Geology and Geophysics of Spring, Cave, Dry Lake, and Delamar Valleys, White Pine and Lincoln Counties and Adjacent Areas, Nevada and Utah: The Geologic Framework of Regional Groundwater Flow Systems

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Geology and Geophysics of Spring, Cave, Dry Lake, and Delamar Valleys, White Pine and Lincoln Counties and Adjacent Areas, Nevada and Utah: The Geologic Framework of Regional Groundwater Flow Systems

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Pertaining to:
Groundwater Applications 54003 through 54021 in
Spring Valley
and
Groundwater Applications 53987 through 53992 in
Cave, Dry Lake, and Delamar Valleys

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CONTENTS

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

FIGURES

NUMBER	TITLE	PAGE

FIGURES (CONTINUED)

FIGURES (CONTINUED)

FIGURES (CONTINUED)

PLATES

NUMBER **TITLE**

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TABLES

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ACRONYMS

2D	two-dimensional
AMT	audiomagnetotelluric
BARCASS	Basin and Range Carbonate Aquifer System Study
EIS	environmental impact statement
GBNP	Great Basin National Park
HGU	hydrogeologic unit
I-15	Interstate Highway 15
LVVSZ	Las Vegas Valley Shear Zone
MT	magnetotelluric
NPS	National Park Service
NTS	Nevada Test Site
NSE	Nevada State Engineer
POD	point of diversion
PSZ	Pahranagat Shear Zone
SNWA	Southern Nevada Water Authority
SR	State Route
US 50	U.S. Highway 50
US 6	U.S. Highway 6
US 93	U.S. Highway 93
USGS	U.S. Geological Survey
WCWCD	Washington County Water Conservancy District

ABBREVIATIONS

afy	acre-feet per year
ft	foot
Ga	billion years
gpm	gallons per minute
km	kilometer
m	meter
Ma	million years
mg	milligram
mi	mile
mi^2	square mile
ohm-m	ohm-meter [unit of electrical resistivity]

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1.0 INTRODUCTION

This report describes the geologic framework of an area of east-central and southeastern Nevada and adjacent western Utah. Included are geologic, hydrogeologic, and geophysical data collected throughout the study area, and updated geologic and hydrogeologic maps and cross sections based on the same presented in Dixon et al. (2007a). These updates were prompted by the analyses of new data collected within the study area since 2007, and the evaluation of more recent published and unpublished literature that, in some instances, required updating interpretations of selected features of the geologic framework. The new data were compiled from new geophysical studies employed and analyzed to better understand the structural framework of the area, and from borehole data from the Southern Nevada Water Authority (SNWA) exploratory drilling and hydraulic-testing program. The study area and Project Basins (Spring, Cave, Dry Lake, and Delamar valleys) are presented in Figure 1-1. Details regarding the Project background and the administrative history regarding the SNWA applications are presented in the Conceptual Plan of Development (SNWA, 2011) and Holmes et al. (2011), respectively.

1.1 Purpose and Scope of Geologic Investigation

The purposes of this report, as with the report by Dixon et al. (2007a), are to (1) provide an overview of the geology for an area encompassing the Project Basins, including a description of how that geology relates to the hydrogeology of the area; (2) present the geologic and hydrogeologic framework of the Project Basins and surrounding area; and (3) evaluate the framework to assess the potential for groundwater flow at selected boundaries.

The scope of this geologic investigation and that which led to the report by Dixon et al. (2007a) included significant data compilation and acquisition, and development of geologic and hydrogeologic surface maps and cross sections. This investigation also included gravity surveys of the Project Basins conducted by the U.S. Geological Survey (USGS) through joint funding agreements with SNWA. Significant fieldwork was done by the authors to improve the geologic understanding of selected areas. The scope of work was defined, in part, to differentiate between aquifers and confining zones, that is, hydrogeologic units (HGUs) with high and low hydraulic conductivity, respectively. The geologic investigation also focused on identifying areas where confining zones of sufficient thickness are present and inhibit groundwater flow.

1.2 Document Organization

This document consists of the following eight sections and Appendix A, which presents photos of the study area and selected points of interest.

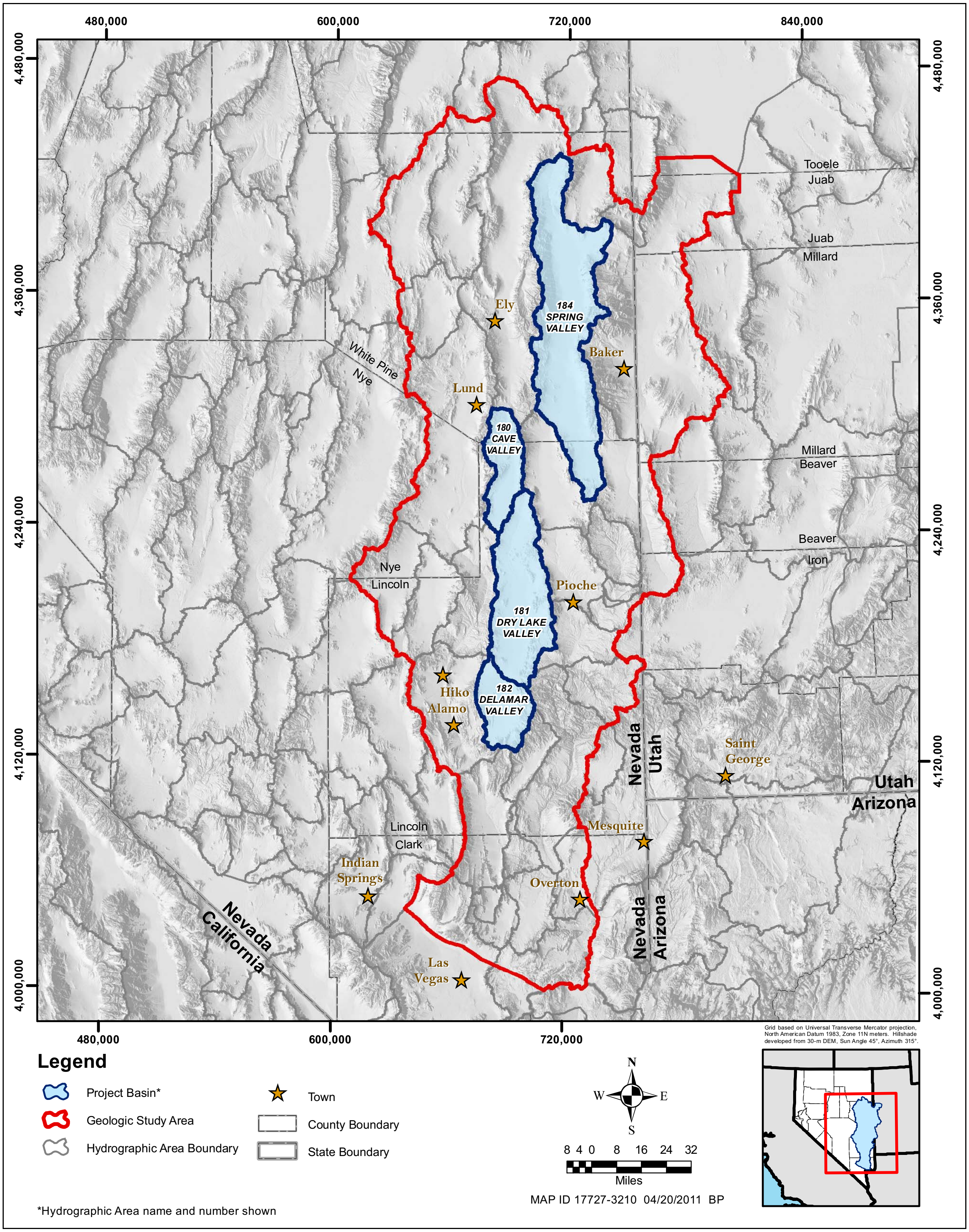

Figure 1-1
Location of Project Basins and Other Hydrographic Areas

- Section 1.0 provides a description of the Project background, the purpose and scope of the geologic investigation, and an overview of the contents of this report.

- Section 2.0 summarizes hydrogeologic concepts used and the geologic setting of the area, including the regional geologic features and drainage (Section 2.1). Section 2.2 discusses features of the geologic framework that affect the movement of groundwater.

- Section 3.0 describes the methodology applied in the geologic analysis, including a description of the objectives of the analysis and technical approach.

- Section 4.0 discusses the geology and hydrogeology of the geologic study area and some of the surrounding basins and ranges that could be in hydrogeologic connection with the basins of the geologic study area (Figure 1-1). Section 4.0 is divided into subsections describing the various aspects of the geology and hydrogeology, as follows:

  - Section 4.1 discusses the general geology and detailed stratigraphy of the geologic study area of this report, notably the geologic units in the study area.

  - Section 4.2 discusses the HGUs of the geologic study area and how they relate to the geologic units.

  - Section 4.3 discusses the evolution of the geologic structure in the geologic study area and how that structure impacts the hydrogeology.

  - Section 4.4 describes the geology in terms of the mountain ranges and adjacent basins within the geologic study area and how the specific geology in these areas affects the hydrogeology.

- Section 5.0 discusses the geophysics of the geologic study area.

- Section 6.0 discusses professional opinions on previous studies in the project area.

- Section 7.0 is a summary of the general geology and general hydrogeology of the geologic study area.

- Section 8.0 provides a list of references cited in the document as well as a list of references used in making the geologic maps and cross sections.

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2.0 Geologic Principles in the Study Area

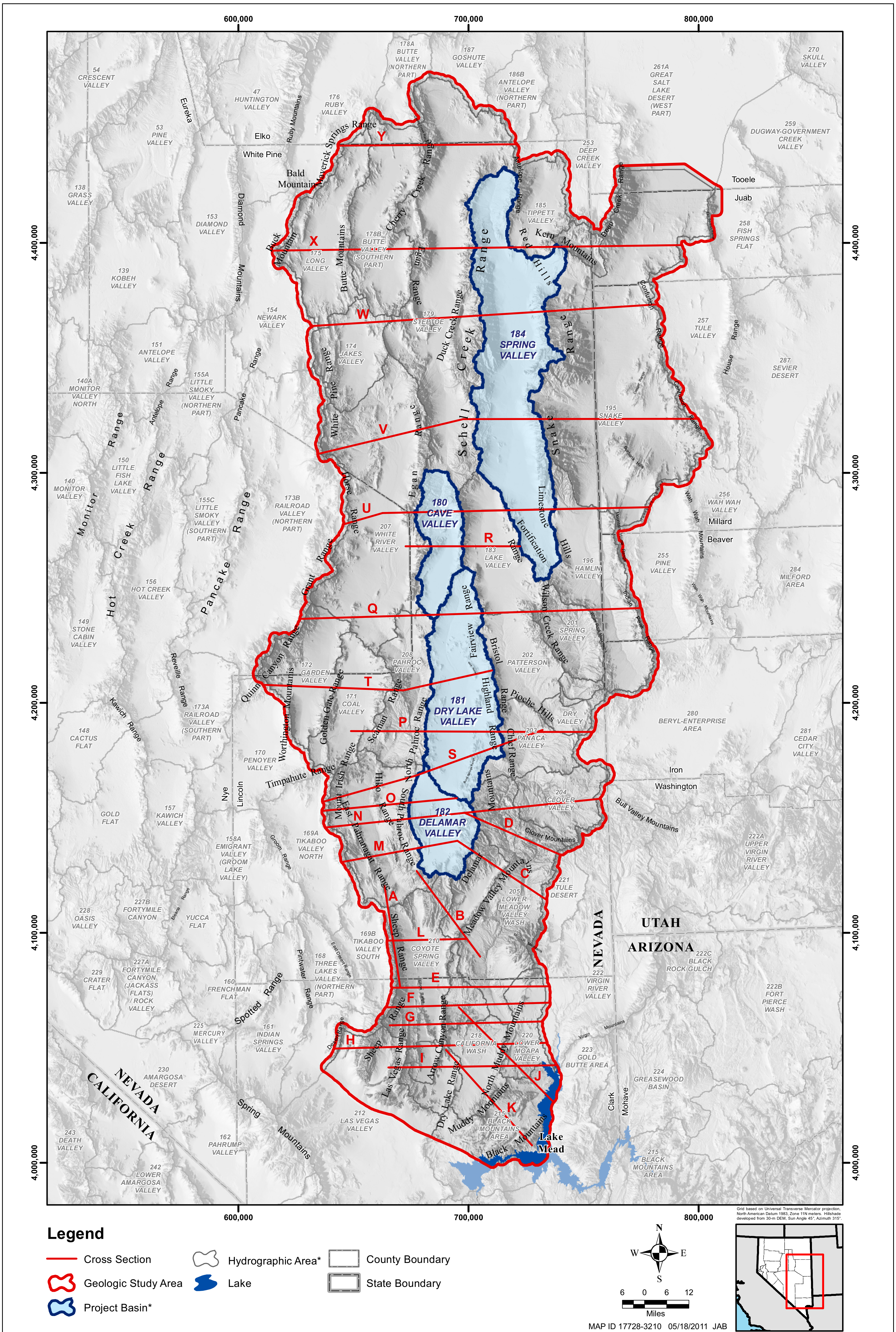
The study area for the geologic investigation encompasses the Project Basins and adjacent basins that may or may not be hydraulically connected to the Project Basins due to the nature of the geologic framework at their boundaries. The principles governing the development of the geologic framework model are discussed in this section, including descriptions of how the geologic framework can affect groundwater flow.

The area covered by this geologic investigation is hereafter referred to as the geologic study area, as delineated by a thick red line on Figure 2-1. The geologic study area is irregular in shape because it is made up of many hydrographic areas, which are individual valleys or basins identified and defined by surface-water drainages. Hydrographic areas are the boundaries named, numbered, and described by Federal, State, and local agencies and used in the administration of their responsibilities. Most hydrographic areas consist of a single topographic basin surrounded by ranges. The four Project Basins are the hydrographic areas that are the main focus of our attention.

2.1 Geologic Setting and Background

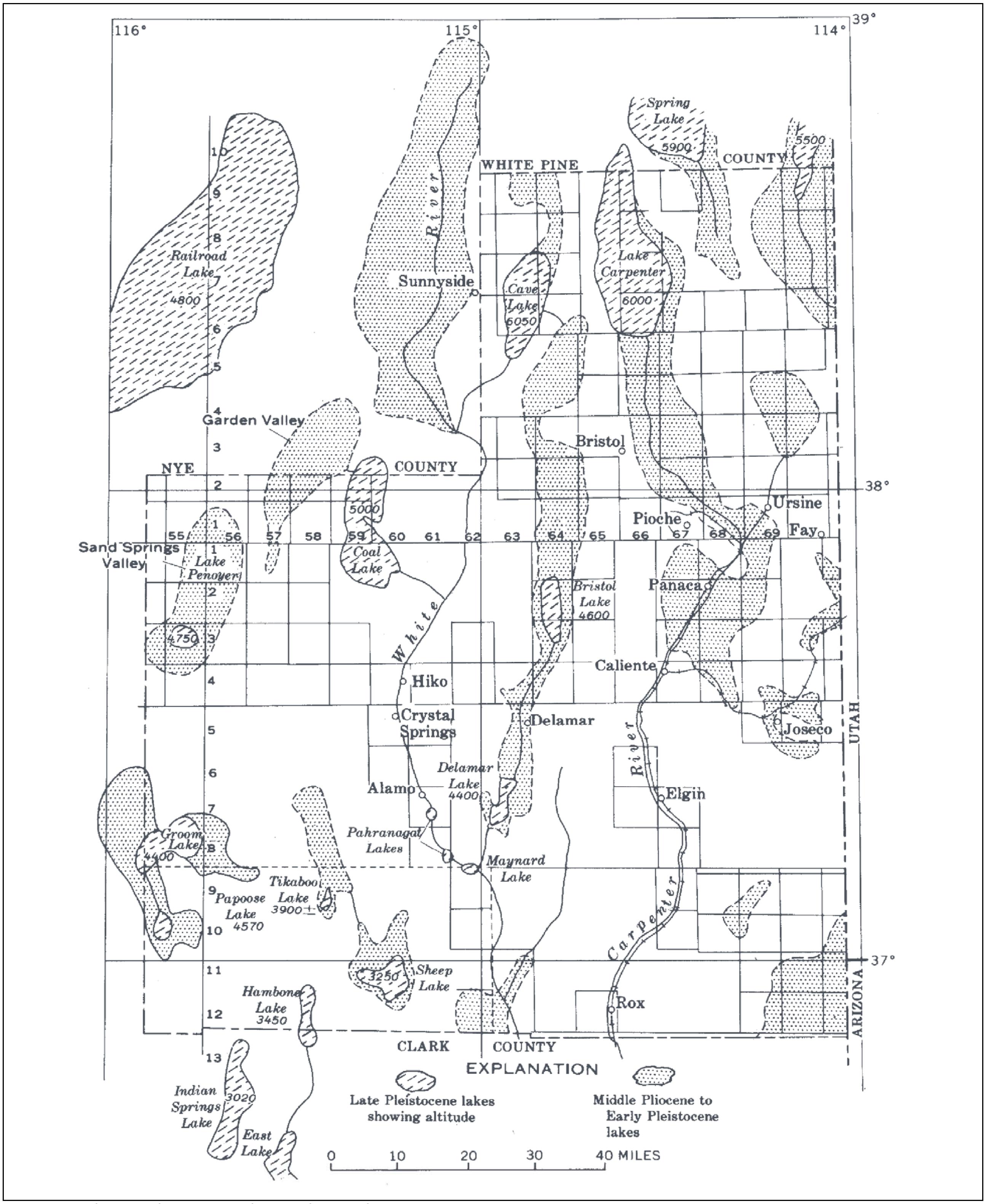
The geologic study area (Figure 2-1) is within the Great Basin subprovince of the Basin and Range physiographic province, characterized by north-trending basins and ranges that are formed by generally north-striking basin-range normal faults. The area has been subjected to several periods of deformation since Precambrian time. The most recent episode of deformation, which produced the present topography, is the basin-range episode of normal faulting. Most springs in the area are controlled by basin-range faults (Volume 3 of SNWA, 2008). The present topography consists of a number of closed basins and partially closed basins, typical of the Great Basin region where surface-water flow is restricted to that region. Exceptions occur only along the southeastern Great Basin boundary, where a few basins have surface water exiting to the Colorado River. These exceptions include the Virgin River, Muddy River, Las Vegas Wash, and the associated basins in which these streams occur.

During wetter periods of Pleistocene time, the latest of which was about 10,000 to 15,000 years before present, ancestral streams connected some closed basins, commonly through a series of ancestral lakes. For instance, the White River and its tributaries flowed southward through much of the western portion of the map area and integrated many of these basins, apparently by overflowing closed basins one by one (Figure 2-2) (Tschanz and Pampeyan, 1970). During this time, the White River joined other perennial streams that flowed southward to join the Colorado River at the vicinity of present-day Lake Mead, at the southern edge of the area. At the present time, over most of its course and as far south as Moapa, Nevada, the White River is intermittent.



Note: Geologic cross sections are presented in Plates 4 and 5. Hydrogeologic cross sections are presented in Plates 8 and 9.

Figure 2-1
Hydrographic Basins, Ranges, and Locations of Cross Sections



Source: Tschanz and Pampeyan (1970, Figure 18)

Figure 2-2
Map of Pliocene and Pleistocene Lakes and Streams in Lincoln County and Adjacent Areas, Nevada

Despite the intermittent nature of surface water, groundwater occurs at different depths 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 and ultimately to areas of groundwater discharge. Together, these aquifers make up the groundwater basin of the hydrographic area. When one hydrographic area is hydraulically connected to that of an adjacent area, and the groundwater in both flows toward a common low discharge area, a groundwater flow system is defined. Some groundwater flow systems consist of many hydrographic areas, and these are called regional groundwater flow systems. Adjacent to these regional groundwater flow systems may be other hydrographic areas that are parts of separate groundwater flow systems. The geologic study area lies within the Carbonate-Rock Province of eastern Nevada and Western Utah as described by Plume and Carlton (1988), and is underlain by an interconnected regional carbonate-rock aquifer. The geologic study area was selected of sufficiently large size so as to allow the investigation of the geologic framework to assess the potential hydraulic continuity or discontinuity between the Project Basins and adjacent areas.

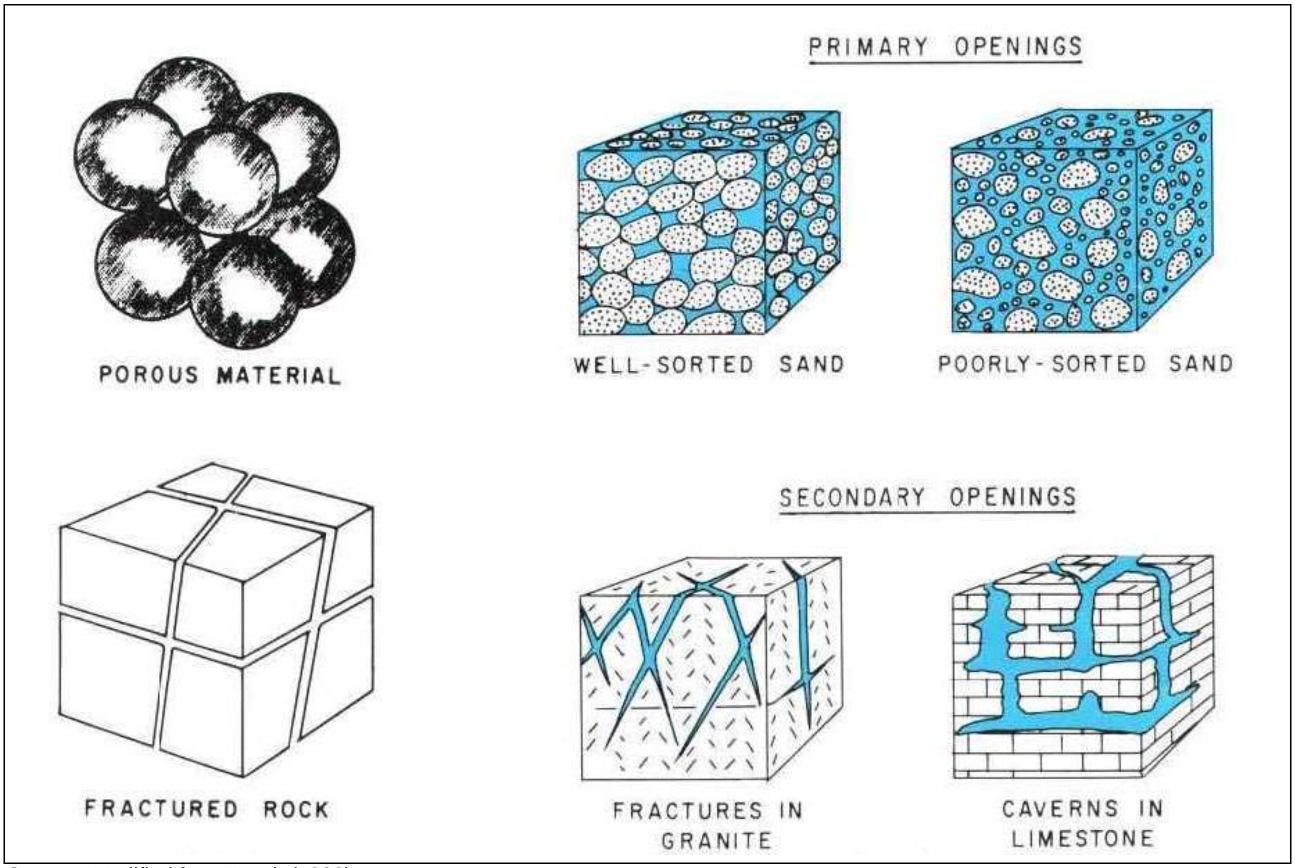
Groundwater flow directions and magnitudes are controlled, in large part, by the geologic framework. The primary regional aquifers in the flow systems consist of Paleozoic carbonate rocks, volcanic rocks (generally Tertiary ash-flow tuffs), and Miocene to Holocene basin-fill sediments. The primary regional confining zones 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. Attributes of the geologic framework that influence groundwater flow are described in the following section.

