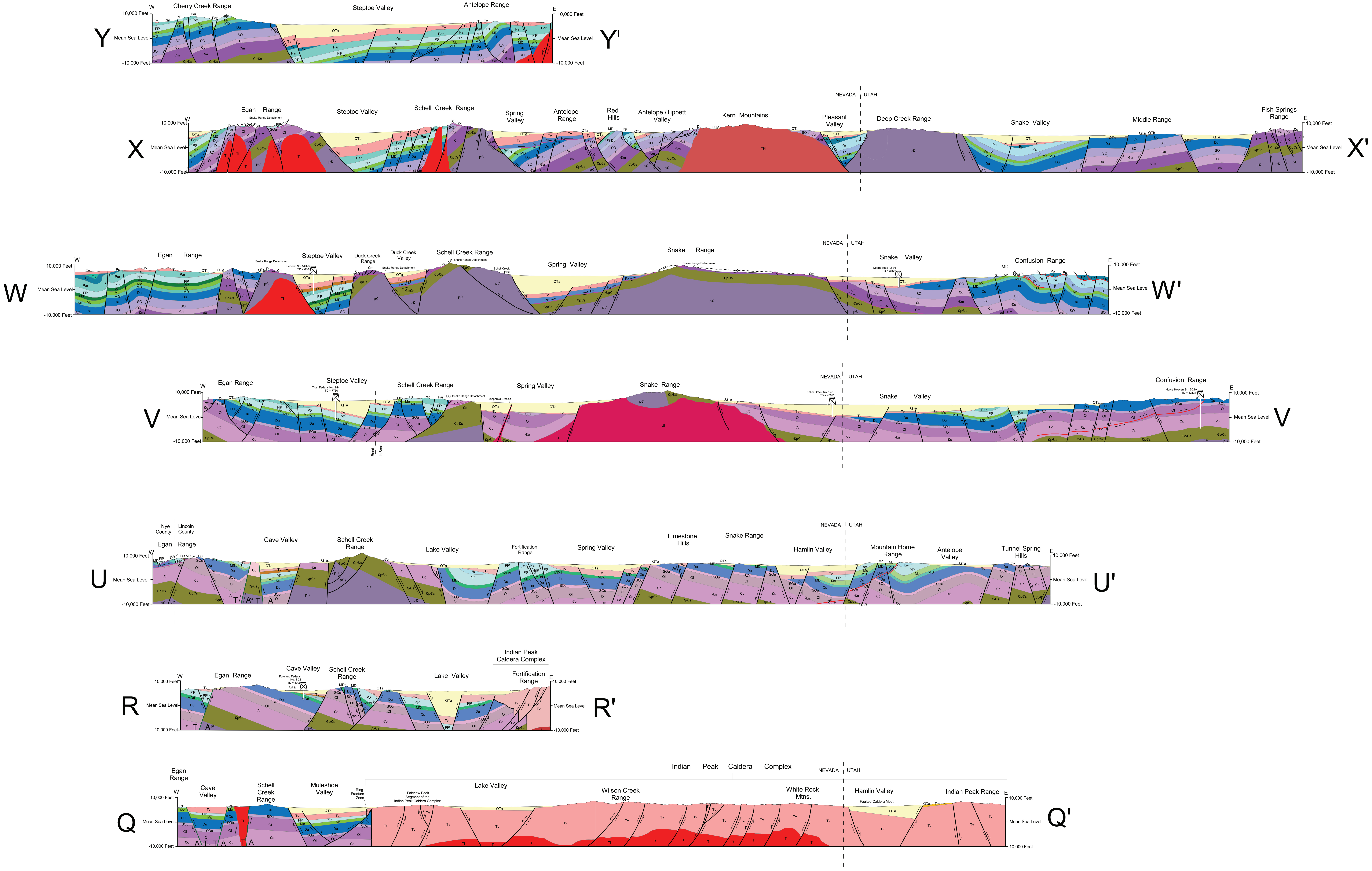
p€ Metamorphosed and crystalline Precambrian basement rocks (Late to Early Proterozoic)—Throughout most of the map area, consists of metamorphosed quartzite of Late Proterozoic age, namely the McCoy Creek Group and, in Utah, also the underlying Trout Creek Group. Locally, in the southern part of the map area, includes crystalline basement rocks.