2.2 Geologic Controls Affecting the Movement of Groundwater

Several factors affect the movement of groundwater in the study area (Figure 2-3). Of these, porosity, permeability, and fractures/joints dominate and determine the rate and amount of flow in the principal aquifers. In basin filled-aquifers, overburden pressures have an undetermined affect on movement of groundwater through the saturated sediments, although permeability is presumed to decrease with depth due to the overburdened pressure.

Groundwater moves by two mechanisms, porous-media flow and fracture flow. Porous-media flow is often considered the primary mechanism of groundwater flow, and the most commonly applied analytical models to quantify the amounts and rates of flow are based on porous-media flow. While it is a significant, if not dominant, component of groundwater movement in many areas, fault-related fracture flow is of greater significance in the Basin and Range.

Fracture flow (also called fracture-dominated flow), in which groundwater moves along open fractures (secondary porosity/permeability) in rocks and sediments, predominates in the geologic study area because all rock units and sediments in the area are heavily faulted. The process of faulting creates not only faults of all sizes but also joints, which are fractures along which there has been no relative movement along the joint surface except for its opening perpendicular to the surface. Most groundwater movement may actually be along fault-caused joints. Joints that are formed by faults are generally oriented parallel to the fault that caused them. Most faults are basin-range, high-angle normal faults, which trend north or within 30 degrees of north and have an average dip at about 60 degrees. The location of faults is found by geologic mapping. Because faults are uneven in



Source: Modified from Heath (1983)

Figure 2-3
Schematic of Primary and Secondary Porosities/Permeabilities of Rock Matrices

their size and distribution across an area, groundwater movement along them is not uniform and therefore cannot be approximated by a formula. Therefore, predictions of flow volumes and rates from fracture flow correspondingly are more approximated than those from porous-media flow. Nonetheless, volumes and rates from fracture flow are considered to be significantly greater than those by porous-media flow. Most regional flow is by fracture flow. In the Basin and Range, fracture flow is especially important within brittle rock types, especially carbonates and ash-flow tuffs, although groundwater movement even in unconsolidated sediments appears to be enhanced and presumably increases in importance as sediments become progressively more consolidated (older). Movement of groundwater is enhanced by fracture flow even in confining zones.

2.2.1 Geologic Controls Affecting Primary and Secondary Porosities

2.2.1.1 Rock Lithology

Rock type partly determines whether groundwater flow will be along primary or secondary porosity. Rock type in turn depends upon the depositional environment, age, and degree of consolidation and brittleness of rock units.

Unconsolidated rocks, which are made up primarily of young (Quaternary) sediments of many depositional environments and exposed at and just beneath the surface, contain fewer fractures by virtue of not being through as many earthquakes (faulting events) as older rocks and not being able to fracture like consolidated rocks. When these unconsolidated deposits are made up of clastic material (that is, particles such as sand or gravel) from a depositional environment such as stream alluvium or multiple sand dunes, they form an aquifer through which fluids are more likely to move by porous-media flow. The younger, near-surface part of the basin-fill sediments in the geologic study area is in this category. Below one or two hundred feet, however, lower (older) basin-fill deposits are progressively more consolidated and therefore progressively more fractured. Yet in the Basin and Range, even young unconsolidated sediments have locally been extensively faulted, and enhanced flow by fractures results. If the unconsolidated deposits are fine-grained sediments such as silt or clay, from a depositional environment such as a flood plain, playa lake, or deep marine basin, they will form a confining unit that, lacking fractures, will not allow movement of measurable groundwater through it.

Consolidated rocks in the Basin and Range, including older parts of the basin fill, will fracture no matter their depositional environment. Consolidated clastic rocks deposited in many ancient depositional environments, as with unconsolidated rocks, are likely to form aquifers whereby some groundwater moves by porous-media flow but most moves by fracture flow. Some consolidated rocks are particularly brittle and therefore will fracture readily. These include carbonate rocks from both marine and lake environments. Marine carbonates, unlike lake carbonates, are thousands of feet thick and widespread in the Basin and Range province, resulting in the great Paleozoic carbonate aquifer in and beyond the geologic study area. Both ash-flow tuffs and basalt lava flows deposited on the surface in volcanic environments are similarly brittle and generally widespread in the Basin and Range province, but in the geologic study area tuffs are rarely more than 1,000 ft thick and basalt flows are either thin or absent.

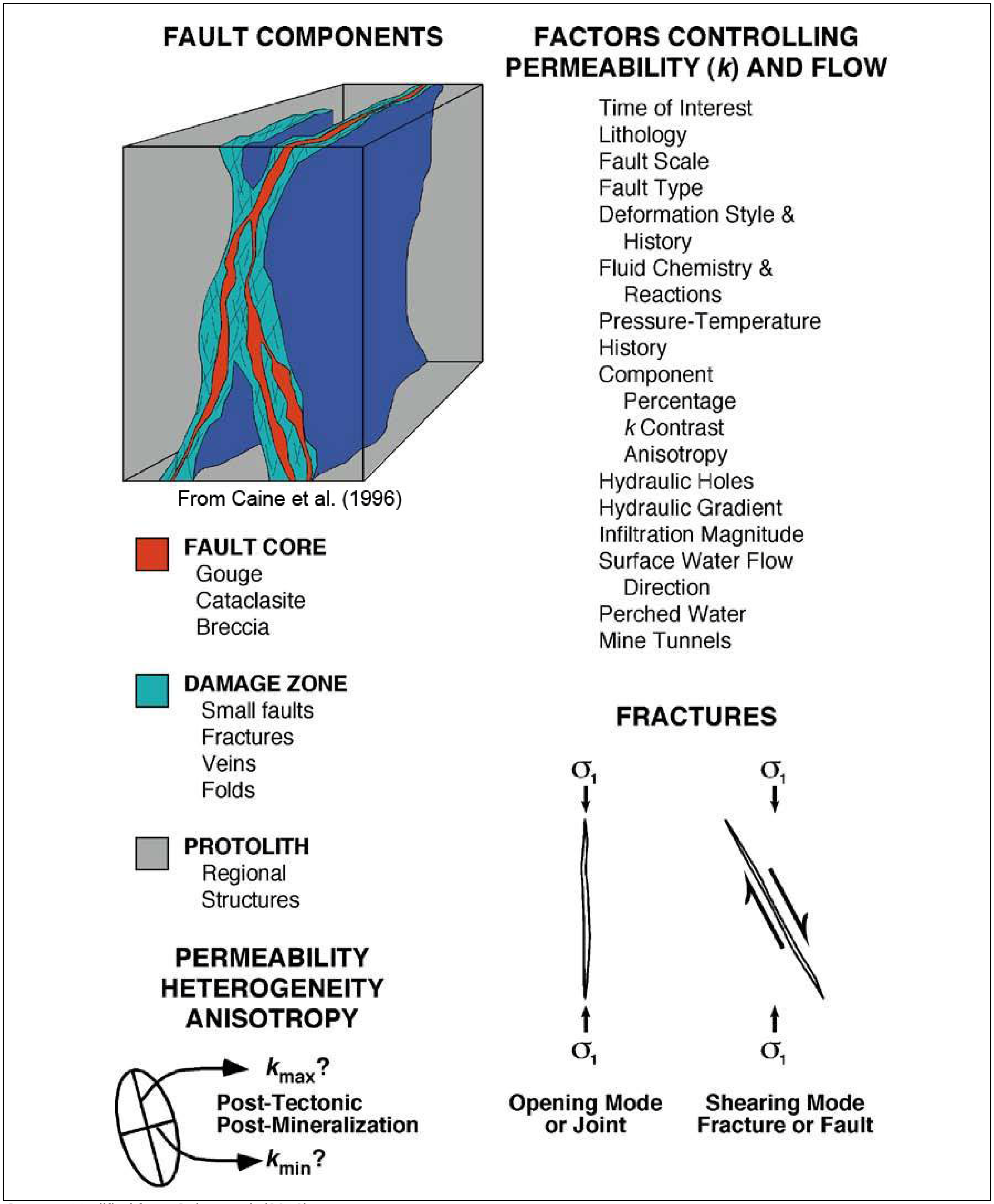
Many consolidated rocks have had their pores closed by heat and pressure (metamorphic and intrusive rocks) or by cementation of material in their pores (quartzite, which was formerly sandstone but now contains few remaining pore spaces). Other consolidated rocks, such as ancient marine shales, consist of clay minerals that are too fine-grained to allow groundwater through them. These consolidated rocks in the geologic study area are fractured but where thick, as with the Precambrian basement rocks and Neoproterozoic to Early Cambrian quartzites that underlie the entire area and the Mississippian Chainman Shale, are in most places confining units whether fractured or not. In some places, however, these rock types are cut by major fault zones that allow groundwater to move through them. Quartzite commonly is brittle and, where thin and sandwiched between aquifer rocks, may shatter like a plate of glass during basin-range faulting, resulting in a fracture-flow aquifer in its own right. The Eureka Quartzite of Ordovician age, which ranges between 600 and 800 ft thick through the geologic study area, is such a unit. Details of rock types and ages of rock units versus their properties as aquifers or confining units in the geologic study area are discussed in Sections 4.1 and 4.2.

2.2.1.2 Structural Controls

The main concept in understanding the movement of groundwater in the geologic study area is that groundwater flows through rock fractures with high-angle faults, in other words, fracture flow. With few exceptions, these faults are the basin-range normal faults associated with basin-range extension of the past 20 million years and that created the present topography of the Great Basin, as discussed in greater detail in Sections 4.1.5.2 and 4.3.2.4. Recognition, understanding, and documentation of this concept have increased for decades, motivated by fracture flow's important role in such topics as isolation of radioactive waste in underground repositories, groundwater transport of radionuclides, cleanup of toxic waste, exploitation of petroleum and geothermal reservoirs, and, of course, movement of groundwater (Haneberg et al., 1999; Faybishenko et al., 2005a and b). Unfortunately, many details in the physics and mathematics of fracture flow are unknown; therefore, only limited success has occurred in constructing mathematical models of fracture flow (Faybishenko et al., 2005b). One of the biggest problems has been that "numerical predictions often do not match field observation results" (Faybishenko et al., 2005a, p. vii). To resolve these issues, field and theoretical case studies have increased in number, especially in the last decade. These studies have been undertaken more commonly for fluid flow in jointed rocks (Faybishenko et al., 2005a) than in the more complicated case of in faulted rocks (e.g., Haneberg et al., 1999). To date, however, models based on the study of fracture flow have been conceptual, theoretical, and engineering-based.

Most of what we know about fracture flow began with U.S. Department of Energy-funded studies, primarily by the USGS, on the Nevada Test Site (NTS) so as to trace movement of contaminated groundwater resulting from hundreds of above- and below-ground nuclear tests (Winograd and Thordarson, 1968, 1975; Laczniak et al., 1996; Leahy and Lyttle, 1998; Rowley and Dixon, 2004). These studies began in the 1950s and resulted in publications on the geology, detailed geologic mapping of the entire NTS, and conclusions from well tests and other hydrologic data. The studies resulted in the discovery of the huge Death Valley regional groundwater flow system (Harrill et al., 1988; Laczniak et al., 1996; Harrill and Prudic, 1998; D'Agnese et al., 2002; Workman et al., 2002a and b; Belcher, 2004). In this flow system, recharge originated in the broad, high mountains of central Nevada, and flow terminated as spring discharge in Ash Meadows, Oasis Valley, and Death Valley. Among the scores of reports that resulted, the words structural "barriers" and "conduits" were introduced (Winograd and Thordarson, 1968, p. 35) to describe faults and other fractures that respectively create dams to flow across them and exhibit high transmissibilities along them.

The most useful studies specific to the conceptualization of the role of faults on flow were those of Caine et al. (1996) and Sibson (1996, 2000) because they dealt with the geology of fracture flow. These studies were done independently of each other. Sibson (1996, 2000) discussed shear mechanisms and large-volume movement of hydrothermal fluids along high-angle faults that result in hydrothermal ore deposits, whereas Caine et al. (1996) applied the work to groundwater flow. Caine et al. (1996) broke high-angle faults into (1) a central core zone (p. A-5 of Appendix A), which is generally of low permeability across it because of gouge and foliation in clay minerals formed along the axis of fault deformation, and (2) outer damage zones on each side of the core, which is likely to be of high permeability across and along them because they consist largely of joints and small faults that are generally parallel to the core zone (Figure 2-4). They pointed out that central core zones are in many places cut by synchronous or later faults and joints, so local flow is hardly unusual across them. Nonetheless, they found that faults generally tend to retard flow across (perpendicular to) them and provide conduits to flow laterally along (parallel to) them. Caine and Forster (1999) and Caine et al. (2010) expanded on these conclusions by adding more field examples and constructing computer models of faults and simulations of fluid flow in these models.



Source: Modified from Caine et al. (2010)

Figure 2-4
Conceptualization of Fault Components and Factors Controlling Permeability and Groundwater Flow

In the last decade, the literature on fracture flow and the role of faults as barriers and/or conduits has become voluminous, but it is beyond the scope of this report to summarize these conclusions. Brief summaries of some of this literature, however, are provided by Rowley and Dixon (2004) and Rowley et al. (2009). Perhaps more important, the authors have published several practical studies for water districts in or adjacent to the geologic study area that have used the concept of faults as barriers and conduits to site production water wells and well fields by drilling faults. For example, parts of the Mesquite basin were geologically mapped at 1:24,000 scale (Williams, 1996, 1997) for the Virgin Valley Water District, and all of the basin was mapped at 1:100,000 scale (Dixon and Katzer, 2002). The purpose of this mapping was to describe the geometry of basin-range faults that provide conduits for southward groundwater flow from the primary recharge area in the broad Clover Mountains north of the basin (Plates 1 and 2). Then Dixon and Katzer (2002) sited production water wells on faults in poorly consolidated basin-fill deposits (Muddy Creek Formation). Well yields of as much as 1,700 gpm and averaging 1,500 gpm were documented by Johnson et al. (2002). Later, a 1:250,000-scale geologic map of this and adjacent areas was prepared by Page et al. (2005a) to portray and discuss fracture-flow concepts of a large area that later became the southeastern parts of Plates 1 and 2.

Additional practical documentation of faults as conduits resulted in additional successful projects east of Mesquite, in Utah. Here, the groundwater resources of the Gunlock well field northwest of St. George were re-evaluated in terms of southward conduit flow along the north-trending Gunlock fault zone (Rowley, 2002; Rowley and Dixon, 2004). The study concluded that wells progressively closer to the Gunlock fault were progressively better producers (as much as 1,400 gpm) and that the well field had sufficient water for increased pumping by the city. High yields in several other well fields in the St. George area can be explained by basin-range faults that pass beneath the well fields, carrying groundwater from high-altitude recharge areas to the north (Biek et al., 2007). The Sand Hollow well field east of St. George, which was designed and constructed, and is managed, by Washington County Water Conservancy District (WCWCD), is artificially recharged by Sand Hollow Reservoir, which lies entirely on the aquifer, the Jurassic Navajo Sandstone. To site additional wells in the field, geologic mapping was done at 1:12,000 scale to find fault conduits in the area, then wells were proposed for WCWCD to drill (Rowley et al., 2004). The first of these drilled was tested at 2,500 gpm (Cram, pers. comm., 2006). The same concept of mapping and siting wells was done for the proposed WCWCD Anderson Junction Reservoir that will artificially recharge the Anderson Junction well field, along Interstate Highway I-15 (I-15) halfway between Cedar City and St. George (Rowley and Dixon, 2010).

For purposes of this report, Figure 2-5 provides a synopsis of whether flow of groundwater is enhanced or impeded by certain types of structures in the geologic study area. Classic basin-range normal faults, which trend mostly north and form during extension (pulling apart) in an east-west direction, provide conduits (enhanced flow) to groundwater flow north or south, assuming that the hydraulic gradient is in these directions, as is the case in virtually the entire geologic study area. Yet these same faults provide barriers (impeded flow) to groundwater flow to the east or west (see Section 4.3.2.4). Innumerable examples of likely conduits created by basin-range normal faults are mapped in the geologic study area (Plate 1), including the major bounding faults on the eastern and western sides of the four project basins. These same faults form likely full or partial barriers to flow east or west through the north-trending ranges and hills on either side of the basins that are defined by the faults.

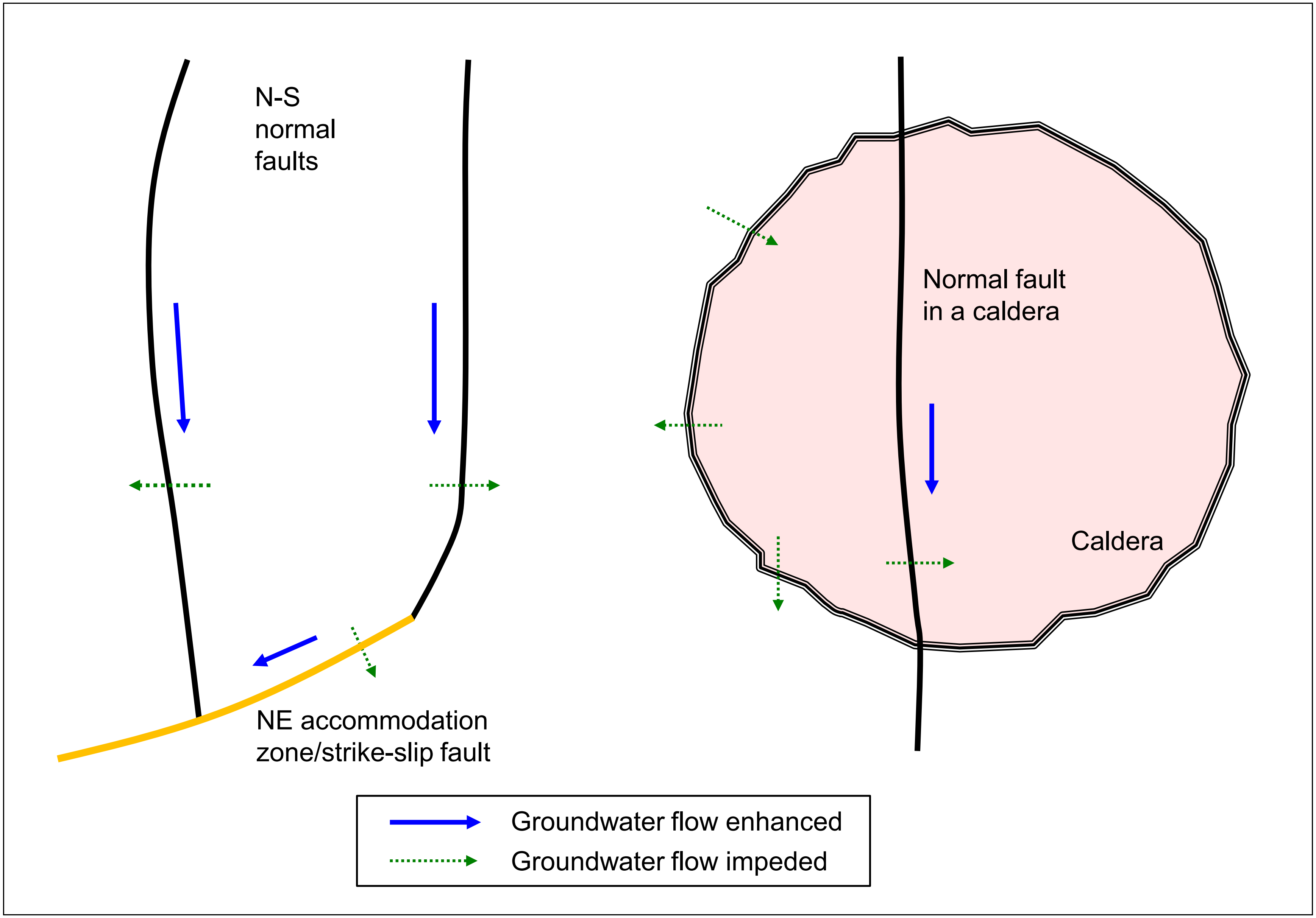


Figure 2-5
Map Showing Enhancement/Impedance of Groundwater Flow along or across Faults and Calderas

In some parts of the geologic study area, such as the Pahranagat Shear Zone (PSZ) at the southern end of Delamar and Pahranagat valleys (Sections 4.4.16 and 4.4.12; Figure 4-12), northeast- or north west-trending faults accommodate the east-west basin-range extension by strike-slip movement (see Section 4.3.2.4). For these accommodation zones, conduits are oriented northeast or northwest and barriers are oriented perpendicular to conduits (Figure 2-5).

Calderas are huge semi-circular collapsed areas above vents for ash-flow tuffs, which are the most voluminous Tertiary volcanic rock type in the Great Basin (see Sections 4.1.5.2 and 4.3.2.3). The semi-circular caldera margin and an aquitard of intrusions that underlies the caldera provide barriers to groundwater flow, except where the caldera is cut by normal faults (Figure 2-5). The caldera margins of the Indian Peak and Caliente caldera complexes are examples that are expected to provide barriers to flow through them, although the Indian Peak caldera complex is in turn truncated by large younger basin-range normal faults that allow northerly flow through its margin (Plate 1).

2.2.1.3 Width of Faults and its Relevance to Groundwater Flow

Faults of small displacement, width, and length can form significant lateral flow conduits along the hydraulic gradient, whether in consolidated or unconsolidated deposits. Faults of large displacement, width, and length can form still larger conduits, especially on the downthrown side, known as a hanging wall (Shipton and Cowie, 2001; Minor and Hudson, 2006). For these reasons, Plates 1 and 2 show regional (major) and subsidiary (smaller) faults, distinguished by geologic mapping based on their amount of offset and their fault length and width.

With respect to the influence of large faults on groundwater flow, what do we know about the width of faults in and near the geologic study area? The literature on the width of large faults in the Great Basin is limited because fault zones consist of broken, sheared, and altered rock that commonly can be disaggregated by one's hands, so the rocks in these fault zones are easily removed by erosion from view in the field. Nonetheless, several examples known to the authors can be given where exposures are especially good. West of the geologic study area, Dixon et al. (1972) mapped north-northeast-striking oblique-slip fault zones, each made up of a series of individually mapped, parallel faults of the same displacement, on either side of the Park Range, west of Little Smoky Valley, Nye County, Nevada; each zone was locally more than half a mile wide and more than 12 mi long. Not far away, along the west side of Hot Creek Valley, Nye County, Ekren et al. (1973) mapped a zone of range-front faults and parallel Quaternary faults of the same normal displacement just east of the range front that is as much as 2.5 mi wide and more than 10 mi long. The major north-northeast-trending oblique-slip Kane Springs Wash fault zone in Kane Springs Valley (Plates 1 and 2, east of the Delamar Range) is about 1.25 mi wide and many miles long (Swadley et al., 1994). The Grand Wash fault zone, a normal fault separating the Colorado Plateau from the Great Basin along the eastern side of Lake Mead, is shown by parallel north-trending bedrock and Quaternary faults at least 1 mi wide (Billingsley and Workman, 2000). Detailed, high-quality geophysics, including seismic and audiomagnetotellurics (AMT) profiles and also gravity and aeromagnetic anomalies, provides even better estimates of fault widths (see Section 5.0). These large faults are almost always shown as zones of disrupted beds and blocks, commonly several miles wide. Hundreds of examples could be cited.

Based on the authors' experience, the influence of faults on groundwater flow is proportional to the width of fault zones, and in turn the width of fault zones is proportional to the magnitude of displacement of fault zones. However, this generalization applies only to high-angle faults, and their influence on groundwater partly depends upon the type and age of the high-angle fault. High-angle normal faults, for example, form in an extensional stress regime (pulling apart, in an east-west direction for basin-range faults), so fractures tend to be more open. Strike-slip faults form during lateral shear so fractures may be tighter. Oblique-slip faults would have properties intermediate between normal and strike-slip faults. Transverse faults (Section 4.3.1) probably are akin to strike-slip faults so can be expected to be relatively tight to groundwater flow. In addition to these qualifiers to the general rules, the age of a fault influences how open its fractures are. An active (seismic) fault, such as many of the range-front faults in the geologic study area, breaks rocks—especially brittle rocks—with each fault movement, whereas an inactive fault, especially one that is pre-Miocene in age, may have been sealed or partly sealed by precipitation of minerals carried by groundwater. In other words, a Holocene fault can be expected to be especially transmissive to groundwater flow.

3.0 METHODOLOGY

The objectives of the geologic analysis and the methods applied in developing the products accompanying this report are described in the following sections. Work products developed as part of this analysis include 1:250,000-scale digital geologic maps (Plates 1 and 2), an explanation of map units (Plate 3), and cross sections (Plates 4 and 5). HGUs were derived by combining geologic stratigraphic units based on their hydraulic properties and spatial distribution as described in Volume 1 of SNWA (2008, Section 4.2, Table 4-1 p. 4-20). The digital geologic maps were then simplified accordingly to construct hydrogeologic maps (Plates 6 and 7) and cross sections (Plates 8 and 9). The geologic map area (red line, Figure 2-1) covers most of White Pine County and Lincoln County, Nevada, as well as large parts of adjacent counties in Nevada and Utah.

3.1 Objectives

The primary objective of this geological analysis was to develop a digital geologic and hydrogeologic framework to further our understanding of the hydrogeology of the study area and to serve as the foundation for developing conceptual and numerical models groundwater flow models of the Project Basins and adjacent areas. The geologic information provided data on the locations of potential boundary flow, extents of HGUs, basin geometries, and important geologic features comprising the framework that may affect local and/or regional groundwater flow. Some of these data were used to describe the geologic setting of selected regional springs, the descriptions of which are presented in Volume 3 of SNWA (2008). The geologic framework model also provides aquifer and aquitard thicknesses for the geologic study area. Geologic evaluations outside of the Project Basins (Figure 2-1) provided a basis for interpretations of groundwater interactions across the basin boundaries. This geologic analysis was manifested through the creation of geologic and hydrogeologic maps and cross sections of the study area.

The data compilation included the distribution, geometry, thickness, composition, and physical properties of geologic units used to define HGUs and potential aquifers and confining zones. Such information was considered 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 as described in Section 2.0 and presented in Figures 2-4 and 2-5. In the geologic study area, most faults trend northerly, parallel to the ranges. Thus, basin-range faults may serve as significant conduits to groundwater flow in the north-south direction. In other parts of the geologic study area, basin-range faults may either direct groundwater flow through a system of barriers and conduits, and/or impede groundwater flow, toward otherwise down-gradient groundwater basins. Part of the objective of this report was to evaluate the potential for these faults to influence groundwater flow, especially how they might act as either barriers or conduits to groundwater flow.

3.2 Technical Approach

The approach used in this investigation was to combine published and unpublished geologic information from dozens of references collected, compiled, and reviewed by the authors. In addition, an evaluation was conducted of borehole information from oil and gas test wells, monitor wells, such as those drilled during the U.S. Air Force's MX missile-siting program of the early 1980s, and borehole information from exploratory test wells and monitor wells constructed by SNWA in support of the Project. Other sources of information included geophysical studies of the region published by USGS and other entities, particularly data from gravity surveys performed by the USGS. These latter studies have given insight as to the framework geometry and thickness of basin fill and depth to underlying rocks within several basins in Lincoln and White Pine counties, Nevada. A final source of evidence is geologic field work performed by the authors of this report.

Based on the evaluation of the compiled data and the expertise of the authors involved in this investigation, geologic maps were constructed for the area (Plates 1 and 2). Geologic cross sections were constructed (Plates 4 and 5) from the geologic maps. Because of the complexity of the geology of eastern Nevada, these maps and cross sections represent a work in progress, inasmuch as new data on crosscutting faults, attitude of bedding surfaces, intrusions, volcanic sequences, and other geologic units and geologic relationships must be continuously evaluated as new information becomes available.

The geologic units were combined into HGUs of similar hydraulic properties and spatial extent. These broad units make up the aquifers, confining zones, and units of intermediate permeability of the area described by this report. These HGUs are displayed in Plates 6 and 7. Cross sections of these units were compiled using the geologic cross sections of Plates 4 and 5 as a basis; these hydrogeologic cross sections are displayed in Plates 8 and 9. Based on the hydrogeologic maps and cross sections, the extents of aquifers, confining zones, and intermediate-permeability rocks could be evaluated, along with potential fault barriers and fault conduits to groundwater flow. The hydrogeologic maps, cross sections, and hydrogeologic interpretations were used to compile the geologic framework model. The hydrogeologic maps and cross sections were also interpreted to evaluate probable groundwater flow paths and flow barriers.

3.3 Geologic Data Compilation

Geologic data were derived from a number of sources, including literature review, review of Nevada and Utah State Engineers' records, and well databases. Well data were obtained from well logs, databases associated with oil and gas test wells drilled within the geologic study area, and from records of exploratory test and monitor wells drilled by SNWA in upper Moapa, Coyote Spring, Delamar, Dry Lake, Cave, and Spring valleys. Not every well had geologic information, but most of them did have useful information to assist in compiling the geologic and hydrogeologic cross sections. As part of the data compilation, geologic experts who have worked within the study area were consulted and studies completed by the USGS were evaluated. This information was reviewed and compared with all other sources of geologic information prior to incorporation into the geologic maps and cross sections.

3.4 Preparation of Geologic Maps and Sections

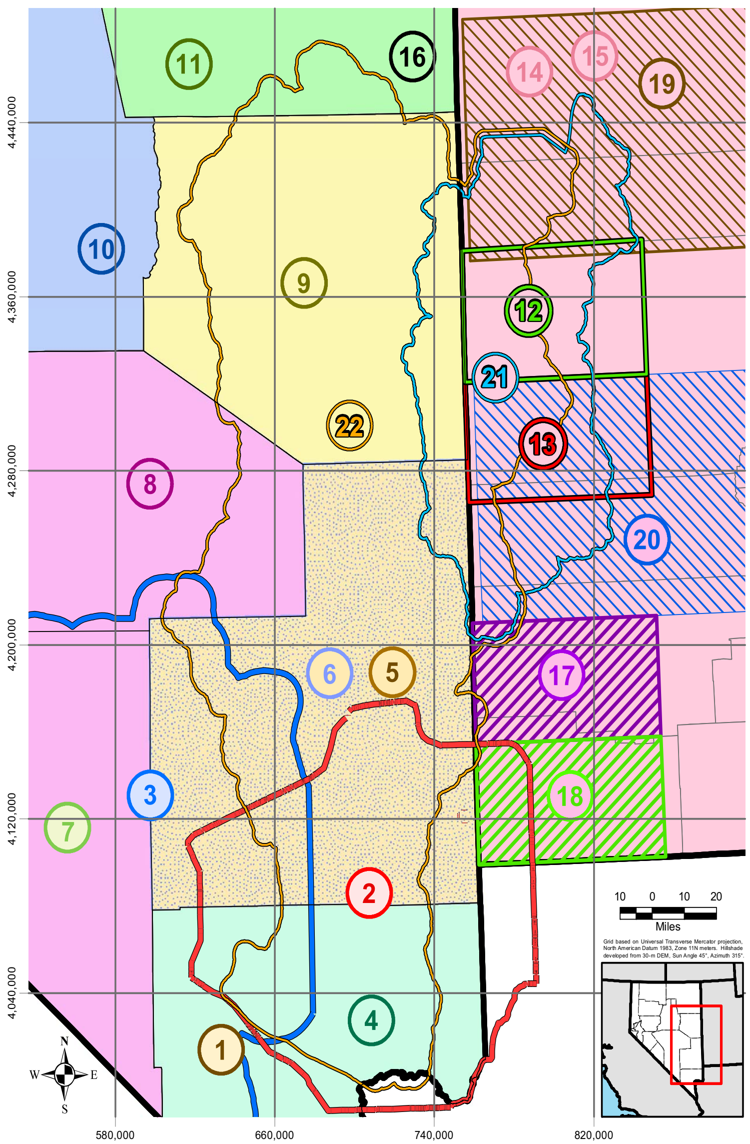
The geology of the southern part of the study area (Figure 3-1) has been discussed by Page et al. (2005a). In this report the geology for this area was digitally mapped at 1:250,000 scale (Plate 2). To the west of this area, digital geologic and tectonic maps were also published at a 1:250,000 scale (Workman et al., 2002a and b), and include some of the southwestern portions of Plates 1 and 2. These geologic maps included significant new and unpublished geologic mapping.

For the maps (Plates 1 and 2), much of the Nevada surface geology was compiled from county 1:250,000-scale geologic maps and the Nevada 1:500,000-scale state geologic map (Stewart and Carlson, 1978). From west to east and north to south, the Nevada counties covered by these maps are southern Elko County (Roberts et al., 1967), eastern Nye County (Cornwall, 1972; Kleinhampl and Ziony, 1985), White Pine County (Hose and Blake, 1976), Lincoln County (Tschanz and Pampeyan, 1970), and Clark County (Longwell et al., 1965). Most of the Utah surface geology was compiled from four 1:100,000-scale maps (Hintze and Davis, 2002a and b; Rowley et al., 2006 and 2008; Biek et al., 2007), two 1:250,000-scale maps (Morris, 1987; Steven et al., 1990), and the Utah 1:500,000-scale state geologic map (Hintze, 1980a). Summary reports on the geology of Millard County (Hintze and Davis, 2003) and the geology of Utah (Hintze, 2005; Hintze and Kowallis, 2009) were also valuable. Both the Nevada and Utah state geologic maps were digitized and re-released as digital files, but not updated with respect to maps and reports published since 1978 and 1980, respectively, by Hess and Johnson (1997), Raines et al. (2003), and Crafford (2007) for Nevada and as Hintze et al. (2000) for Utah.

Nearly all of the regional geologic maps (Figure 3-1) were published decades ago. A significant part of the entire map area was compiled by Terrascan Group, Inc. (Howard, 1978), but it compiled the same county maps without updating them. As part of the USGS Basin and Range carbonate-rock aquifer system study (BARCASS), Sweetkind et al. (2007a) compiled a 1:500,000-scale, digital geologic map of a large area that includes all but the eastern edge of the area of Plate 1. However, their map was compiled from Stewart and Carlson (1978), Hintze (1980a), Hintze et al. (2000), and Raines et al. (2003), from which all faults were removed. To that file, Sweetkind et al. (2007a) added some gravity interpretations, some dotted “geophysically determined faults,” and some sketched faults. Two diagrammatic cross sections accompanied this map, but neither matched the topography, geology, or geophysics of their map.

The plates and text of this report incorporate all known revisions and reinterpretations of previously published reports and geologic maps that were deemed necessary. Small-scale geologic maps used in the creation of Plates 1 and 2 are indexed in Figure 3-1. Commonly, new maps and reports were more detailed (published at larger scale). Not all of these maps and reports are cited in the text because of their large number, although all of them are listed in Section 8.0. In addition, Plates 1 and 2 include some new, unpublished field observations and geologic mapping.

The geologic and hydrogeologic maps and sections and the explanation of geologic units of this study area (Plates 1 through 9) cover an area of about 25,000 mi^2. The compilation of the geologic maps of



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' × 60' quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, 55 p., scale 1:100,000.
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., 2002, Geologic map of the Death Valley ground water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies MF-2381-A, scale 1:250,000. Digital GIS data provided.
4. Longwell, C.R., Pampeyan, E.H., Bowyer, B., 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, 187 p., scale 1:250,000.
6. Ekren, E.B., Orkild, P.P., Sargent, K.A., and Dixon, G.L., 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1041, scale 1:250,000.
7. Cornwall, H.R., 1972, Geology and mineral deposits of southern Nye County, Nevada: Nevada Bureau of Mines and Geology Bulletin 77, 49 p., scale 1:250,000.
8. Kleinhampl, F.J., and Ziony, J.I., 1985, Geology of northern Nye County, Nevada: Nevada Bureau of Mines and Geology Bulletin 99A, 172 p., scale 1:250,000.
9. Hose, R.K., and Blake, Jr., M.C., 1976, Geology and mineral resources of White Pine County, Nevada, Part 1, Geology: Nevada Bureau of Mines and Geology Bulletin 85, p. 1-35., scale 1:250,000.
10. Roberts, R.J., Montgomery, K.M., and Lehner, R.E., 1967, Geology and mineral resources of Eureka County, Nevada: Nevada Bureau of Mines and Geology Bulletin 64, 152 p., scale 1:250,000.
11. Coats, R.R., 1987, Geology of Elko County, Nevada: Nevada Bureau of Mines and Geology Bulletin 101, 112 p., scale 1:250,000.
12. Hintze, L.F., and Davis, F.D., 2002, Geologic map of the Tule Valley 30' × 60' quadrangle and parts of the Ely, Fish Springs, and Kern Mountains 30' × 60' quadrangles, northwest Millard County, Utah: Utah Geological Survey Map 186, scale 1:100,000.
13. Hintze, L.F., and Davis, F.D., 2002, Geologic map of the Wah Wah Mountains North 30' × 60' quadrangle and part of the Garrison 30' × 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., and Brown, K.D., 2000, Digital Geologic Map of Utah, Utah Geological Survey Map 179DM, scale 1:500,000.
15. Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineralogical Survey, scale 1:500,000.
16. Hess, R.H., and Johnson, G.L., 1997, Nevada Bureau of Mines and Geology County Digital Mapping Project, Open File report 97-1, Nevada Bureau of Mines and Geology, scale 1:250,000. These data were digitized from the county Geology and Mineral Resource Bulletins published by the NBMG. Digital products cover Clark, Lincoln, White Pine, Southern Nye, Northern Nye, Elko and Eureka counties.
17. Rowley, P.D., Williams, V.S., Vice, G.S., Maxwell, D.J., Hacker, D.B., Snee, L.E., and Mackin, J.H., 2006, Interim geologic map of the Cedar City 30' × 60' quadrangle, Iron and Washington Counties, Utah: Utah Geological Survey Open-File Report 476DM, scale 1:100,000. Rowley, P.D., Hacker, D.B., Maxwell, D.J., Maxwell, J.D, and Boswell, J.T., 2008, Interim geologic map of the Utah part of the Deer Lodge Canyon, Prohibition Flat, Uvada, and Pine Park quadrangles (east part of the Caliente 30' × 60' quadrangle), Iron and Washington Counties, Utah: Utah Geological Survey Open-File Report 530, scale 1:24,000.
18. Biek, R.F., Rowley, P.D., Hacker, D.B., Hayden, J.M., Willis, G.C., Hintze, L.F., Anderson, R.E., and Brown, K.D., 2007, Geologic map of the St. George and east part of the Clover Mountains 30' × 60' quadrangles, Washington and Iron Counties, Utah: Utah Geological Survey Map 242, scale 1:100,000.
19. Morris, H.T., 1987, Preliminary geologic map of the Delta 2° quadrangle, Tooele, Juab, Millard, and Utah Counties, Utah: U.S. Geological Survey Open-File Report 87-185, scale 1:250,000.
20. Steven, T.A., Morris, H.T., and Rowley, P.D., 1990, Geologic map of the Richfield 1° × 2° quadrangle, west-central Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1901, scale 1:250,000.
21. Rowley, P.D., Dixon, G.L., Burns, A.G., and Collins, C.A., 2009, Geology and hydrogeology of the Snake Valley area, western Utah and eastern Nevada, *in* Tripp, B.T., Krahulec, Ken, and Jordan, J.L., eds., Geology and geologic resources and issues of western Utah: Utah Geological Association Publication 38, CD, p. 251-269 + Plate 1 (scale 1;250,000).
22. This study and Dixon, G.L, Rowley, P.D., Burns, A.G., Watrus, J.M., and Donovan, D.J., Ekren, E.B., 2007, Geology of White Pine and Lincoln Counties and adjacent areas, Nevada and Utah—The geologic framework of regional groundwater flow systems: Southern Nevada Water Authority, Las Vegas, Nevada, Doc. No. HAM-ED-0001, variously paginated, scale 1:250,000.

Figure 3-1
Previous Large-Scale Mapping Used to Evaluate Geology and to Create the Geologic and Hydrogeologic Maps of Plates 1 and 2

Plates 1 and 2 required many name changes to specific geologic units throughout this large geologic study area. Map scale required some lumping of units with others. New names or new correlations required other changes. In many places, facies changes resulted in major changes in the lithology of a specific unit, and in other places, different formation names were used essentially for the same unit. In some instances, 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 the north, as in White Pine County (Hose and Blake, 1976), but a generally inconsequential shale horizon included within other units in the southern map area, as in Clark County (Longwell et al., 1965). 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 and these correlations were generally 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 Limestones (Hose and Blake, 1976).

During map compilation, a hard copy of the available digital file—generally the county map—was modified by hand, then digitized. Before this compilation, all available new geologic data about the area were accumulated, assimilated, and evaluated. The new data included reports, different concepts, detailed or regional maps, geophysics, and well logs. Some new interpretations conflicted with old interpretations, necessarily resulting in different placement of contacts and faults. Decisions on the eventual linework were based on what appeared to be scientifically the most reasonable alternative and depended primarily on the judgement and experience of the authors.

The maps (Plates 1 and 2) include 25 new geologic cross sections (Plates 4 and 5), most of which generally trend east-west. In addition, geologic cross sections were drawn through many springs in the geologic study area (Volume 3 of SNWA, 2008). The cross sections on Plates 4 and 5 are roughly evenly spaced across the map area at the same scale as the map and at locations chosen to best show specific geologic and structural relationships important to the interpretation of the hydrogeology. In addition, hydrogeologic maps (Plates 6 and 7) and hydrogeologic cross sections (Plates 8 and 9) were constructed, where geologic units with similar hydrologic properties such as porosity and permeability were combined into HGUs, 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 areas. A geologic map by Terrascan Group, Inc. (Howard, 1978) presented associated cross sections that were used to help interpret some of the cross sections in this report. In addition, the geologic map of Elko County (Coats, 1987) was used to help interpret Cross Section Y—Y' (Plate 4), along the northern edge of the map area. The cross sections of Page et al. (2006) aided in constructing the cross sections in the southern part of the geologic study area. The cross section of Smith et al. (1991) was useful in constructing Cross Section X—X' (Plate 4) near the northern margin of the geologic study area.

Unlike compilation of the geologic map, most cross sections are newly authored for this report. The first step in the construction of cross sections is to satisfy the three-dimensional geometry of the rocks at depth based on the types, attitudes, and thicknesses of rocks and structures on the surface. The most difficult part of making cross sections is dealing with the near absence of subsurface information. Therefore, geophysics and well logs near the line of section are valuable. Fortunately, aeromagnetic and gravity geophysical data were available for much of the area. Unfortunately, well logs, AMT profiles, and seismic profiles are rare. Where local information on the third dimension is not available, analogies are made with areas in other parts of the Great Basin where seismic and drill-log data provide ideas about how the rocks and structures look at depth. And here, as in compilation of geologic maps, the judgment and experience of the authors are of paramount importance.

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 in Nevada from 1907 through 1988. This compilation was supplemented by 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; Alam, 1990; Alam and Pilger, 1991), were used to aid in the interpretation of geologic cross sections and structure sections. Gravity maps and AMT profiles were completed by USGS as part of USGS/SNWA joint funding agreements (Mankinen et al., 2006, 2007, and 2008; McPhee et al., 2005, 2006a and b, 2007, 2008, and 2009; Mankinen and McKee, 2009 and 2011; Scheirer, 2005; Scheirer et al., 2006). The gravity data were converted to depth-to-basement data and were used to aid in constructing the cross sections.

A technical review of the entire text and plates was done by M.A. Kuntz, Emeritus Geologist of the USGS, Denver, Colorado. At least 90 percent of his suggestions were accepted by the authors. This resulted in many improvements to the text and plates.

4.0 GEOLOGY AND HYDROGEOLOGY

4.1 Geology and Stratigraphy

4.1.1 Overview

The geology of the geologic study area (Figure 2-1, Plates 1 and 2) 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:

- 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 and 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.

In Eocene to middle 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 tuffs. The caldera margins formed new groundwater flow paths 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 graben and horst 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. But more commonly, basin-range faults provide conduits to groundwater flow, especially from north to south. These north-south conduits may also double as barriers to east or west flow.

The age of the rocks in the geologic study area is summarized in a Geologic Time Scale chart (Figure 4-1). The oldest rocks are Early Proterozoic (Paleoproterozoic) and Late Proterozoic (Neoproterozoic) 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 Neoproterozoic age. The Proterozoic rocks pass conformably upward into rocks of similar type and thickness, though less metamorphosed, that are Neoproterozoic 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 geologic 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, in and northwest of the geologic 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 geologic study area are largely nonmarine clastic rocks, thin where deposited and in most places they have been removed by erosion. Mesozoic and older rocks were deformed during the Sevier deformational event. At this time, the geologic 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 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 geologic study area.

Middle Tertiary (Eocene to middle Miocene) time marked the continuation of calc-alkaline intrusion and resulting volcanism, the terminal product of relatively rapid subduction beneath western North America that began in the Triassic Period (Atwater, 1970; Lipman et al., 1972; Hamilton, 1995; Schellart et al., 2010). 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 at least several thousand feet 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; outflow ash-flow tuffs, on the other hand, traveled as far as 100 mi from their source caldera, so accumulated to aggregate thicknesses exceeding 1,000 ft in most of the geologic study area.