Open Water

Plate 2. Explanation of Geologic Units for the Maps and Cross Sections: GEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS OF NEVADA AND UTAH

Southern Nevada Water Authority

MAP ID 12449 06/15/2006 JMB



Explanation of Geologic Units Shown on Cross Section

QTa	Quaternary and Tertiary basin-fill deposits
QTb	Quaternary and Tertiary thin basalt flows and cinder cones
Tv	Tertiary volcanic ash-flows, flows and ash-fall tuffs
Ts1	Tertiary fluvial and lacustrine sediments
Ti	Tertiary intrusive rocks
TKi	Tertiary-Cretaceous intrusive rocks
Ji	Jurassic intrusive rocks
Ƭs	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
PIP	Permian and Pennsylvanian Riepe Spring Limestone and Ely Limestone, undivided
IP	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	Upper Mississippian Chainman Shale
MD	Lower Mississippian to Upper Devonian Joana Limestone and Pilot Shale, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Dg	Upper and Middle Devonian Guilmette Formation
Ds	Middle and Lower Devonian Simonson Formation
SO	Silurian and Ordovician sedimentary rocks, undivided
SOu	Silurian and Upper Ordovician dolomite, undivided
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
€c	Cambrian carbonate sedimentary rocks, undivided
€u	Lower Ordovician? And Upper Cambrian limestone and shale, undivided
€m	Upper and Middle Cambrian limestone and shale
€p€s	Middle Cambrian to Late Proterozoic sedimentary rocks
p€	Late to early Proterozoic metamorphosed and crystalline Precambrian basement rocks

Geologic Structure

- Normal Fault
- Thrust Fault
- Strike-slip Fault
- Detachment Fault
- Formation Contact
- Projection

Oil Well Data Used in Cross Sections

Nevada: Nevada Bureau of Mines and Geology
Utah: Utah Division of Oil, Gas and Mining

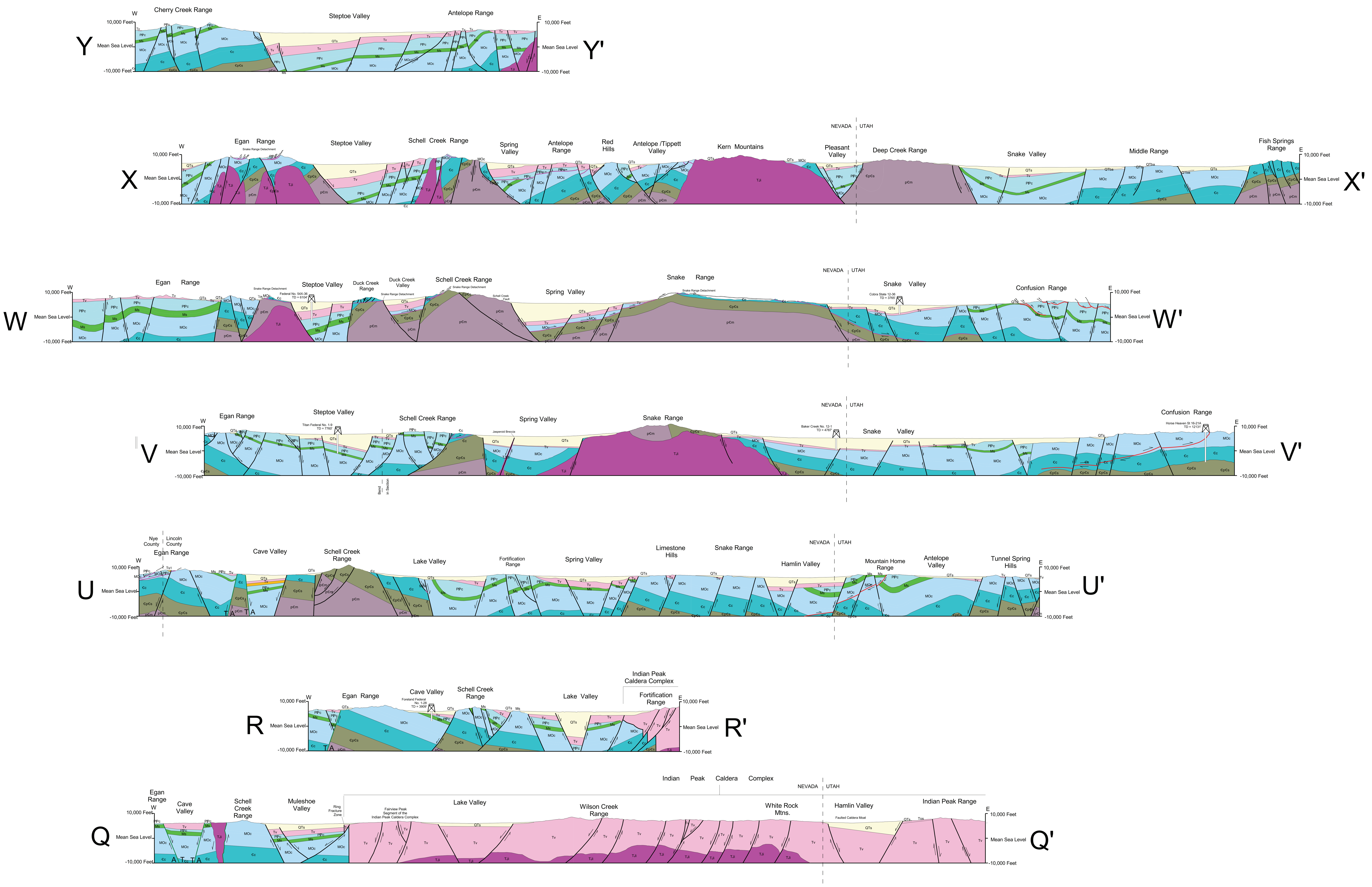
SCALE 1:250,000
NO VERTICAL EXAGGERATION