Starting at about 20 Ma ago (middle Miocene), subduction ceased or slowed and extensional deformation increased in the Great Basin (Christiansen and Lipman, 1972; Christiansen and Yeats, 1992; Rowley and Dixon, 2001; Schellart et al., 2010). Basin-range deformation, characterized by

ERA	PERIOD	EPOCH	TIME	PROCESSES AND ROCK TYPES
Cenozoic	Quaternary	Holocene	Present	Valley-Fill Alluvium
		Pleistocene	2.6 Ma	
	Tertiary	Pliocene	5.3 *Ma*	Start Basin-Range Faulting (20 Ma) Volcanics and Older Sediments Emplacement of Calderas
		Miocene	23 *Ma*	
		Oligocene	33.9 *Ma*	
		Eocene	55.8 *Ma*	
		Paleocene	65.5 Ma	
Mesozoic	Cretaceous			Sevier Orogeny, Intrusions Continental Sediments
	Jurassic			
	Triassic		251 Ma	
Paleozoic	Permian			Antler Orogeny, Intrusions Chainman Shale, Carbonates
	Pennsylvanian			
	Mississippian			
	Devonian			
	Silurian			
	Ordovician			
	Cambrian		542 Ma	Quartzite and Shale
Precambrian			~4.5 Ga	

Source: Adapted from GSA (1999)

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

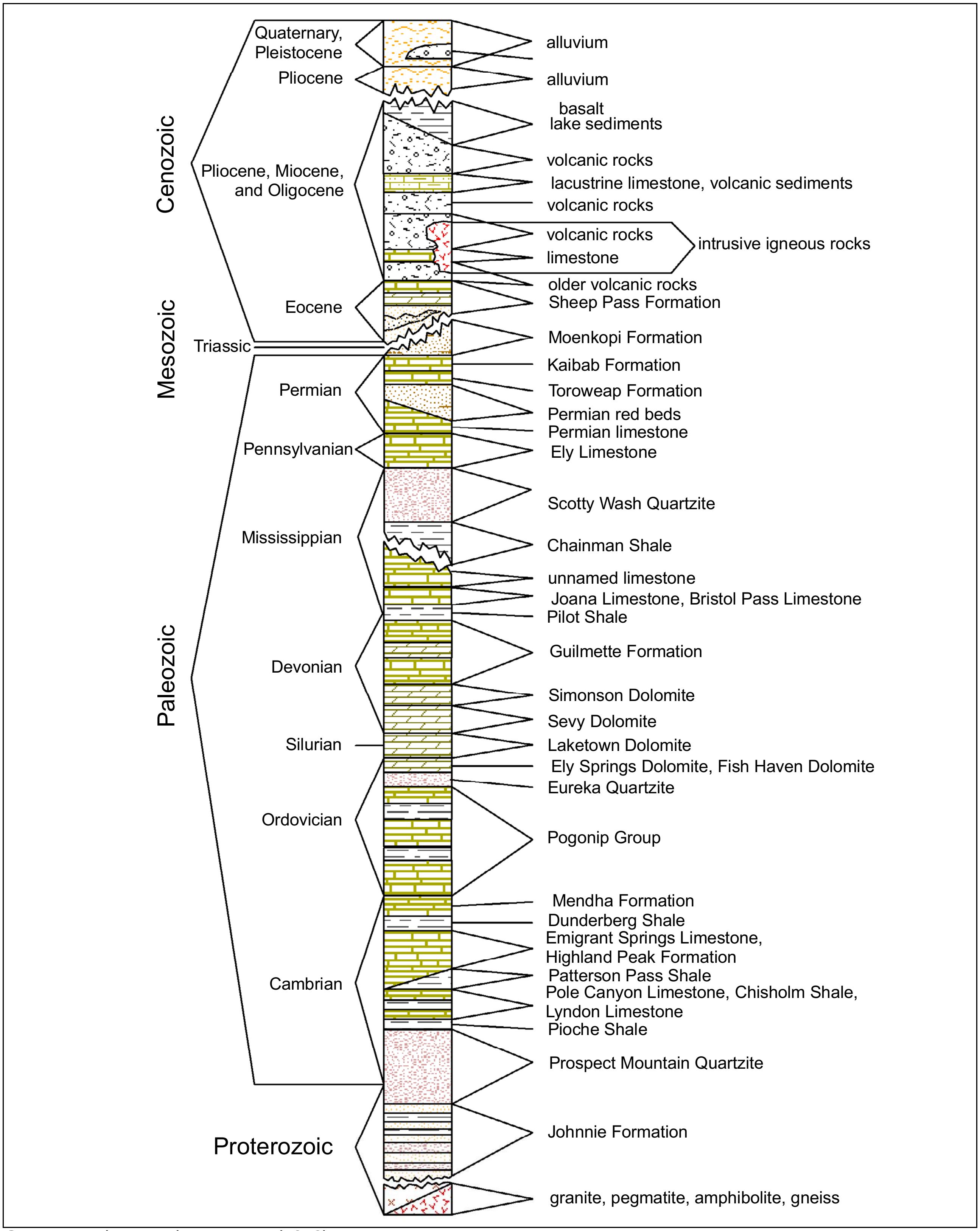
vertical (normal) faulting, began to form alternating mountain ranges and valley basins. The main pulse of this basin-range faulting began about 10 Ma ago, during which time the present topography formed. As valleys formed, they were filled by debris eroded from the adjacent mountain ranges, creating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

Individual rock units, structures, basins, and ranges are described in the following sections. 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 (Figure 4-2), White Pine (Figure 4-3), and Clark counties (Figure 4-5), Nevada, and western Utah (Figure 4-4). The Utah area consists of western Iron, Beaver, and Millard counties and the southwestern corner of Juab County.

4.1.2 Proterozoic Rocks

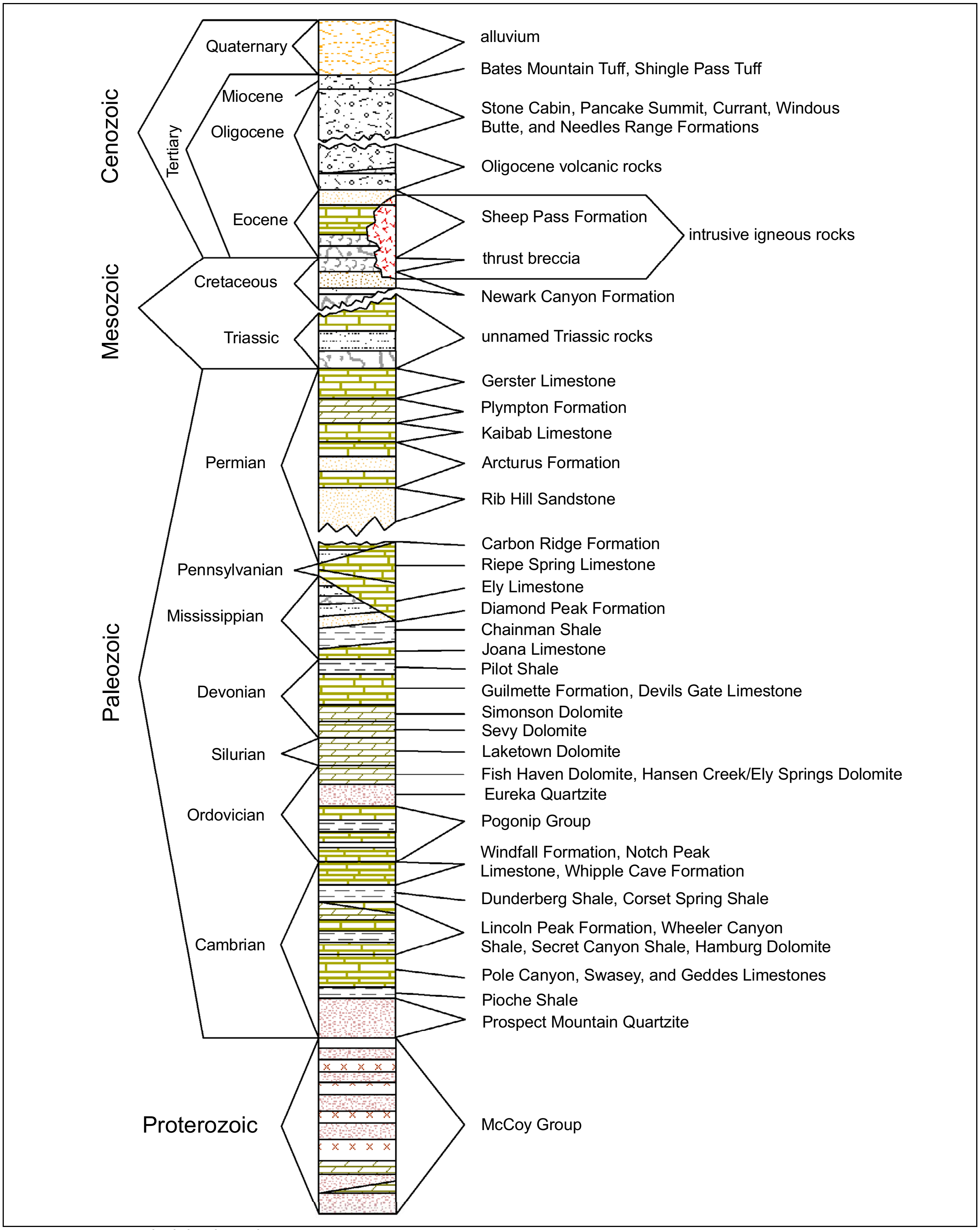
The oldest rocks are in and adjacent to the southern part of the geologic study area in the Beaver Dam Mountains, Mormon Mountains, Virgin Mountains, northeastern Spring Mountains, and the Desert Range (Plate 2) (Tschanz and Pampeyan, 1970; Longwell et al., 1965). These rocks are crystalline metamorphic rocks of Paleoproterozoic age (Page et al., 2005a) that have been mapped in this report as Precambrian rocks (p€). Over most of the geologic study area, however, the oldest rocks are Neoproterozoic to Lower Cambrian quartzite. These Neoproterozoic to Cambrian units 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, 1974; Stewart, 1976).

In White Pine County and adjacent Utah, the principal Neoproterozoic 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 Neoproterozoic age and similar in appearance. The Trout Creek Group is estimated at 11,600 ft thick (Hintze and Kowallis, 2009) 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 Neoproterozoic. The McCoy Creek and Trout Creek units are mapped in the geologic study area as Precambrian rocks (p€).



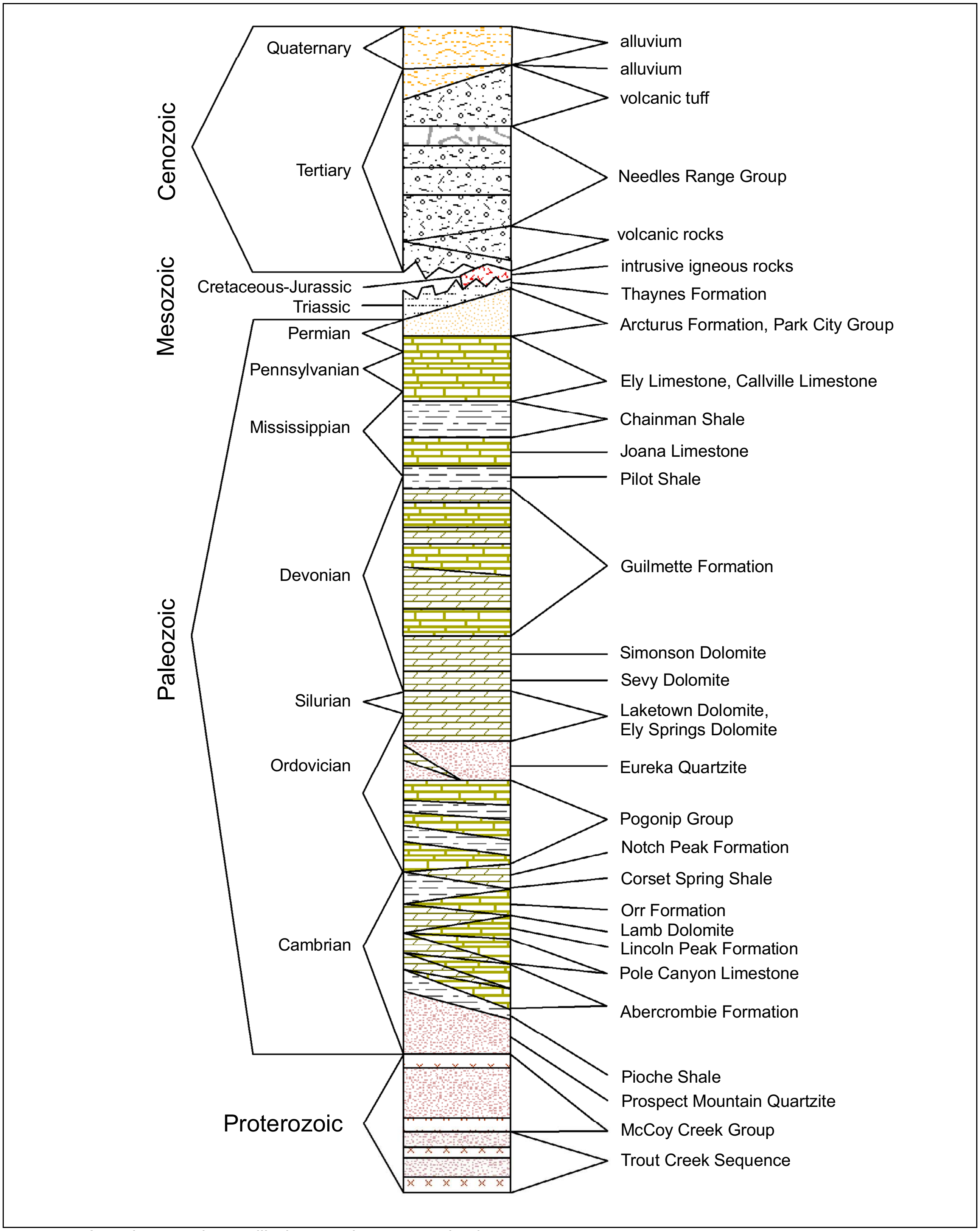
Source: Tschanz and Pampeyan (1970)

Figure 4-2
Geologic Units of Lincoln County, Nevada



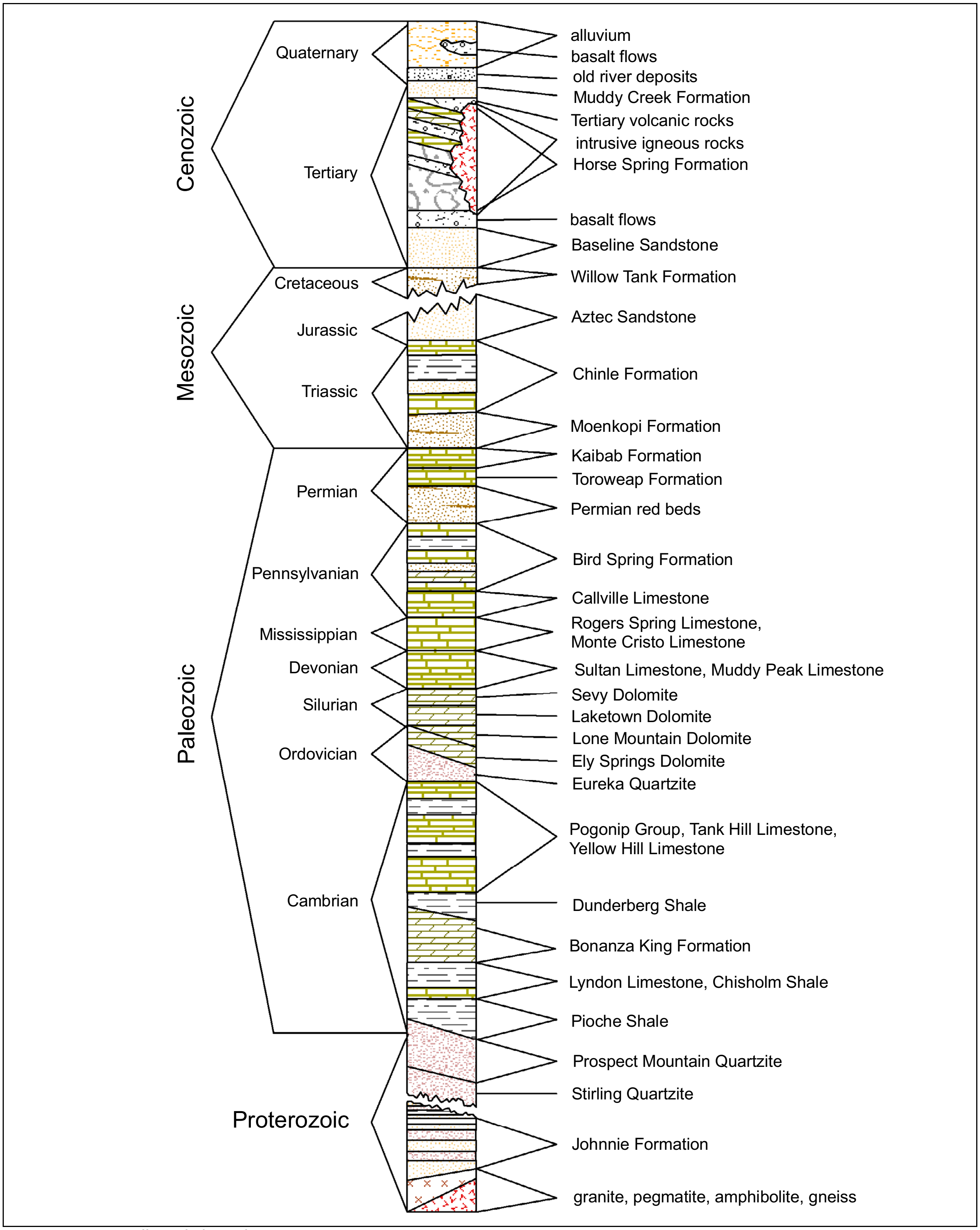
Source: Hose and Blake (1976)

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



Source: after Hintze and Kowallis (2009, Charts 45 and 46)

Figure 4-4
Geologic Units of Western Utah



Source: Longwell et al. (1965)

Figure 4-5
Geologic Units of Clark County, Nevada

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 in the southern part of the geologic study area is partly Neoproterozoic. In the study area, complete sections are uncommon, but the unit ranges from 3,000 to nearly 8,000 ft thick (Tschanz and Pampeyan, 1970). Thickness decreases southward to just a few hundred feet in the Mormon Mountains. The Prospect Mountain Quartzite in the southern half of the geologic study area is correlated with three units mapped in and west of the southern part of the geologic study area: the Stirling Quartzite (Neoproterozoic and Early Cambrian), the Wood Canyon Formation (Early Cambrian), and the Zabriskie Quartzite (Early Cambrian) (Stewart, 1970, 1974, and 1984; Rowley et al., 1994).

In the southern part of the geologic study area, the Stirling Quartzite is at least 2,000 ft thick and the base is not exposed. Link et al. (1993) considered the Stirling Quartzite to postdate the Neoproterozoic McCoy Creek Group. In the Desert Range and above the Gass Peak thrust in the Las Vegas Range, the Wood Canyon Formation, a quartzite, is 1,000 to 3,000 ft thick.

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 €p€s in White Pine County. These rocks are partly correlative with the Carrara Formation at the NTS and in portions of Clark County.

Cambrian carbonate rocks range in thickness from almost 5,000 ft over most of the geologic study area to about 7,500 ft just southwest of the study area. The map unit is mostly middle Cambrian labeled €m. In the southern half of the geologic study 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 about 4,500 ft thick (Tschanz and Pampeyan, 1970). To the west, in the Groom mining district, it is 5,400 ft thick.

In the northern part of the geologic study area, the Cambrian carbonate rocks consist of many named units of generally similar lithology, total thickness, and age (Hose and Blake, 1976). Just to the northwest, in the Eureka area, these were originally named, from base to top, the Eldorado Dolomite, the Geddes Limestone, the Secret Canyon Shale, and the Hamburg Dolomite (Roberts et al., 1967). 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 geologic study area and areas to the west. In the Cherry Creek Mountains and extending into western 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 Middle Cambrian carbonate sequence is roughly equivalent to the Bonanza King Formation to the south (Longwell et al., 1965). See Figures 4-2 to 4-5 for geologic sections in different areas of the map.

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 (Ꞓu); in some cross sections, the map unit is combined with Ꞓm as Cambrian carbonate rocks, undivided (Ꞓc). In White Pine County and in Utah, the Ꞓu 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 geologic study area, the Ꞓu limestone unit is the Nopah Limestone. See Figures 4-2 to 4-5 for geologic sections. The Dunderberg Shale generally is about 300 ft thick over most of the geologic study area, but it is as much as 1,400 ft thick in the southern Ruby Mountains (Hose and Blake, 1976). The overlying limestone ranges in thickness from 400 to 4,000 ft, generally being thickest on the western side of the geologic study area (Tschanz and Pampeyan, 1970).

4.1.3.2 Ordovician to Devonian Rocks

The Ordovician to Silurian parts of the rock column in the geologic study 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 geologic study 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 Quartzite is a major marker bed throughout most of the geologic study area (Plates 1 and 2). Just northwest of the geologic study 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 mostly a 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 equivalent in age to, the Lone Mountain Formation, a unit with reef 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 Formation is a western facies of 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 geologic study area have been mapped as, in ascending order, the Sevy Dolomite, Simonson Dolomite, and Guilmette Formation, all of which formed on a shallow-water marine carbonate platform. Where combined, they are mapped as Devonian rocks, undivided (Du) or, when local Silurian rocks are included, as Devonian and Silurian sedimentary rocks, undivided (DS). In the southern part of the geologic 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 Sevy and Simonson Dolomites (Ds) and Guilmette Formation (Dg). Sandberg et al. (1997) redefined the upper part of the Simonson Dolomite in Nevada, or the lower part of the Guilmette Formation in Utah (Hintze and Kowallis, 2009), as the Fox Mountain Formation. 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 geologic study area from about 450 ft in the Snake Range to 1,300 ft in the Limestone Hills and southward (Tschanz and Pampeyan, 1970). This thickness decreases south of the Pahranagat Range, and the unit disappears south of the Delamar Mountains. The Simonson Dolomite is resistant, dark- and light-gray dolomite about 900 to 1,200 ft thick over most of the geologic study 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 were locally reduced in thickness by faulting. The Fox Mountain Formation consists of thin (generally 100 to 150 ft), gray limestone except for dolomite in its upper part.

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). The middle part of the Guilmette Formation consists of the Alamo Breccia Member, which is as thick as 300 ft northwest of Alamo, Nevada. It was formed by the cataclysmic Alamo bolide impact event (Warme et al., 2008). 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). The Sultan Limestone is equivalent to the Muddy Peak Limestone in the Muddy Mountains.

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 clastic 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 resulted in the Antler Highland located along the western side and northwest of the geologic study 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 and 8). Where these four units are thin, they are categorized 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. In the Muddy Mountains, the Mississippian Rogers Spring Limestone has a similar lithology and is considered to be equivalent in age to the Monte Cristo (Longwell et al., 1965). The general equivalent of the Chainman Shale southwest of the geologic study area is the Eleana Formation (Mississippian and Upper Devonian), which is several thousand feet thick (Workman et al., 2002a). 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), Ochre Mountain Limestone (Utah), and West Range Limestone (Upper Devonian) in northern Lincoln County, Nevada.

The Upper Mississippian Chainman Shale is a soft, black, impermeable shale that is between 200 and 2,000 ft thick. This unit is mapped as unit Mc over the northern part of the geologic study area, but the Chainman is thin in the southern part of the geologic study area and here is included within a sequence of more permeable carbonate rocks. It is a regional confining unit (called the “upper aquitard”) separating the lower carbonate aquifer from the upper carbonate aquifer over all except the southern part of the geologic study area. Paleotopography during deposition and post-depositional erosion resulted in substantial variations in Chainman thickness. The unit was mapped (Hintze and Davis, 2002a) 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.

In the northwestern part of the geologic study 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 generally included in the upper aquitard with Chainman. The Diamond Peak is generally equivalent to the Scotty Wash Quartzite in the southern part of the geologic study 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 geologic 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 (ℙ). In the Utah part of the geologic study 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 geologic study area and the Callville Limestone in the southern and eastern part of the geologic 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 geologic study area, they are shown as Permian and Pennsylvanian rocks, undivided (Pℙ). The rocks in the Pℙ unit are unnamed in Lincoln County and range from 3,500 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 geologic study area as Pc, or where thinner is included within the Pℙ map unit.

The Bird Spring Formation is an Upper Mississippian to Lower Permian limestone in the southern part of the geologic study area that is roughly equivalent in age 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 a sequence of limestone beds with sandstone and dolomitic limestone layers. The formation is as much as 8,000 ft thick in the Spring Mountains and Las Vegas Range (Page et al., 2005b) and at least 5,400 ft thick in the Meadow Valley Mountains (Pampeyan, 1993). The Bird Spring is included in the Pℙ map unit, as is the Brock Canyon Formation in the northwestern part of the geologic study area and the Oquirrh Group (Lower Permian and Pennsylvanian) in the northeastern part of the geologic study area.

The Lower Permian Rib Hill Sandstone (Pr) overlies the Carbon Ridge Formation in the northwestern part of the geologic study 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 the name for a sequence of poorly resistant, gray limestone, sandstone, and siltstone that is 2,700 to 3,400 ft thick (Hose and Blake, 1976). In the northwestern part of the geologic study 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. In the southern part of the geologic study area, the Par map unit includes a redbed sequence, and in the southeastern part of the map, the map unit includes the Queantoweap Sandstone.

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 suggests that the unit was originally fairly extensive in the geologic study area but has been partly removed by erosion over most of 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 geologic study 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. The Kaibab Limestone and Toroweap Formation in Clark County have a maximum combined thickness of 1,300 ft in the Muddy Mountains (Bohannon, 1983). In Clark County, their lithology is dominated by cherty limestone, sandstone, and red shale, with local gypsum beds (Bohannon, 1983; Page et al., 2005b).

4.1.4 Mesozoic Rocks

Mesozoic rocks were deposited locally or have been largely removed by erosion in the geologic study 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 northeastern part of the geologic study area (Hintze and Davis, 2002a). 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. In Clark County, however, the Moenkopi Formation is about 2,000 ft thick and of similar lithology, with gypsum beds in the upper part of the formation (Page et al., 2005b).

The Upper Triassic Chinle Formation includes a basal unit, the Shinarump Conglomerate Member, which is a resistant gray sandstone and conglomerate that ranges from 10 to 250 ft thick. The balance of the formation is of soft, variegated mudstone and siltstone that is widely exposed above the Moenkopi in the southern part of the geologic study area (Bohannon, 1983; Page et al., 2005b). This mudstone and siltstone have been measured to be about 1,000 to 3,300 ft thick within the geologic study area. The Luning Formation (Upper Triassic) is locally exposed northwest of the area. All Triassic rocks in the geologic study area have been combined as Triassic sedimentary rocks (ŦRs).

Jurassic sedimentary rocks (Js) are exposed in the southern part of the geologic study area. These rocks are dominated by the Lower Jurassic Aztec Sandstone, a brick-red, buff, and light-gray, fine- to medium-grained eolian sandstone containing large-scale cross beds. The Aztec is 600 to 3,600 ft thick. The equivalent Navajo Sandstone is about 2,000 ft thick in the southeastern part of the geologic study area. It is here underlain by the Moenave (lower) and Kayenta (upper) Formations, both of Early Jurassic age and mostly made up of fine-grained sandstone and siltstone of eolian and fluvial origin, with a combined thickness of 500 to 3,000 ft. The Navajo is here overlain by the Temple Cap (lower) and Carmel (upper) Formations, both of Middle Jurassic age and made up of sandstone, limestone, siltstone, and shale of mostly marginal marine origin and with a combined thickness of about 900 ft. The map unit also includes the Dunlap Formation (Lower Jurassic) in the northwestern part of the geologic study area.

Cretaceous synorogenic sedimentary rocks (Ks) are present but uncommon in the geologic study area. Most of this area was a highland undergoing erosion at that time. The Lower Cretaceous Newark Canyon Formation is exposed in the northwestern part of the geologic study 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 geologic study area, are thin and patchy in the map area but extensive and thick east and south of the area. Upper Cretaceous through Paleocene fault breccias, primarily from thrust faults related to Sevier deformation, are locally exposed in the geologic study area.

In Clark County, Cretaceous sedimentary units include from older to younger the Willow Tank Formation (Lower Cretaceous) and the Baseline Sandstone. The Willow Tank Formation is 300 to 450 ft thick and consists of a basal conglomerate and overlying fine-grained sediments, including bentonitic clay, and is primarily restricted to the Muddy Mountains. The Baseline Sandstone consists of about 3,000 to 5,000 ft of gray and red, well-bedded sandstone and conglomerate. In the southeastern (Utah) part of the geologic study area, the Upper Cretaceous Cedar Mountain Formation and overlying Iron Springs Formation consist of mudstone, shale, sandstone, and conglomerate about 3,000 ft thick.

Plutonic rocks related to the Middle Jurassic through Paleocene Sevier deformational event are exposed locally throughout the geologic study area (Maldonado et al., 1988). Of these, much of the southern Snake Range is intruded by a Middle and Upper Jurassic batholith (Miller et al., 1999) and Jurassic quartz monzonite and diabase that have been identified in the House Range and in the Burbank Hills, respectively, both in Utah near the eastern edge of the geologic study area (Hintze and Davis, 2002a and b, and 2003). Other plutons of quartz monzonite to granodiorite, mostly of Middle Jurassic age, form a north-trending belt along the eastern edge of White Pine County, Nevada, extending from the southern Snake Range to the Clifton Hills of western Utah. A north-trending plutonic belt of Cretaceous age is exposed in eastern White Pine County, Nevada, extending into the Deep Creek Range of western Utah and including the main mass of the large Kern Mountains granite batholith of apparent Cretaceous and Eocene age (Best et al., 1974; Miller et al., 1999). On the geologic maps, these plutonic rocks are shown as Jurassic (Ji), Cretaceous (Ki), Tertiary to Cretaceous (TKi), or Tertiary (Ti) intrusive rocks. Geophysics shows that the batholith extends eastward, downthrown beneath Snake Valley and buried by basin-fill sediments (Mankinen and McKee, 2009). An east-trending string of small Lower Cretaceous plutons extends from Eureka through Ely, Nevada.

4.1.5 Cenozoic Rocks

Cenozoic rocks in the geologic study 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 maps, 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 the youngest of the three main sequences, however, are mapped respectively as Quaternary to late Tertiary basaltic rocks (QTb) and Quaternary to late Tertiary alluvium (QTa).

4.1.5.1 Latest Cretaceous to Miocene Sedimentary Rocks

The oldest Cenozoic sedimentary rocks (Ts1) are thin and poorly exposed in the geologic study area but are more common in eastern Clark County and southwestern Utah. These units were deposited with, or unconformably deposited on, rocks deposited and deformed during the Sevier orogeny. In eastern Nevada, the principal Ts1 unit is the Sheep Pass Formation of Eocene to Oligocene age (Hose and Blake, 1976; Druschke et al., 2009). The Sheep Pass Formation occupies a basin about 15,000 mi^2 in size over an area extending south from Ely and Eureka, Nevada, to Penoyer and northern Pahranagat valleys (Fouch et al., 1991; Druschke et al., 2009). The unit is mostly nonresistant, gray conglomerate, sandstone, mudstone, and limestone, with a thickness of 600 to 3,000 ft in the geologic study area.

In the southeastern part of the geologic study area, the mostly resistant Grapevine Wash Formation and overlying Claron Formation are included within the Ts1 map unit. The Grapevine Wash Formation, poorly constrained in age as Late Cretaceous to early Tertiary but considered by Hintze et al. (1994) to postdate Sevier deformation, consists of as much as 2,000 ft of gray, tan, and red conglomerate and sandstone. The Claron Formation, also poorly constrained in age but likely of a restricted age ranging between Paleocene and Oligocene, is sandstone, limestone, and conglomerate as much as 2,000 ft thick.

Similar sedimentary rocks (Ts2, Ts3, and Ts4) of various names and ages, from Oligocene to Miocene, are exposed in the geologic study area. These include the Gilmore Gulch Formation of about 30 Ma (Ts2), exposed in the northwestern part of the area. The Horse Spring Formation, about 12 to 20 Ma, and the red sandstone unit, 11 to 12 Ma, that overlies it are mapped as Ts4 in the southern part of the geologic study area (Bohannon, 1983 and 1984). The Horse Spring Formation consists of conglomerate, sandstone, siltstone, claystone, limestone, dolomite, tuff, and gypsum as much as 10,000 ft thick.

4.1.5.2 Tertiary Volcanic Rocks

Volcanic rocks make up the primary Cenozoic rock type in the geologic study area. The older (Eocene to middle 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 typically thin, generally less than 1,000 ft, but the aggregate thickness of all of these tuffs is several thousand feet in many places. Isopach (thickness) maps of most tuffs in the study area were given by Sweetkind and duBray (2008).

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 related 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 geologic study 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 Great Basin. 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 and underlain by batholiths whose cupolas provide the vents 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 geologic study area. The ages of vents in this belt are about 38 Ma and locally older (Eocene) along the northern margin of the area, and 36 Ma farther south (Rowley, 1998). An east-trending gap in vent areas, about 30 to 60 mi wide north-south, occurs south of Ely and Preston, Nevada, and a volcanic plain of thin outflow tuffs underlies the gap. The axis of the next igneous belt to the south, the Pioche-Marysvale igneous belt, is south of 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 mi 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-mi-long and 25 mi wide. Its caldera source has not been found but Gans et al. (1989) suggested that it may be buried beneath northern Spring Valley, which is near the center of the area of deposition of the Kalamazoo Tuff. Gravity data (Section 5.1.1) gave no support for this hypothesis but hint that it is more plausible that the caldera is buried beneath southern Tippett Valley. 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 a 45 to 30 Ma age range are scattered throughout the belt; most of these represent source areas of volcanic rocks that have since been removed by erosion. One of these plutons (Best et al., 1974) is at the eastern end of the composite-age Kern Mountains pluton. This and other Eocene to Oligocene plutons and batholiths in the northern Snake Range, Kern Mountains, and

Deep Creek Range represent initial calc-alkaline magmatism beneath these ranges (Miller et al., 1999) that later were uplifted during basin-range extension.

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 such as the Seaman Range volcanic center. The largest vent area in the belt is the Indian Peak caldera complex (Best et al., 1989a) in the southeastern part of the geologic study 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 mi east-west by 150 mi north-south.

Intracaldera megbreccia deposits result from landsliding of the outside wall of a caldera margin into a caldera following rapid eruption of huge ash-flow tuff sheets and the collapse of the caldera floor to fill the erupted parts of the underlying magma chamber. These megabreccia deposits (Tmb) are mapped only in the Indian Peak caldera complex on the geologic map (Plate 1) and cross section Q—Q' (Plate 4), but on the hydrogeologic map (Plate 6) and cross sections (Plate 8) these rocks are included within the Tertiary volcanic rocks (Tv). Megabreccia deposits (Tmb) are also mapped in and west of the southern Sheep Range on the geologic map (Plate 2) and cross section H—H' (Plate 5), and these deposits do not include significant volcanic rocks, but instead result from large gravity slides off the Sheep Range. On the hydrogeologic map (Plate 7) they are mapped with Tertiary older sediments (Tos), but on hydrogeologic cross section H—H' (Plate 9) they are too thin to be shown so are included in surficial deposits (QTs).

A cluster of smaller calderas west of the Indian Peak caldera complex 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 geologic study 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 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 geologic study area.

In the Delamar-Iron Springs igneous belt, at the southern edge of the geologic study area, the largest igneous centers are the Caliente and Kane Springs Wash caldera complexes. The Caliente caldera complex erupted ash-flow tuffs that spread over an area about 150 mi east-west by 100 mi north-south. It had an unusually long history of activity, at least 10 Ma. The regional ash-flow tuffs derived from it include the Swett (23.7 Ma) and Bauers (22.8 Ma) Tuff Members of the Condor Canyon Formation, Racer Canyon Tuff (18.7 Ma), Hiko Tuff (18.3 Ma), tuff of Tepee Rocks (17.8 Ma), tuff of Dow Mountain (17.4 Ma), tuff of Acklin Canyon (17.1 Ma), tuff of Rainbow Canyon (15.6 Ma), Ox Valley Tuff (13.5 Ma), and probably the Leach Canyon Formation (23.8 Ma) (Rowley et al., 1995; Scott and Swadley, 1995; Snee and Rowley, 2000). The Kane Springs Wash caldera complex, just to the south, erupted the tuff of Narrow Canyon (15.8 Ma), tuff of Boulder Canyon (15.1 Ma), and Kane Wash Tuff (14.7 to 14.4 Ma) (Scott et al., 1995 and 1996; Scott and Swadley, 1995). The total thickness of volcanic rocks in the igneous belt generally does not exceed 1,000 ft outside the caldera complexes.

The younger (middle Miocene to Quaternary) bimodal sequence, which postdates the calc-alkaline 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 categorized on the geologic map as unit QTb, rhyolite domes and flows as Tr4, and tuffs as Tt4. All the volcanic rocks derived from the Kane Springs Wash caldera complex, and those that postdate the tuff of Tepee Rocks from the Caliente caldera complex, are included within the bimodal assemblage. The tectonic environment during bimodal magmatism was east-west extension, with the direction of principal maximum compressive stress generally oriented vertically, creating an 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 middle Miocene alluvium Holocene (QTa) and are considered to be aquifers, especially 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 geologic study 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 may be 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 lakes were pluvial lakes of Pleistocene 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; Currey, 1982; Currey et al., 1984). These lakes, however, were short lived and produced fine-grained materials that rarely exceeded a few tens of feet in thickness. Quaternary basin-fill deposits are mostly thin (several hundred feet) and overlie Pliocene and upper Miocene basin-fill sediments that may be thousands of feet thick, depending on the throw of the basin-range faults that produced the basins. Data from boreholes in Snake Valley indicate several hundred feet of Tertiary evaporites within the deepest part of the basin.

The concept that extensional basins contain coarse-grained sediments on their margins and fine-grained sediments in their interiors may be valid for periods of time that are geologically short (thousands of years) but is invalid for larger periods (tens of thousands of years) because of the vagaries of the sizes of storms that deposit sediments, of climate changes, of integration of some basins, and of timing of the deformation of basin-bounding versus within-basin faults. In other words, basin margins may become basin centers and vice versa, over 10 Ma. Therefore, in practice, 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-fill sediments that were then eroded away by streams and redeposited as younger basin-fill sediments. Sweetkind et al. (2007b), in a short chapter on the hydrogeologic setting of the BARCASS area, endorsed the conceptual model of coarse- versus fine-grained deposits depending on distance from basin margins. They proposed two hydrogeologic units for extensional basins: coarse-grained basin-fill deposits (their hydrogeologic unit CYSU) from the margins of closed basins and fine-grained basin-fill deposits (unit FYSU) from the interiors, with the former an aquifer and the latter a confining unit. Mapping experience in the Great Basin, especially revealing where deposits in closed basins have been eroded following drainage integration by a through-flowing stream so that underlying deposits are now visible, shows that no vertical plug of fine-grained sediments is in the interiors of basins as envisioned by Sweetkind et al. (2007b). Plate 1 includes thin surficial deposits in and on the flanks of the ranges, such as stream deposits, landslides, and spring deposits, that are not individually separated in this report or on the maps because of their limited extent.

In some places the basin-fill sediments have local names that were categorized as QTa on the geologic map. One such local unit is the Muddy Creek Formation (Bohannon, 1984) of 5 to 11 Ma in southern Lincoln and Clark counties. The Muddy Creek consists of locally gypsiferous shale, siltstone, and fine-grained sandstone. Another named unit is the Panaca Formation, consisting of about 2- to 10-Ma sandstone, siltstone, shale, and conglomerate, and located in the central part of the geologic study area (Rowley and Shroba, 1991). Other units of similar lithology to the Panaca Formation are the Horse Camp Formation in the northwestern part of the area (Brown and Schmitt, 1991) and the Salt Lake Formation northeast of the area. All these units are generally more than 1,000 ft thick and locally as much as 10,000 ft thick.

4.2 Hydrogeologic Units

HGUs are rock units grouped so that they are more useful for hydrogeologic studies. As given on Plates 6 and 7 and listed in Table 4-1, HGUs are a set of geologic formations that are grouped into aquifers or confining units based on their physical properties. By defining HGUs, the evaluation of groundwater occurrence and movement is facilitated as is the development of conceptual and numerical models of groundwater flow. The geologic units (Plate 3) that make up each HGU are listed below under the discussion of HGUs. This grouping reflects lithologic properties rather than more traditional geologic groups, which are based on genetic sequences.

Table 4-1
Brief Summary of Hydrogeologic Units

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. Generally moderate permeability but may be high where fractured.
QTb	Quaternary and Tertiary basalt - Quaternary and late Tertiary mafic volcanic rocks. Generally permeable but not hydrologically significant regionally because mostly thin.
Tv	Tertiary volcanic rocks - Miocene to Eocene volcanic rocks. Good to moderate permeability, commonly a significant aquifer.
Tos	Older Tertiary sediments - Primarily created for the cross sections; includes the older Tertiary alluvial and lacustrine section below the volcanic section and megabreccia deposits west of the Sheep Range. Of moderate permeability where fractured.
TJi	Tertiary to Jurassic intrusive rocks - Includes all plutons. Generally impermeable except where fractured.
KŦs	Cretaceous to Triassic siliciclastic rocks - Thicker where near the Colorado Plateau and generally of low permeability. More abundant in the southern part of the geologic study area. A confining unit of limited extent.
PIPc	Permian and Pennsylvanian carbonate rocks - Includes Ely Limestone, Bird Spring Formation, Park City Group, and other units. May include thin Triassic carbonate rocks in the Butte Mountains. Also includes Permian red beds, undifferentiated. A highly permeable aquifer.
Ms	Mississippian siliciclastic rocks - Includes Chainman Shale, Scotty Wash Quartzite, Diamond Peak Formation, and Eleana Formation. The Chainman Shale and Scotty Wash Quartzite are not differentiated in Lincoln County, except in the Egan and Schell Creek Ranges. Where mapped, is a confining unit of low permeability, but where thin were combined with adjacent aquifer units.
MOc	Mississippian to Ordovician carbonate rocks - Joana Limestone (Monte Cristo Formation) to Pogonip Group, also includes thin Chainman Shale in most of Lincoln and Clark counties. The Pilot Shale, Eureka Quartzite, Guilmette Formation, Simonson Dolomite, Sevy Dolomite, and Laketown Dolomite are also included. A highly permeable aquifer.
€c	Cambrian carbonate rocks - Includes the Bonanza King, Highland Peak, Lincoln Peak, and Pole Canyon formations. A highly permeable aquifer.
€p€s	Cambrian and Precambrian siliciclastic rocks - Includes the Wood Canyon Formation, Prospect Mountain and Stirling quartzites, Chisholm Shale, Lyndon Limestone, and Pioche Shale. Generally impermeable except where fractured.
p€m	Precambrian metamorphic rocks - Precambrian X, Y, and Z high-grade metamorphic rocks, generally Paleoproterozoic. It also includes the Johnnie Formation in the south and the McCoy Creek and Trout Creek groups in the Schell Creek, Deep Creek, and Snake ranges. Impermeable except where fractured.

HGUs must be distinguished from hydrostratigraphic units (Maxey, 1964; Seaber, 1992; Donovan, 1996), which are based on the material properties of porosity and permeability. Hydrostratigraphic units are independent of age, formation boundaries, and saturation.

HGUs, as opposed to hydrostratigraphic units, reflect geologic history, conform to informal and formal formation boundaries, and define many of the large-scale differences and spatial distributions of porosity and permeability. HGUs largely define units that could be called regional aquifers and confining zones and would be of Group or Supergroup rank in formal stratigraphic terminology because they are made up of units of formation rank. These formal distinctions are not critical in the context of this report because the units are informal and conform to geologic unit boundaries, but this discussion should give the reader a sense of the purpose, scale, and general approach used to develop the units and the challenges in developing traditional geologic correlations. 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) consist primarily of moderately to intensely metamorphosed Precambrian "basement" rocks, forming the most significant aquitard in the geologic study area because it underlies the entire geologic study area (Page et al., 2005a; Hintze and Kowallis, 2009). The largest exposure in the area of Plate 6 is on the eastern side of the Schell Creek Range, north of U.S. Highway 50 (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. Additional Precambrian basement rocks are on Plate 7 in the southern part of the geologic study area in the Mormon Mountains, the Desert Range, and the Black Mountains at Lake Mead. These rocks include Precambrian metamorphic and crystalline rocks, the McCoy Creek Group, Trout Creek Group, and the Johnnie Formation. On the geologic maps and cross sections (Plates 1 and 2), this map unit has the symbol p€.

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 Neoproterozoic and Early Cambrian. The unit is quartzite with a substantial thickness of shale also present, thus a major aquitard. 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, and the bulk of the unit is mapped as the Prospect Mountain Quartzite. The permeability of the unit is low except in areas where fractured or weathered. The difference in permeability between p€m and €p€s in exposed sections is considered minor, although the €p€s unit is expected to be slightly more permeable than the older p€m (Belcher et al., 2001). On the geologic maps and cross sections, this unit consists of the symbol €p€s.

4.2.3 Cambrian Carbonate Rocks

The Cambrian carbonate unit (€c) consists of Middle and Upper 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. It has high permeability, especially where faulted, and therefore is a major aquifer. In the southern part of the geologic study area, the unit constitutes about half the thickness of the Paleozoic section. The Cambrian carbonate aquifer includes a thin, spatially limited confining unit, the Dunderberg Shale. This unit is of limited extent and is too thin to be considered capable of limiting flow on a regional basis. On the geologic maps and sections, this unit consists of the rocks with the symbols of both €m and €u and, on the cross sections, also the rocks with the symbol €c.

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 as on Plate 8, Cross Section P—P' but has a wide variation in thickness as on Plate 8, 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 where faulted.

The Mississippian to Ordovician carbonate aquifer includes the Ordovician Eureka Quartzite and Pilot Shale, which are confining zones. Neither of these formations is considered a significant aquitard at the scale of Plates 6 to 9, and the brittle 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. From oldest to youngest, the symbols for the rocks on the geologic maps and sections that are combined in this HGU are the following: Ol, SOu, SO, Ds, Dg, Dn, Dd, Du, DO, DS, MD, and MDd.

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 they are thin. The clastic rock unit is derived from erosion of highlands in north-central Nevada associated with the Antler upland. It is thickest (about 3,500 ft) on the western side of Plate 8, Cross Section Y—Y'. 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 degrees north latitude). In the Snake Range, the rock unit is too thin to comprise a confining unit. On the geologic maps and sections, the unit consists of the rocks with the symbols Mc and Md.

4.2.6 Permian and Pennsylvanian Carbonate Rocks

The Permian and Pennsylvanian carbonate unit (PIPc) 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 geologic study area, these rocks are continuous with the Arcturus and Park City groups, which are predominantly carbonate rocks. In the Butte Mountains in the northwestern part of the area, a small section of Triassic rocks is included in this unit. The unit is thickest near Robinson Summit in the Egan Range, with a thickness of ~10,000 ft at Plate 8, 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 geologic study area. From oldest to youngest, the symbols for the rocks on the geologic maps and sections that are combined in this HGU are the following: IP, PIP, Pr, Pa, Par, and Pp.