Southern Nevada Water Authority

PLATE 3. CROSS SECTIONS SHOWING GEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

MAP ID 12450 06/15/2006 JMB

PLATE 4. HYDROGEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH



Cross Section Explanation

Hydrogeologic Units

Unit	Description
QTs	Quaternary and Tertiary sediments - mostly sediments younger than late Miocene or contemporaneous with volcanic section.
QTb	Quaternary and Tertiary basalt - Very late Tertiary to modern mafic flows locally important in central Nye County and the Escalante Desert.
Tv	Tertiary volcanic rocks - mostly Miocene and Oligocene, but includes other Tertiary, maybe even older rocks.
Tos	Tertiary siliciclastic rocks
TJi	Tertiary to Jurassic igneous rocks - plutons are generally older to the north and west.
KTRs	Cretaceous to Triassic siliciclastic rocks, very localized units that are typically conglomerate with or without freshwater limestone. In or near the Colorado Plateau, very large units of variable but generally low permeability.
PPc	Permian and Pennsylvain carbonate rocks - Ely Limestone (Bird Spring Formation) to Park City Group (Kaibab), includes Triassic rocks in Butte Mountains.
Ms	Mississippian siliciclastic rocks - Chainman Formation, Diamond Peak Formation and others, not differentiated in Lincoln County (except in the Egan Range).
MOc	Mississippian to Ordovician carbonate rocks - Pogonip to Joana Limestone (Monte Cristo). Chainman Shale in Lincoln and Clark Counties, Pilot Shale and Eureka Quartzite are always assumed to be a part of this unit.
Ꞓc	Cambrian carbonate rock - Bonanza King, Highland Peak and Pole Canyon Formations
ꞒpꞒs	Cambrian and pre-Cambrian siliciclastic rocks - Wood Canyon Formation, Prospect Mountain Formation and Pioche Shale.
pꞒm	Pre-Cambrian metamorphic rocks - Originally for pre-Cambrian X and Y or older high grade metamorphic rocks, includes McCoy Creek Group in Schell Creek Range.

Geologic Structure

- Normal Fault
- Thrust Fault
- Strike-slip Fault
- Detachment Fault
- Projection
- Hydrogeologic Contact

Oil Well Data Used in Cross Sections

Nevada: Nevada Bureau of Mines and Geology
Utah: Utah Division of Oil, Gas and Mining

SCALE 1:250,000
NO VERTICAL EXAGGERATION

Southern Nevada Water Authority

PLATE 5. CROSS SECTIONS SHOWING HYDROGEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

MAP ID 12452 06/15/2006 JMB