4.2.7 Cretaceous to Triassic Siliciclastic Rocks

The Cretaceous to Triassic clastic unit (KŦRs) consists of Mesozoic rocks in eastern Lincoln and Clark counties. The unit includes the Triassic Moenkopi and Chinle formations and the Jurassic Aztec and Navajo sandstones. These units are locally beneath thrust faults that carry 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. The symbols for the rocks on the geologic maps and sections that are combined in this HGU are ŦRs, Js, and Ks.

4.2.8 Tertiary to Jurassic Intrusive Rocks

The Tertiary to Jurassic intrusive unit (TJi) includes all plutons in the geologic study area. Mesozoic plutons form either a significant part of, or the bulk of, several large ranges in the northeastern part of the 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 except in areas where fractured or weathered. The symbols for the rocks on the geologic maps and sections that are combined in this HGU are Ji, Ki, TKi, and Ti.

4.2.9 Older Tertiary Sediments

The older Tertiary sedimentary unit (Tos) consists mostly of older Tertiary clastic sediments (Eocene to Oligocene age) below the volcanic section. The unit reaches a maximum thickness of 4,000 ft in Railroad Valley, west of the geologic study area, and a similar thickness in the southern part of the area. The permeability is moderate, especially where well fractured. On the geologic map and cross sections, the unit consists of the rocks with the symbol Ts1 where they underlie the Tertiary volcanic rocks HGU, and includes megabreccia with the symbol Tmb on the geologic map on and west of the southern Sheep Range.

4.2.10 Tertiary Volcanic Rocks

The Tertiary volcanic unit (Tv) includes 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. Most of the exposed bedrock in Delamar, Dry Lake, Patterson, Little Spring, Rose, Eagle, Kane Spring, and Clover valleys are of volcanic rock. Outflow rocks are generally less than 3,000 ft thick, but intracaldera rocks may locally be more than 10,000 ft thick.

The Tertiary volcanic unit consists of a number of units of variable permeabilities: ash-flow tuffs are brittle and generally permeable, whereas lava flows are less permeable. In general, the permeability is considered good to moderate, but where faulted, the unit is more permeable and in some places, it may be an important aquifer. From oldest to youngest, the symbols for the rocks on the geologic maps that are combined in this HGU are the following: Tmb in the Indian Peak caldera complex but not west of the southern Sheep Range, Ta1, Ta2, Ta3, Ta4, Tr1, Tr2, Tr3, Tr4, Tt1, Tt2, Tt3, and Tt4. The symbol for the rocks on the geologic sections is Tv.

4.2.11 Quaternary and Tertiary Basalt

The Quaternary and Tertiary basalt unit (QTb) resulted from Quaternary and late Tertiary mafic volcanism. The deposits are thin but locally cover significant 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. The largest outcrops are located in north-central Nye County (Plate 1), and there are also extensive outcrops of this unit in southern Lincoln and northern Clark counties (Plate 2). Basalt is brittle and has high permeability, but because of the limited thickness and distribution, it does not have regional significance as a HGU. On the geologic maps and cross sections, the unit consists of the rocks with the same symbol (QTb).

4.2.12 Quaternary and Tertiary Sediments

The Quaternary and Tertiary sedimentary sequence (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 places, 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), such as Dry Lake and Panaca valleys on Plate 8, Cross Section P—P'. 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 surface feature throughout the Great Basin. Overall, the map unit has moderate permeability but may be high where fractured. The symbols for the rocks on the geologic maps that are combined in this HGU are Ts2, Ts3, Ts4, and QTa. On the cross sections, the symbol for the rocks in this HGU is QTs.

4.3 Structural Geology

This section discusses the structural framework of the geologic 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 as conceptualized in Section 2.0.

4.3.1 Evolution of the Regional Structure

Three main structural events affected the geologic study area: (1) Late Devonian to Late Mississippian Antler compressive deformation, (2) Late Jurassic to early Tertiary Sevier compressive deformation, and (3) late Cenozoic basin-range extensional deformation. In addition to these structural 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 geologic study area.

The Late Devonian to Late Mississippian Antler compressive deformation affected the northwestern part of the geologic study 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 Eureka, Nevada (Carpenter et al., 1994; Saucier, 1997). The thrusts transported deeper-water sedimentary rocks eastward as much as 100 mi. 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 mountain ranges of the geologic study area. Eastward-directed overthrusts emplaced Neoproterozoic to middle Paleozoic rocks over Neoproterozoic 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 mi (Page et al., 2005b). Tectonic shortening caused by thrusting in southern Nevada is at least 22 to 45 mi (Stewart, 1980; Burchfiel et al., 1974). Except for the southern part of the geologic study area, most of the area has been considered to be the western hinterland of the deformation. In other words, Sevier deformation created Late Cretaceous to early Tertiary highlands (hinterlands) that in turn shed most major thrusts and clastic debris primarily to the east (Vandervoort and Schmitt, 1990; Druschke et al., 2009). Some of the thrusts, including the Gass Peak, however, have been projected northward into the hinterland in the central and northern part of the geologic study area, including the Timpahute Range, Worthington Mountains, Golden Gate Range, Grant Range, Pancake Range, and Newark Valley (Vandervoort and Schmitt, 1990; Dobbs et al., 1994; Taylor et al., 2000). Most of the thrusts in the Confusion Range appear to represent minor movement along bedding planes in weak beds during tight folding of Sevier age. Anderson (1983), however, interpreted the faults to have formed by gravity sliding into the axis of a synclinorium. Sevier-type deformation is shown schematically on Figure 4-6, and the Sevier-age Glendale/Muddy Mountains thrust in the Muddy Mountains 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 the areas where they are known. Therefore, transverse zones are delineated as speculative zones of potential disruption on Plates 1 and 2.

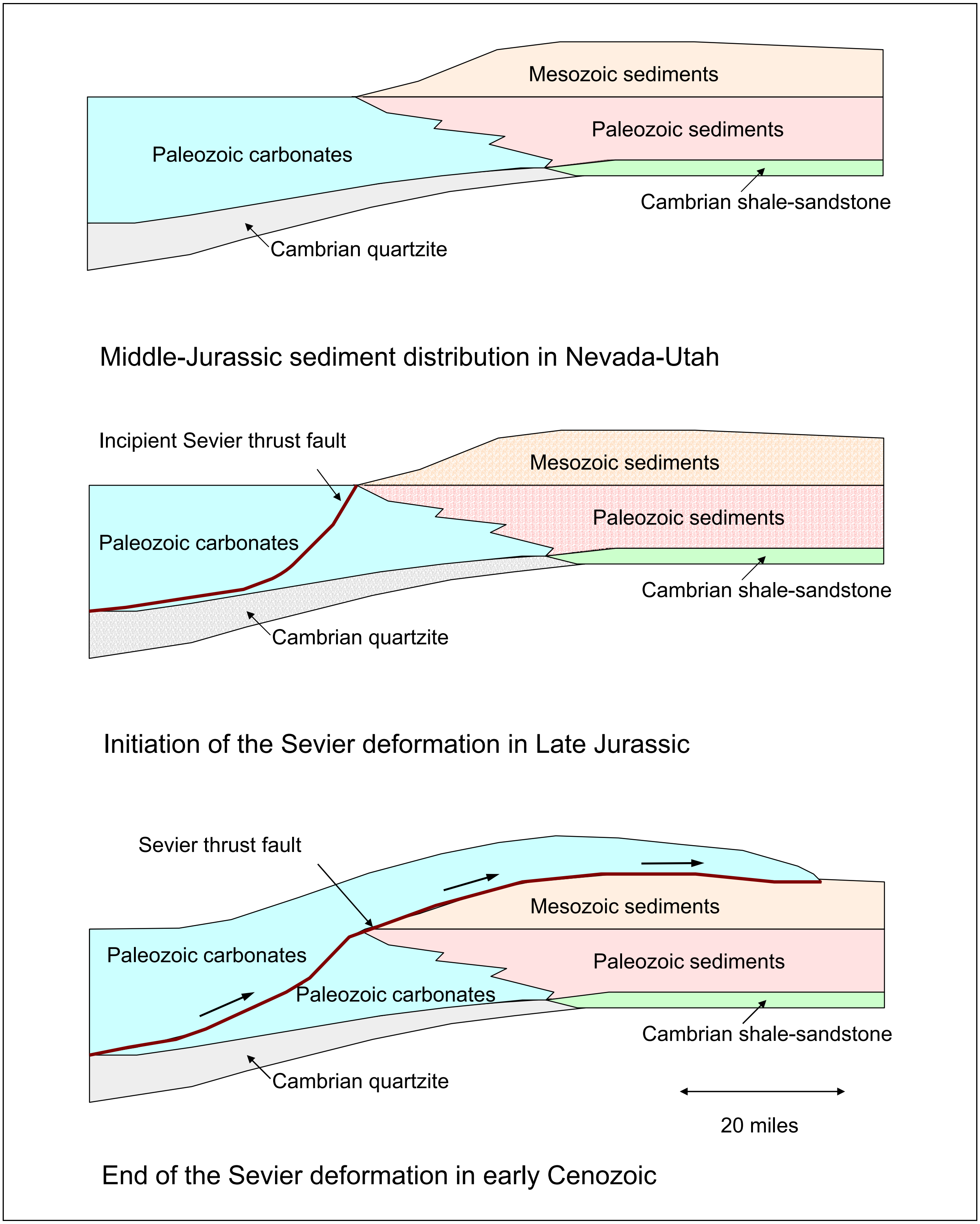
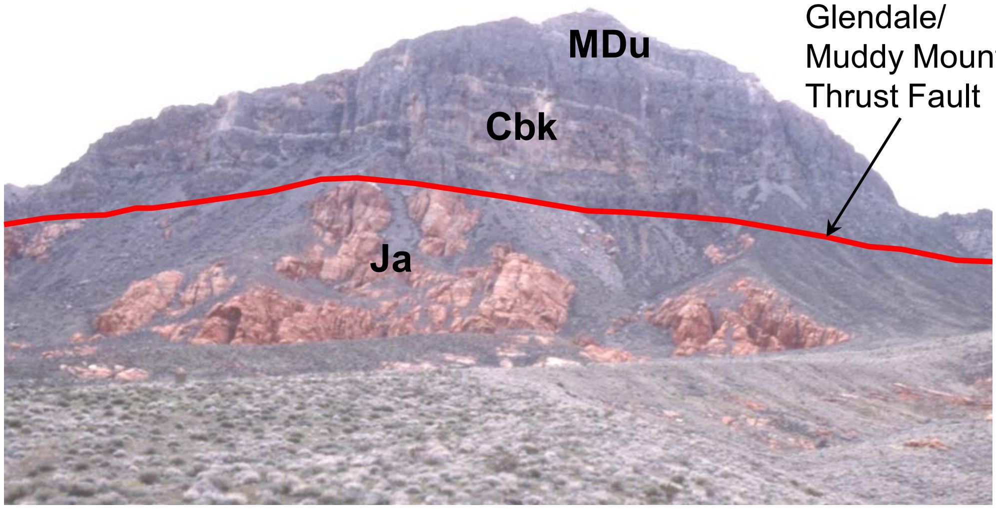


Figure 4-6
Schematic Diagram of Sevier Thrust Sheets, Illustrating the Movement of Paleozoic Carbonates over Cratonic Sediments



Ja – Jurassic Aztec Sandstone
MDu – Mississippian-Devonian carbonates, undifferentiated
Cbk – Cambrian Bonanza King Formation

Figure 4-7
Paleozoic Carbonates Thrust over Jurassic Aztec Sandstone in the Muddy Mountains near Muddy Peak

Transverse zones bound parts of most igneous belts in the Great Basin. They also define the northern and southern sides of the Caliente caldera complex, representing structures by which this caldera spread east and west to a degree much more profound than most other caldera complexes in the Great Basin. Transverse zones are poorly known and have been mapped in detail only locally, so they are projected with limited evidence between areas where they are known. Some transverse zones seem to be discontinuous along strike (along their east-west trend), so they may be present for several miles or tens of miles, then be absent or buried for miles, then be present again. Such is the case with the Sand Pass transverse zone (Rowley, 1998; Rowley and Dixon, 2001), which bounds the northern and southern side of the Kern Mountains but progressively to the east is buried beneath the surficial sediments of Snake Valley, absent through the carbonate bedrock of the northern Confusion Range and western Middle Range (Plates 1 and 6), and present in the carbonate bedrock and basin-fill sediments of the central and eastern Middle Range and of Sand Pass (Rowley et al., 2009, Plate 1). Farther east, east-trending features are absent in the Drum Mountains and Thomas Range (Rowley et al., 2009, Plate 1), but they are prominent east of the Thomas Range most of the way to and east of the Wasatch front in central Utah (Stoeser, 1993; Rowley, 1998; Rowley and Dixon, 2001).

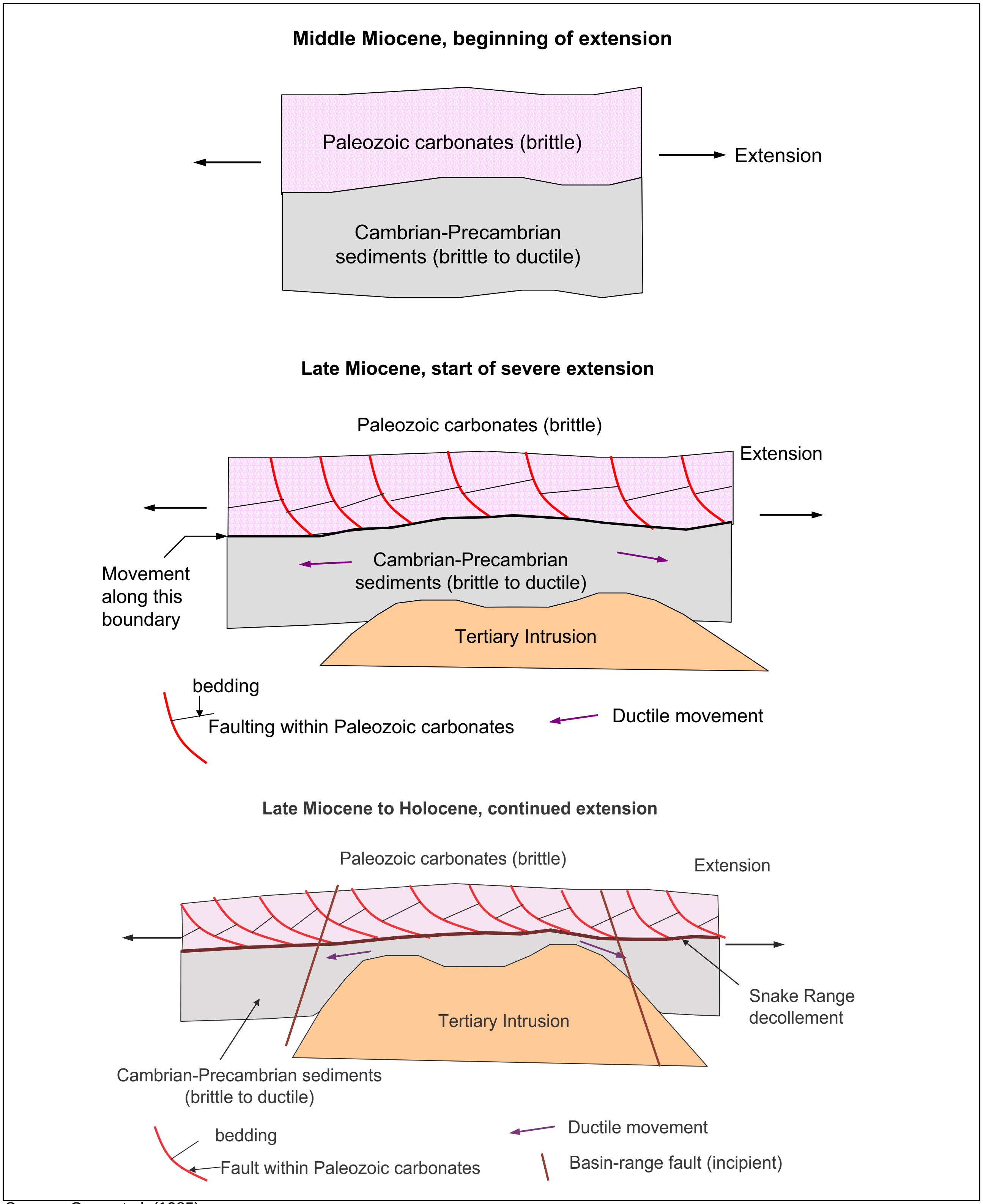
The third structural event, the basin-range episode of extensional deformation, began at about 20 Ma and continues today. It is characterized by east-west extension and resulted primarily in north-striking normal faults. Over some parts of the Great Basin, early phases of this deformation produced north-striking 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 that began after 10 Ma for most parts of the Great Basin. The orientation of 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. An example is the presence of Miocene lacustrine limestones and associated clastics in the North Pahroc and Pahranagat ranges (Tschanz and Pampeyan, 1970) that were originally deposited in one or more 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. Examples of such accommodation zones are the east-northeast, left-lateral PSZ at the southern end of Pahranagat Valley and the northeast-trending, left-lateral Kane Spring fault zone west of the Meadow Valley Mountains (Ekren et al., 1977). Vertical displacement on some normal faults in the study area far exceeded 10,000 ft. In and near the study area, the dominant topography is alternating complex horsts and grabens (Mankinen and McKee, 2009; McPhee et al., 2009). An alternative view of basin-range structure, in which the abundance of and amount of displacement on normal faults and their effect on groundwater flow is much less than presented here, is given by Sweetkind et al. (2007b, Figure 9), who envisioned a topography of tilt blocks faulted on only one side. 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 (e.g., Hazzard and Turner, 1957; Misch, 1960; Nelson, 1966), yet these geologists correctly recognized that the faults partly followed weak beds in the Pioche Shale. The rocks above these faults, however, were not thickened and compressed as above thrust faults but instead were stretched and attenuated, and younger rocks were emplaced on older rocks (Hose and Blake, 1976). The first workers to recognize the significance of the faults were Moores et al. (1968) and Armstrong (1972), from work west of the study area. These workers concluded that most of these low-angle faults are Tertiary expressions of structural extension. The faults formed after rapid uplift of the ranges, in which the tops of the uplifted blocks were structurally stripped (or attenuated or denuded) by low-angle faults that verged into the adjacent low areas, much like large gravity slides. They called them attenuation or denudation faults. Most formed during the basin-range episode of deformation.

In and west of the study area, the major low-angle fault, called the Snake Range decollement, emplaced Middle Cambrian carbonates and some younger rocks over Middle Cambrian carbonates and Lower Cambrian to Neoproterozoic quartzite. Whitebread (1969) mapped this feature over a large part of the southern Snake Range that includes Great Basin National Park (GBNP). Coney (1974) mapped small-scale structures in the fault plane in the Snake Range and found that upper-plate rocks on the east side of the range traveled eastward, and those on the west side of the range traveled westward. Hose and Blake (1976) showed the decollement as it was then known. Following a comprehensive study, Miller et al. (1983) and Gans et al. (1985, 1989) reinterpreted the fault as an Eocene to Miocene low-angle fault caused by stretching and thinning during uplift as a metamorphic core complex. They suggested that the decollement may represent the ductile-brittle transition zone uplifted by the core complex (see Figure 4-8) (Miller et al., 1983; Gans et al., 1985, Gans, 2000b). Rocks have been thinned by the elimination of strata due to the faulting.

Later work indicated that, whereas the decollement had an older (late Eocene and early Oligocene) history, most displacement on it was middle Miocene and later, coinciding with basin-range



Source: Gans et al. (1985)

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

deformation (Miller et al., 1999). Some geologists (Allmendinger et al., 1983; Bartley and Wernicke, 1984; Kirby and Hurlow, 2005; Sweetkind, 2007a) interpreted the decollement to be a major detachment fault in the Great Basin and to have many miles (37 mi according to Bartley and Wernicke, 1984, p. 652) of eastward displacement of the upper plate relative to its underlying footwall. However, Gans and Miller (1985, p. 411) pointed out that the fault plane occupies the same stratigraphic position (top of the Pioche Shale) and does not "cut downsection to the east," so they therefore concluded that it could not have "a large amount of translation" and more likely represents "decoupling along the stratigraphic horizon in the Pioche Shale." Miller et al. (1999) later reinterpreted the amount of eastward translation on the decollement on the crest and eastern side of the Snake Range to about 7 to 9 mi, although they acknowledged that movement on the decollement on the western side of the range was westward, as first recognized by Coney (1974).

Probably the decollement represents movement along a weak stratigraphic horizon on the steep upper flanks of rapidly rising ranges (Figure 4-8). Finally, in their most recent conclusions about the structure, 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 three episodes of structural deformation and one episode of volcanism on the groundwater flow in the geologic study area. 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.

4.3.2.1 The Antler Deformation

The Antler episode of compressive deformation probably had the least direct effect on groundwater flow of any structural event. Most of the thrust faults associated with this tectonic event are west and northwest of the geologic 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 mostly within the northern half of the geologic 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 groundwater flow in the region than the Antler event. The Sevier event resulted in major thrust faults, especially in the southern part of the geologic study area but locally in the central and northern part of the area. Gouge and mylonitic zones along these thrusts have created barriers to groundwater flow, particularly in the Sheep Range, the Pahranagat Range, the Delamar Mountains, and in several other ranges in the southern part of the area. Furthermore, these thrust faults brought western assemblage carbonates over eastern assemblage cratonic clastic sedimentary rocks of Triassic through Cretaceous age. These cratonic confining units generally also are flow barriers. Some of these geologic barriers to flow are several thousand feet thick, as in the Muddy, Meadow Valley, and Clover mountains. In other places, thrust faults brought Precambrian and Cambrian siliciclastic rocks over the carbonate units, as in the Sheep and Las Vegas ranges along the Gass Peak thrust and in the Delamar Mountains along the Delamar thrust. In contrast to barriers to flow caused by the Sevier deformation, northerly conduits may have resulted from a concentration of fractures developed along the axes of open shallow anticlines, most of which trend north.

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 fault structures that formed during this time are poorly known but likely included strike-slip and normal faults, including detachment faults. The region appears to have been characterized by mild east-west extension and strike-slip faults of northeast and northwest strikes. The caldera complexes and their associated ring faults and other margin structures were mostly barriers to groundwater flow. Perhaps more important than the caldera margins themselves are the intracaldera intrusions that underlie the calderas, which caused hydrothermal clay to form by heating and convective overturn of ancient groundwater and contact metamorphism of intracaldera ash-flow tuff. Faults and associated joints that postdate and cut the calderas locally 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 middle 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 had trends at high angles to the extension direction formed as accommodation zones during the same east-west extension. The north-striking high-angle faults and resultant fractures generally provide conduits to groundwater flow north or south along the hydraulic gradient, rather than flow barriers (e.g., Rowley and Dixon, 2004). 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 (Figures 2-4 and 2-5). 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, welded 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—create rock fractures, acting like a hammer on a plate of glass. These brittle rocks in the Great Basin cannot help but be significantly fractured throughout, commonly creating important aquifers (Winograd and Thordarson, 1975; Dettinger, 1992; Dettinger et al., 1995; Burbey, 1997; Rowley and Dixon, 2004).

Some normal faults are low-angle—that is, denudation, detachment, or attenuation faults. Their effect on groundwater flow is much less important than that from high-angle faults. These low-angle fault zones may result 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 low-angle faults of the Snake Range decollement may locally prevent rainfall from infiltrating the range. But a more profound effect on infiltration is caused by the underlying Proterozoic and Cambrian metamorphic rocks and quartzite, which also provide barriers to east or west flow through the ranges.

4.4 Descriptions of Basins and Ranges and Potential for Interbasin Groundwater Flow

This study concentrated on specific basins or hydrographic areas within or adjacent to the geologic study area. The basins and ranges, their structure and geometry, and the potential for interbasin groundwater flow between them are described in this section. Mountain ranges adjacent to the basins are described in more detail than the valleys themselves due to their greater exposures of pre-Quaternary geologic units. Because of this, the discussion below is organized by ranges, and the adjacent basins are discussed within these sections going from north to south and west to east, starting in the northwestern part of the map

The potential for interbasin groundwater flow is discussed within the text and is illustrated by Figure 4-9. The figure shows the likelihood of groundwater flow across boundaries between hydrographic areas based primarily on lithology and structure. Smaller boxes on the figure show areas where more detailed maps and cross sections are provided. On Figure 4-9, the potential for interbasin groundwater flow is geologically classified as likely, permissible, or unlikely. The hydrographic area boundaries identified as likely or permissible zones for groundwater flow are approximate locations and are not meant to represent the exact location of interbasin groundwater flow. More specific flow routes and their estimated volumes of groundwater are provided in the accompanying hydrologic report (Burns and Drici, 2011). A similar investigation of flow routes and volumes, but with different interpretations, was given in the results of the BARCASS (Knochenmus et al., 2007; Welch et al., 2007); their interpretations will be discussed in Section 6.0.

Specific flow pathways are controlled by topographic and geologic features, whose accurate, detailed geologic mapping and understanding are critical to interpreting flow routes between basins. Where the potential for such interbasin flow is classified as likely, the basin boundary is generally topographically low, the bedrock at and beneath the surface of the boundary is an aquifer or otherwise permeable due to fracturing, and the orientation of structures (mostly faults but also the dip of beds) is favorable (parallel to the trend of faults and beds) instead of unfavorable (perpendicular to the faults and beds) with respect to the boundary orientation, allowing groundwater to pass through the boundary. However, locally, water-level or hydraulic-gradient data at such a boundary may indicate groundwater flow away in both directions from the boundary, one type of groundwater divide. Where the potential for interbasin flow is classified as unlikely, the basin boundary is generally topographically high, the bedrock making up the subsurface of the boundary is commonly, although not necessarily, a confining unit, and the orientation of structures at the boundary is unfavorable with respect to the orientation of the boundary. Where the potential for interbasin flow is classified as

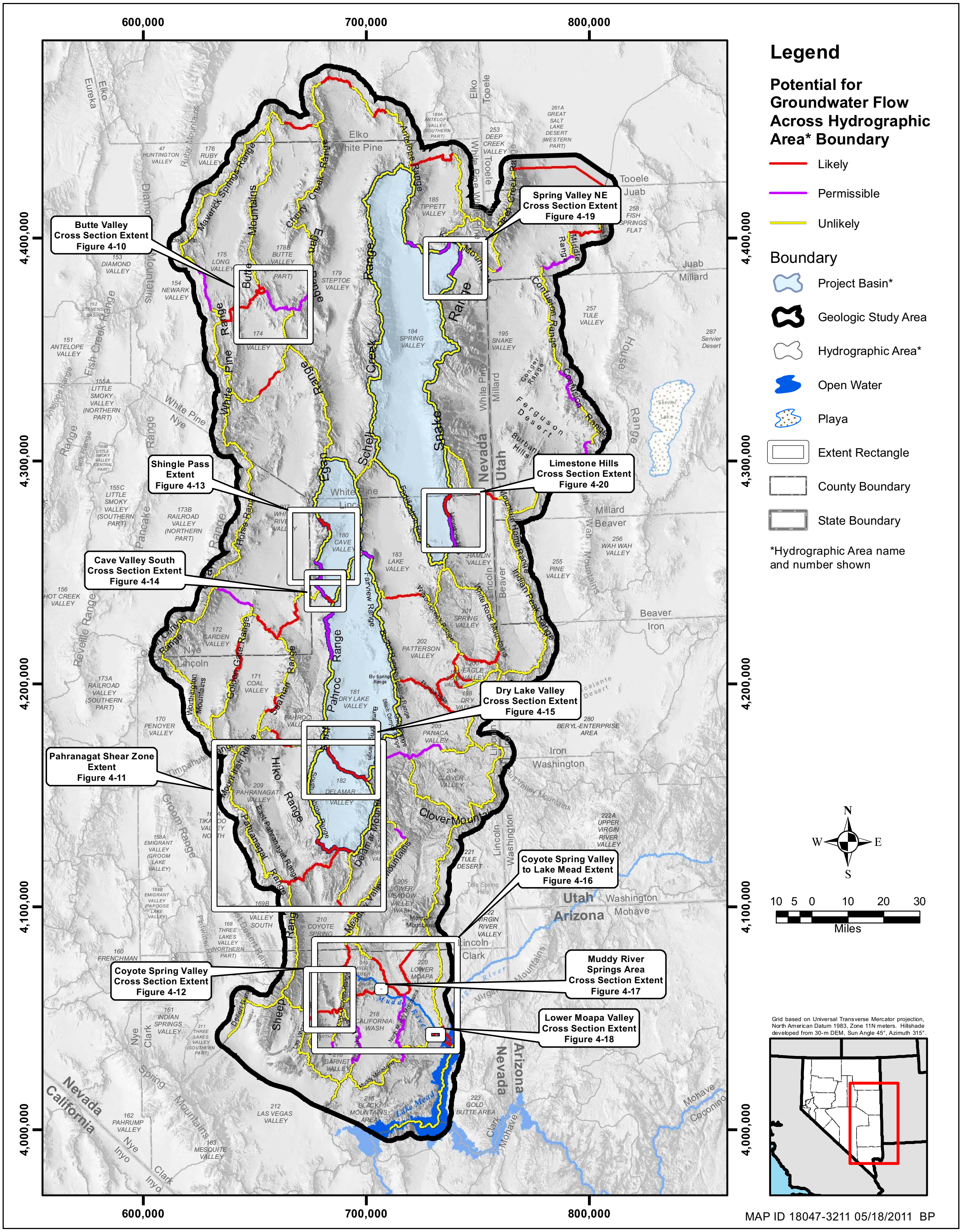


Figure 4-9
Potential for Interbasin Groundwater Flow within the Geologic Study Area

permissible, the basin boundary has been evaluated with respect to topographic and geologic data and determined to have a significant likelihood for flow through it.

4.4.1 Ruby Mountains, Bald Mountain, and Buck Mountain

The Ruby Mountains, just west of the geologic study area, is a horst in which large amounts of vertical uplift resulted in detachment (attenuation) faults along the margins. In other words, the range is a metamorphic core complex formed during major uplift (Howard et al., 1979; Wright and Snoke, 1993). Most rocks in the range dip east and are early Paleozoic in age. The Ruby Mountains is cored by a Jurassic to Miocene batholith and Precambrian to Lower Cambrian rocks, which constitute confining zones.

Bald Mountain consists of east-dipping lower Paleozoic rocks cored by Jurassic intrusions that formed major deposits of gold, silver, and other metals (Hitchborn et al., 1996). Bald Mountain joins Buck Mountain, a horst of subhorizontal middle Paleozoic rocks. A low, south-trending narrow arm of Buck Mountain joins the White Pine Range to the south, and flow is permissible from Long Valley into Newark Valley through Beck Pass in the arm (Figure 4-9; Section 4.4.2). The intrusions provide a barrier to flow across Bald Mountain.

Ruby Valley is a deep graben bounded by the Ruby Mountains to the west, the Maverick Springs Range (Section 4.4.2) to the east, and Bald Mountain to the south. Probably this graben is locally about 5,000 ft deep. On the western side of the Ruby Mountains and Bald Mountain is Huntington Valley, a graben that is several thousand feet deep. This valley is bounded on the west by the Diamond Mountains. A groundwater divide is present between Huntington Valley and Newark Valley (Harrill et al., 1988). Newark Valley is bounded by the Diamond Mountains to the west and by Bald and Buck mountains to the east. This valley is another graben with locally more than 5,000 ft of valley fill (Plates 4 and 8, Cross Section X—X'); it is further described in Section 4.4.3. Seismic profiles disclose Sevier thrusts beneath the basin-fill deposits (Dobbs et al., 1994).

4.4.2 Maverick Springs Range

The Maverick Springs Range of northern White Pine County, Nevada, is a low, northeast-trending range of mostly east-dipping upper Paleozoic rocks uplifted along a normal fault on the western side. The range bounds the southeastern edge of Ruby Valley. The eastern side of the Maverick Springs Range is bounded by a normal fault, down to the east, that separates it from Long Valley to the east. The northern end of the Maverick Springs Range is cored by a Tertiary pluton (Plates 4 and 8, Cross Section Y—Y') that continues north into Elko County, Nevada, as a broad series of hills, floored by cupolas of a Tertiary stock or batholith. The southern half of the Maverick Springs Range joins Buck Mountain to the south, separated by a down-to-the-west normal fault in the Alligator Ridge area, site of a major gold deposit (Nutt, 2000). The pluton in the Maverick Springs Range is a barrier to groundwater flow east or west across the northern part of the range, and flow is theoretically possible but considered unlikely through carbonate rocks above and around the pluton. The east dip of the beds would preferentially cause mountain recharge to flow eastward.

Long Valley, at the northwestern part of the study area, is narrow and shallow at its northern end but it widens and deepens to at least 3,000 ft to the south. The fault zone that bounds the western side of the Maverick Springs Range in Ruby Valley passes south through Mooney Basin (between the southern Maverick Springs Range and the Bald Mountain-Buck Mountain ridge) and is potentially a conduit for groundwater flow between southern Ruby Valley and western Long Valley. Most groundwater in Long Valley flows southward along north-trending faults and fractures in the valley, then into Jakes Valley to the southeast (Figure 4-9) (Harrill et al., 1988). One potential exception to all flow passing from southern Long Valley to Jakes Valley is a flow path from southwestern Long Valley through Beck Pass (north of the White Pine Range) into Newark Valley to the west. Such a path was suggested by Harrill et al. (1988), although they did not assign a volume to that flow. This route is classified as permissible because Beck Pass is low with respect to the two valleys and is underlain by surficial sediments of unknown although probably small thickness. Furthermore, most rocks at and beneath the pass are aquifers consisting of upper Paleozoic carbonates and lower Tertiary ash-flow tuff. Although no west-trending structure has been mapped at or near the pass, the rocks are potentially fractured due to north-trending range-front faults on either side of the pass. Such range-front faults, as well as the north-striking beds, are likely to be barriers to significant flow across the basin boundary.

4.4.3 Butte Mountains and White Pine Range

The Butte Mountains is located east of Long Valley; the range is west of central and southern Butte Valley. The Butte Mountains is a 40-mi-long, north-trending horst of east-dipping to anticlinally folded, upper Paleozoic sedimentary rocks (Hose and Blake, 1976; Otto, 2008). Southward, the Butte Mountains joins the eastern side of the north-trending, 50-mi-long White Pine Range across a low range of hills of upper Paleozoic carbonate rocks and Tertiary volcanic rocks. The southern end of the Butte Mountains also joins with several repeated fault ridges of the Egan Range (Section 4.4.9) to the east across a similarly low range of volcanic hills that forms the southern end of Butte Valley.

The northern White Pine Range is a generally low, broad series of horsts and grabens (Gans, 2000a). One of the grabens becomes Long Valley to the north, and the eastern horst becomes the Butte Mountains to the north. The northern White Pine Range is underlain largely by upper Paleozoic rocks, but middle Paleozoic rocks underlie some of the horsts (Lumsden et al., 2002) and Tertiary volcanic rocks underlie some of the grabens (Plates 4 and 8, Cross Section W—W'). The middle Paleozoic rocks included repeated fault blocks containing the Chainman Shale. The Chainman shale and faults of the horsts and grabens form a groundwater barrier between Jakes Valley and Railroad Valley to the west. The southern end of the White Pine Range has considerable elevation (as much as 11,500 ft) and is made up mostly of east-dipping, lower to middle Paleozoic rocks. The range here has a large eastward bulge, the White River caldera, which includes an underlying resurgent dome that undoubtedly is responsible for the high relief of the range (Plates 4 and 8, Cross Section V—V'). West of the caldera, the rocks include Cambrian to Precambrian siliciclastic rocks intruded by a Tertiary pluton. The north-trending axis of the caldera contains a narrow, north-striking graben; it is likely that the graben transmits groundwater flow between Jakes Valley and the White River Valley (Figure 4-9), respectively north and south of the caldera. The siliciclastic and intrusive rocks of the southern White Pine Range form a groundwater barrier between White River Valley and Railroad Valley. East-dipping sedimentary rocks in the range allow recharge to flow preferentially eastward from the range into the White River Valley.

Butte Valley, east of the Butte Mountains, is a graben similar to Long Valley. Butte Valley contains upper Paleozoic rocks at a shallow depth, with overlying Tertiary volcanic rocks in the southern part of the valley. The valley fill is a maximum of about 4,000 ft thick, in turn overlying less than 1,000 ft of Tertiary volcanic rocks. A narrow horst is within the northern end of Butte Valley (Plates 4 and 8, Cross section Y—Y').

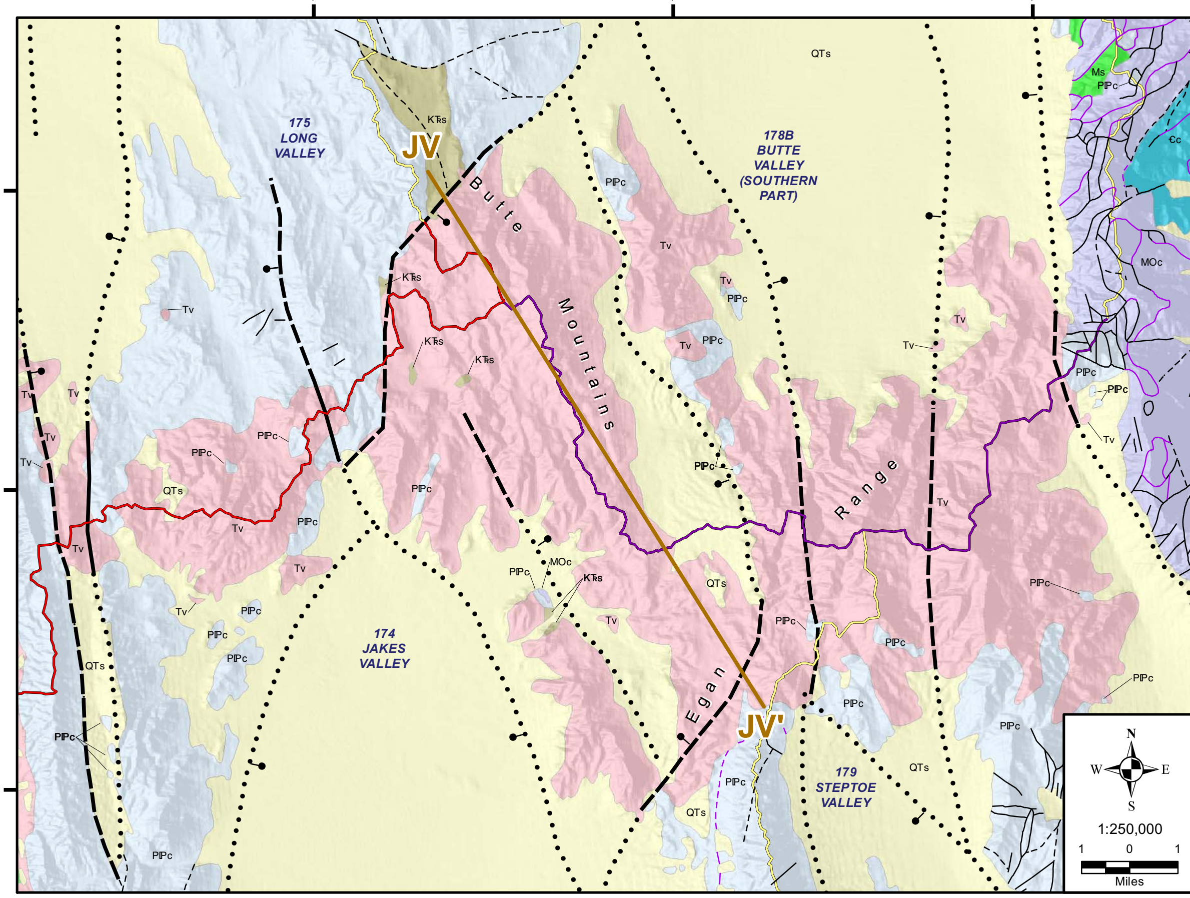
Based on the geologic framework, a flow path at the northern boundary of Jakes Valley is likely, with permissible boundaries extending south and east from there (Figure 4-9). This area is shown on a detailed geologic map of the volcanic hills that extend from the southern Butte Mountains across several western ridges of the Egan Range to define the southern end of Butte Valley (Figure 4-10). The flow path is along faults and fractures, from the southwestern part of Butte Valley into Jakes Valley. The geologic cross section (boundary flow profile) across the western part of the volcanic hills (Figure 4-10) is drawn perpendicular to this flow path.

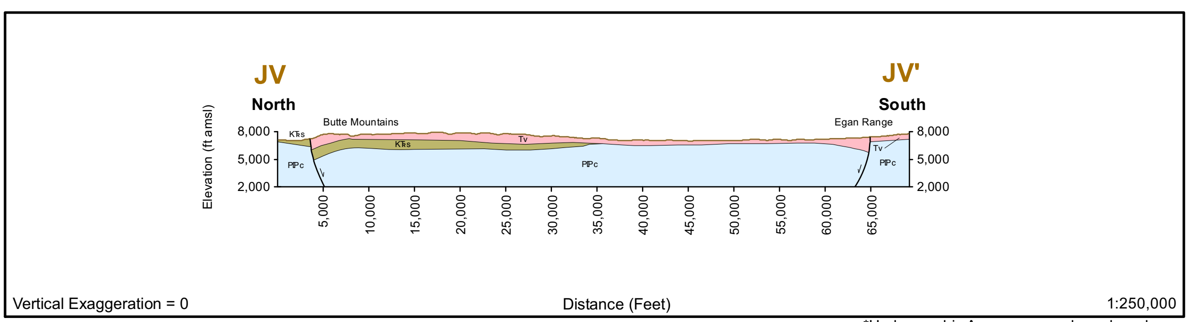
In places, the volcanic rocks south of Butte Valley have been eroded off, exposing underlying Triassic and upper Paleozoic carbonate rocks. The profile is drawn generally parallel to the basin boundary and perpendicular to the permissible flow path. A detailed analysis of gravity anomalies was performed by Mankinen and McKee (2011) of the USGS to further understand possible flow paths (Section 5.1.2 and Figure 5-8). The analysis suggests that the primary structure is the large fault at the left (northwest) end of the cross section. This fault shows up as a prominent structure identified by maxspots on the isostatic residual gravity map (Figure 5-8). Summit Spring, along the fault near the basin boundary, suggests the presence of water in the fault zone. Another major fault, shown at the southeastern end of the profile, may also provide a conduit for groundwater to Jakes Valley.

A second permissible flow path, from southeastern Butte Valley southeastward to Steptoe Valley along the range-front fault on the western side of the Egan Range (eastern edge of Figure 4-10), would be in part within fractured volcanic rocks on the western downthrown side of this fault zone. If so, flow would pass beneath a low, unnamed pass between the headwaters of north-flowing Combs Creek and those of south-flowing Smith Valley.

Jakes Valley, south of the Butte Mountains, may be as deep as 6,500 ft (Plates 4 and 8, Cross Section W—W'), with Tertiary volcanic rocks and upper Paleozoic carbonate rocks beneath about 5,000 ft of basin-fill sediments. Most of interbasin flow to Jakes Valley is thought to come from Long Valley (Harrill et al., 1988), with some smaller amount likely from Butte Valley as previously described. However, as part of BARCASS, Knochenmus et al. (2007) and Welch et al. (2007) suggested an additional but significant volume passes from Steptoe Valley northwest beneath the northern business district of Ely, Nevada, then through the northern Egan Range to Jakes Valley; this hypothesis is discussed in Section 6.0. However, this boundary is interpreted here as a boundary of unlikely flow. Groundwater out of southern Jakes Valley is likely to travel to the southeast beneath the ephemeral surface-water outlets (Jakes Wash area) from Jakes Valley to White River Valley, as well as southward along parts of the graben in the White River caldera.

West of the White Pine Range, Newark Valley is a shallow graben, narrowing and becoming shallower to the south, as described in Section 4.4.1. West of the southern end of the White Pine Range, Newark Valley opens out southward into Railroad Valley, a broad deep graben. East of the axis of the White River caldera, the White Pine Range is dropped down by many down-to-the-east





*Hydrographic Area name and number shown

Legend

Hydrogeology

Map Unit - Description

QTs Quaternary-Tertiary sediments

Tv Tertiary volcanic rocks

KTRs Cretaceous-Triassic clastic rocks

PIPc Permian-Pennsylvanian carbonate rocks

Ms Mississippian clastic rocks

MOc Mississippian-Ordovician carbonate rocks

Regional Faults

Normal fault

Solid where known; dashed where inferred; dotted where concealed. Bar and ball on downthrown side of fault.

Subsidiary Faults

Normal fault

Detachment fault

Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain. Bar and ball on downthrown side of fault.

Cross Section profile

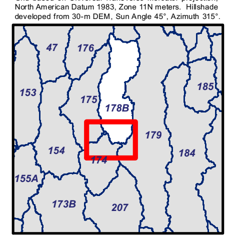
Potential for Groundwater Flow Across Hydrographic Area* Boundary

Permissible

Likely

Unlikely

Grid based on Universal Transverse Mercator projection, North American Datum 1983, Zone 11N meters. Hillshade developed from 30-m DEM, Sun Angle 45°, Azimuth 315°.



MAP ID 18073-3210 05/25/2011 BP

Figure 4-10
Hydrogeologic Map and Cross Section of Area between Butte Valley and Jakes Valley

normal faults that also create White River Valley to the east. Although relatively shallow at this latitude, near Preston and Lund, Nevada, White River Valley widens and becomes a deep, broad graben to the south, with a depth of more than 5,000 ft (see Section 4.4.4).

4.4.4 Horse, Grant, and Quinn Canyon Ranges

At the southern side of the White River caldera in northern Nye County, Nevada, the east-striking, oblique-slip Currant Summit fault zone (Moores et al., 1968; Williams and Taylor, 2002), part of the Prichards Station transverse zone, structurally separates the White Pine Range to the north from the small, 20-mi-long, north-trending Horse Range to the south. The Horse Range consists of east-dipping, lower to middle Paleozoic sedimentary rocks (Plates 4 and 8, Cross Section U—U'). The Horse Range is uplifted on its western side against thick, east-dipping volcanic rocks and basin-fill sediments to the west. The basin-fill sediments fill Horse Camp Basin (Moores et al., 1968; Brown and Schmitt, 1991), and the volcanic rocks form the eastern flank of the northern Grant Range and underlie the basin.

The Grant Range is 40 mi long, increasing in width southward. It, in turn, passes into the high, broad Quinn Canyon Range to the south, which is 15 mi north-south by 20 mi east-west. These ranges are bounded on the west by the deep graben of Railroad Valley, whereas the Horse and Grant ranges are bounded on the east by the large, deep graben of White River Valley. The Grant Range is underlain mostly by east-dipping Cambrian through Permian carbonate rocks (Lumsden et al., 2002) cut by several east-verging Sevier thrust faults (Taylor et al., 2000) and, in turn, intruded by a large Tertiary pluton in the central and southern parts of the range (Plates 4 and 8, Cross Section Q—Q'). Low-angle Tertiary detachment faults dip into Railroad Valley from both sides, especially the Grant Range on the east. Many subsurface detachments were detected during widespread exploration for oil in Railroad Valley (Lund et al., 1991; Schalla and Johnson, 1994; French and Schalla, 1998; Ehni and Faulds, 2002). The carbonate rocks plunge generally northward in the range, so Cambrian and Precambrian siliciclastic rocks and the Tertiary intrusive rocks form the core of the southern Grant Range and likely act as a barrier to groundwater flow between Railroad and White River valleys.

The Quinn Canyon Range, south of the Grant Range, is bordered by Garden Valley to the east, the southern end of Railroad Valley to the north and northwest, and Penoyer Valley (Sand Spring Valley) to the south. Garden Valley is a narrow graben several thousand feet deep, between the Quinn Canyon and Golden Gate Ranges (Plates 4 and 8, Cross Sections T—T' and Q—Q'). The Quinn Canyon Range is underlain by all or parts of several calderas (Ekren et al., in press), making up the southeastern part of what is referred to on Plate 1 as the central Nevada caldera complex. This feature, called a caldera complex by Best et al. (1993) and Scott et al. (1995), is not, however, a true caldera complex because not all of it has subsided as a caldera; instead, individual calderas are separated by pre-caldera rocks, so it might better be considered a cluster of adjacent calderas. The southwestern end of the Quinn Canyon Range, including the southern edge of the “caldera complex,” passes into Lincoln County, where it is a narrow prong of outflow volcanic rocks. East of this prong and south of the main massive part of the range underlain by the caldera is Penoyer Valley (Sand Spring Valley), which is the single-basin Penoyer Valley Flow System (Harrill et al., 1988).

The calderas of the main mass of the Quinn Canyon Range are underlain by intracaldera (resurgent) plutons (see Plates 4 and 8, Cross Section T—T') that likely limit east-west groundwater flow between Railroad Valley and White River/Garden valleys. Fault conduits between Railroad Valley and Penoyer Valley are likely limited due to the presence of a buried caldera margin and perhaps the strong range-front fault along the western side of the Quinn Canyon Range.

Gravity surveys on the eastern side of White River Valley (Scheirer, 2005) suggest that the valley is underlain by many thousands of feet of basin-fill sediments and volcanic and carbonate rocks. We interpret that the White River Valley contains at least as much as 5,000 ft of valley fill (Dixon et al., 2007a and c) (Plates 4 and 8, Cross Sections Q—Q' and U—U'). The valley narrows southward east of the Seaman Range (here called Pahroc Valley) as the ephemeral White River was incised into Pleistocene basin-fill sediments during canyon cutting following drainage integration with the Colorado River (Dixon, 2007) (Plates 4 and 8, Cross Section T—T'). White River Valley receives its primary interbasin flow from Jakes Valley (Harrill et al., 1988). However, Welch et al. (2007) suggested an additional but significant contribution from Steptoe Valley that passes southwest through the southern part of Ely, then through the northern Egan Range (see, however, Section 6.0). In the southwest part of White River Valley, the geology is such that groundwater flow is permissible from southwestern White River Valley to Garden Valley. Also, it is likely for groundwater to flow from southwestern White River Valley into Coal Valley, and beneath the intermittent White River east of the Seaman Range into Pahroc Valley.

Springs are abundant in White River Valley, especially in the center of the valley and near Nevada Highway 318, which is west of the eastern side of the valley. Those in the center of the valley are warm and hot springs, some of which supply lakes that together were grouped and set aside as the Wayne Kirch Wildlife Management Area, managed by the Nevada Department of Wildlife. As far as we can tell, virtually all springs in White River Valley come up along north-trending basin-range faults, many of them with Quaternary displacement. Hydrologic data and geologic cross sections of most springs in White River Valley are discussed in Volume 3 of SNWA (2008), including Hot Creek Spring in the Kirch Wildlife Management Area (see also Section 6.2.2.1).

4.4.5 Worthington Mountains and Timpahute Range

The northern end of the narrow, 15-mi-long, north-trending Worthington Mountains is just southeast of the Quinn Canyon Range. The Worthington Mountains define the northeastern side of Penoyer Valley and the western side of southern Garden Valley. The Worthington Mountains consists mostly of west-dipping Ordovician through Mississippian rocks that are uplifted along a north-striking fault on the eastern side of the range. The range contains the east-verging Freiburg thrust, which placed Ordovician rocks on Ordovician and Devonian rocks during Sevier deformation (Taylor et al., 2000).

The Worthington Mountains extend southward into the Timpahute Range, an east-trending block of heavily faulted mountains. The Timpahute Range separates the southeastern side of Penoyer Valley from northern Tikaboo Valley. The Timpahute Range is underlain by Upper Cambrian through Permian sedimentary rocks, unconformably overlain by Tertiary volcanic rocks. The Paleozoic rocks are cut by several Sevier thrusts, the lowest of which places Devonian rocks over Devonian through Permian rocks. The uppermost thrust places Cambrian through Ordovician rocks above younger rocks (Taylor et al., 1994). The western end of the range includes the Tempiute mining district of tungsten and silver, associated with two Tertiary granite stocks. The range is heavily broken by north-south basin-range faults and synchronous east-west faults. The east-west faults, which define the southern margin of the range, are part of the Timpahute transverse zone, which also controls the northern side of the Caliente caldera complex.

Garden Valley, east of the Worthington Mountains, terminates southward against the eastern Timpahute Range. Garden Valley is a graben containing about 3,000 ft of basin-fill sediment (Plates 4 and 8, Cross Section T—T'). Penoyer Valley is bounded on the east by a range-front fault and on the south by the east-west Timpahute transverse zone. Penoyer Valley probably contains several thousand feet of basin-fill sediments.

Groundwater flow to the west of the southern Worthington Mountains is theoretically possible through the fractured Paleozoic carbonate and Tertiary volcanic rocks because of the north-northeast-striking faults connecting Garden Valley with Penoyer Valley at the northern end of the Worthington Mountains. This flow, however, has been considered minor by Belcher (2004) and for the purposes of this study is deemed unlikely (Figure 4-9). The eastern Timpahute Range is underlain by a granitic pluton and, therefore, groundwater flow between Garden Valley and the eastern arm of northern Tikaboo Valley is unlikely.

4.4.6 Golden Gate Range, Mount Irish, Pahranagat Range, and Northern Sheep Range

The Golden Gate Range is a 40-mi-long, string of low north-trending faulted hills that passes southward into Mount Irish, a 10-mi by 10-mi range bounded by east-striking faults. Mount Irish is the northernmost part of the larger, 35-mi-long Pahranagat Range, which continues southward to the 50-mi-long Sheep Range. The northern end of the Golden Gate Range, located in Nye County, Nevada, forms the western side of White River Valley and the eastern side of Garden Valley. The main part of this range forms the boundary between Garden and Coal valleys in Nye and Lincoln counties. In Nye County, the Golden Gate Range consists of Devonian through Pennsylvanian rocks overlain by Tertiary volcanic rocks. Here and farther south, the range is a west-tilted horst; the main controlling normal fault is on the eastern side. In Lincoln County, the rocks of the Golden Gate Range are Devonian to Pennsylvanian sedimentary deposits, of which Ordovician through Devonian rocks are thrust over Devonian to Mississippian rocks (Plates 4 and 8, Cross Section T—T'). In the central Golden Gate Range, the range is cross cut by two faults along related gaps that would allow groundwater to flow in a west to east direction into Coal Valley (Figure 4-9).

The Mount Irish Range is a stubby, east-trending block that is the eastern continuation of the Timpahute Range and is controlled by east-striking faults of the Timpahute transverse zone. Mount Irish is made up of Ordovician through Mississippian rocks containing the same thrusts including the Gass Peak thrust that occur in the Timpahute Range (Plates 4 and 8, Cross Sections O—O' and S—S') (Taylor et al., 1994 and 2000). The Mount Irish block closes the southern end of Coal Valley and it is unlikely that north-striking faults through the block allow groundwater flow at this location.

The Pahranagat Range, including a separate parallel structural block along the eastern side that is called the East Pahranagat Range, is bounded by Tikaboo Valley on the west and shallow Pahranagat Valley (Tingley et al., 2010) on the east. The Pahranagat Range (Page et al., 2005a; Jayko, 1990 and 2007) is a horst bounded on both sides by major normal faults (Plates 4 and 8, Cross Sections M—M' and N—N'). In the north, the range dips gently west but in the south it is a syncline. The east-verging

Gass Peak thrust of Sevier age runs the length of the range, placing Middle Cambrian to Devonian rocks on Devonian to Mississippian rocks. The East Pahranagat Range locally consists of an overturned fold of Devonian to Pennsylvanian rocks. Tertiary volcanic rocks unconformably overlie the folded and thrust-faulted Paleozoic rocks and are thickest where downfaulted into a graben between the Pahranagat Range and East Pahranagat Range. At their southern ends, the Pahranagat and East Pahranagat Ranges are separated from the northern Sheep Range by a series of east-northeast-striking splays of the predominantly left-lateral PSZ (Ekren et al., 1977; Johnson, M. 2007a). Figure 4-11 shows the PSZ with respect to basin boundaries and topographic features. The southern splay of the PSZ is the Maynard Lake fault zone (Plates 5 and 9, Cross Section A—A') (Tschanz and Pampeyan, 1970; Jayko, 1990 and 2007). The western part of this fault is interpreted to join the main north-south normal fault that defines the western side of the Sheep Range, and the eastern part of the fault is interpreted to join the main north-south normal fault that defines the western side of the Delamar Mountains (Figure 4-11). In this interpretation, the Maynard Lake zone—like the others of the PSZ—is an accommodation or transfer fault that transfers east-west extension (pulling apart) into left-lateral shear. In this scenario, in those places where faults strike north, all east-west extension is taken up by normal movement down the dip of the fault plane, and where faults strike northeast, east-west pulling apart is taken up by mostly left-lateral movement.

The northern Sheep Range is a narrow, abrupt mountain mass of Cambrian and Ordovician sedimentary rocks that make up the leading edge of the Gass Peak thrust fault of Sevier age (Plates 5 and 9, Cross Section L—L'; Page et al., 2005a). It is geologically likely that the subparallel faults of the PSZ provide conduits from southern Pahranagat Valley through the Pahranagat Range to Tikaboo Valley South. The most likely of these fault conduits is through the unnamed low pass between the Pahranagat Range and the Sheep Range, where the largest left-lateral fault zone, the Maynard Lake fault zone, cuts through brittle Tertiary ash-flow tuffs and Devonian dolomite at the pass (Figure 4-11).

Pahranagat Valley (see also Section 4.4.12), between the East Pahranagat Range on the west and the Hiko Range on the east, is a remarkably well-watered valley containing the agricultural communities of Hiko and Alamo, Nevada, and two large lakes that are the home of the Pahranagat National Wildlife Refuge (U.S. Fish and Wildlife Service). Structurally the valley is a shallow graben (Plates 4 and 8, Cross Sections S—S', O—O', N—N', and M—M'). Several large regional springs, including Hiko and Crystal springs and Ash Spring (Section 6.2.3.3), are controlled by basin-range faults (Dixon and Van Liew, 2007; Volume 3 of SNWA, 2008).

4.4.7 Southern Sheep Range, Las Vegas Range, and Elbow Range

The southern Sheep Range is underlain by mostly Cambrian and Ordovician carbonate rocks that dip eastward (Plates 5 and 9, Cross Sections E—E', F—F', G—G', and H—H') (Guth, 1980). The range is a large tilt block uplifted along major north-striking, basin-range normal faults on its western side. The range is on the upthrown western side of the low-angle, west-dipping Gass Peak thrust. The thrust transported Neoproterozoic to Cambrian quartzite and Cambrian to Devonian carbonate rocks eastward over Cambrian to Mississippian rocks. Within the Sheep Range, north-striking basin-range faults are abundant, but some cross-faults that strike east to east-northeast also have been mapped. Quaternary basin-range faults define much of the eastern side of the range (Dohrenwend et al., 1996).

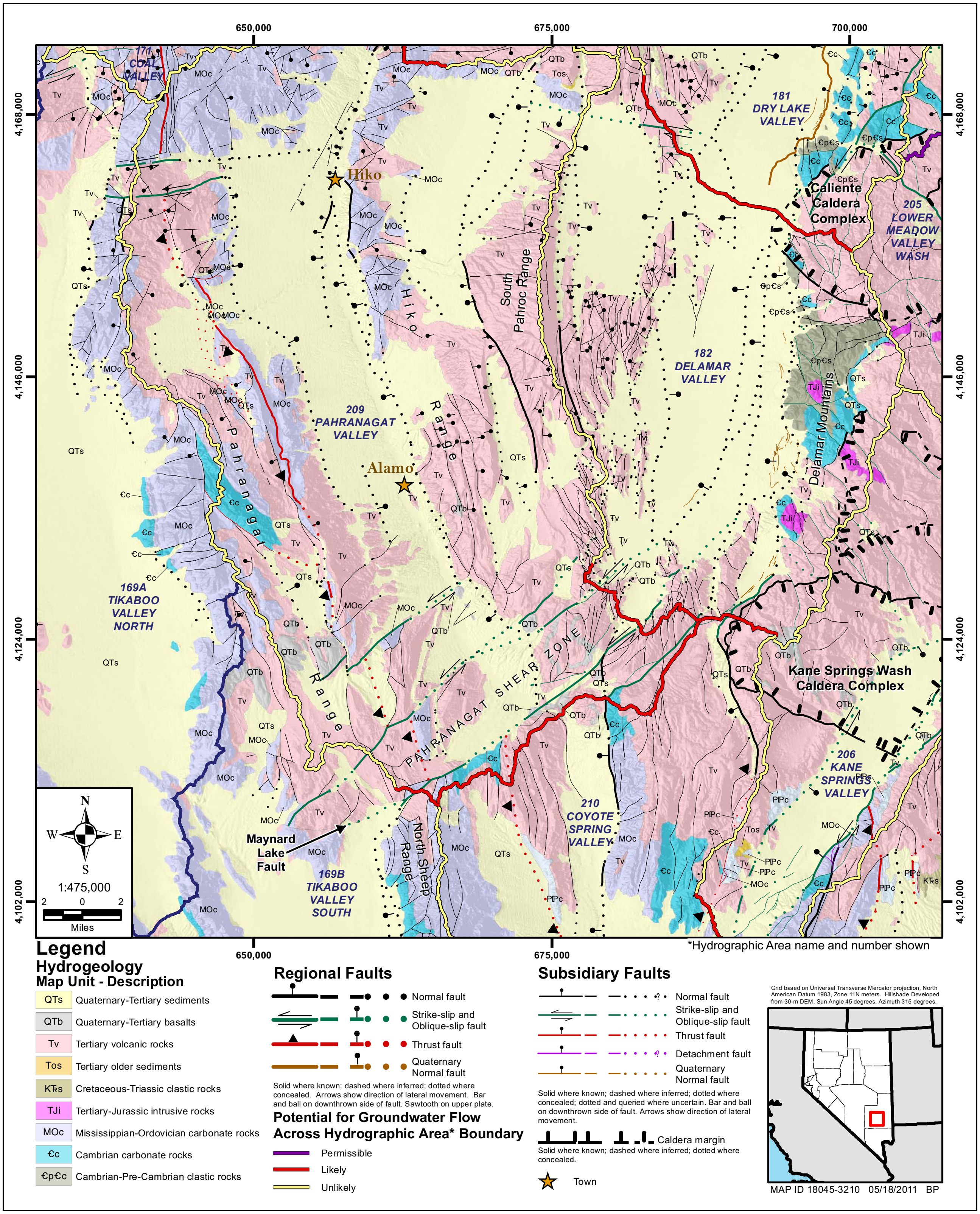


Figure 4-11
Hydrogeologic Map and Basin Boundaries of Pahranagat and Delamar Valleys and Vicinity

A small, north-trending range (Figure 4-11) lies east of the northwestern arm of Coyote Spring Valley and west of Pahranagat Wash, U.S. Highway 93 (US 93), and the northeastern arm of Coyote Spring Valley. The small range is considered part of the northern Sheep Range but is separated from the high Sheep Range to the west by the northwestern arm of Coyote Spring Valley. The northern end of this small range terminates against the Maynard Lake fault zone of the PSZ. This small basin-range tilt block consists largely of east-dipping volcanic rocks (Jayko, 1990 and 2007) that rest unconformably on Pennsylvanian and Permian carbonate rocks. North-striking normal faults within, west, and east of the small range pass into the Maynard Lake fault zone and transfer their normal slip to oblique slip. The buried north-striking trace of the Gass Peak thrust fault passes beneath the normal faults near the western side of the small range.

The Las Vegas Range northwest of Apex is defined by the Gass Peak thrust, which transported rocks as old as the Cambrian Wood Canyon Formation eastward over Mississippian, Pennsylvanian, and Permian carbonate rocks of the Bird Spring Formation (Plates 5 and 9, Cross Sections F—F', G—G' H—H', and I—I') (Maldonado and Schmidt, 1991). Most of the range is made up of folded Bird Spring limestone, with the Gass Peak thrust exposed along its western side (Maldonado and Schmidt, 1991; Page, 1998). The small Elbow Range, which bounds the Las Vegas Range on the northeast, is made up of thrusted and folded Bird Spring Formation (Page and Pampeyan, 1996) that has been uplifted as a horst (Plates 5 and 9, Cross Sections E—E' and F—F'). The southern ends of the Sheep Range and Las Vegas Range, and continuing east, of the Arrow Canyon Range (Section 4.4.17), Dry Lake Range (Section 4.4.21), and Muddy Mountains (Section 4.4.21) terminate against the west-northwest-striking, oblique-slip (right-lateral and normal) Las Vegas Valley Shear Zone (LVVSZ), which defines the northern side of the Las Vegas basin (Workman et al., 2002a and b; Page et al., 2005a and b; Beard et al., 2007).

Faults of the PSZ, notably the Maynard Lake fault zone, provide likely flow paths from southern Delamar Valley (Section 4.4.12) to the southern boundary of Pahranagat Valley. The Maynard Lake fault zone provides a partial barrier to southward flow from southern Pahranagat and Delamar valleys, effectively damming the groundwater at this location (Rowley and Dixon, 2001; Rowley et al., 2001; Dixon et al., 2007a; Johnson, M. 2007b). Significant groundwater, however, works its way south through the barrier into Coyote Spring Valley (Harrill et al., 1988), largely along the north-trending normal faults and fractures bounding the small north-trending range west of US 93 and along the large north-trending normal fault east of US 93 that defines the eastern side of the northeastern arm of Coyote Spring Valley (Figure 4-12). All these north-trending faults join the Maynard Lake fault zone. In addition, some groundwater from Delamar Valley may follow the conduit into Coyote Spring Valley created by the unnamed fault of the PSZ south of the Maynard Lake fault.

The many basin-range faults that underlie and define the sides of Coyote Spring Valley provide the pathways for southward groundwater flow (Harrill et al., 1988; Schmidt and Dixon, 1995). About 15 mi south of the northern end of Coyote Spring Valley, faults on the western side of the Elbow Range and eastern side of the Sheep Range (Figure 4-12) provide pathways for groundwater flow to the south and Hidden Valley. Gravity data in Coyote Spring Valley (Phelps et al., 2000) indicate that much of Coyote Spring Valley is relatively shallow except for deeper internal grabens downthrown along faults just west of the Meadow Valley Mountains and west of the northern Arrow Canyon Range (see Section 5.2). The deeper graben just west of the Meadow Valley Mountains is oriented

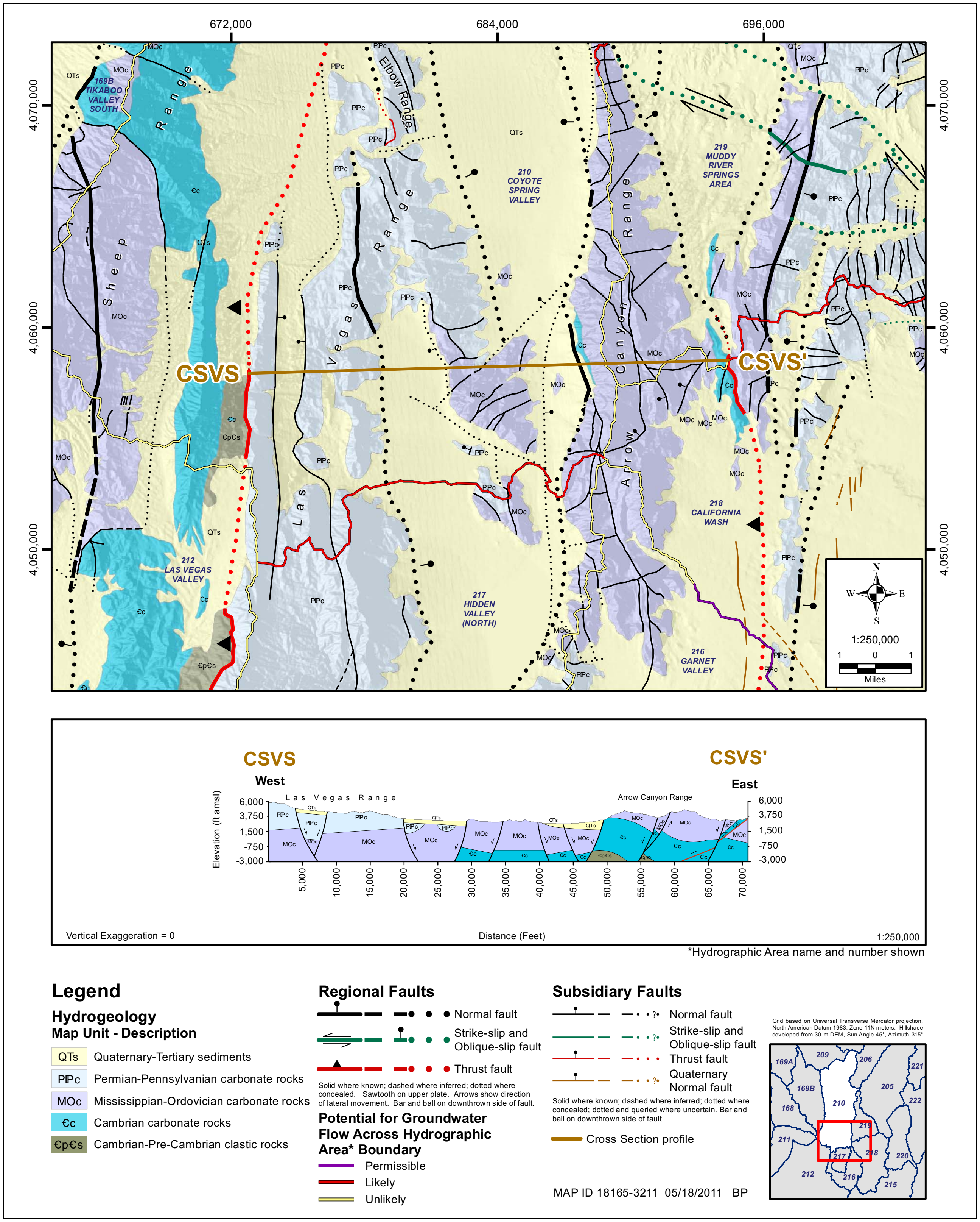


Figure 4-12
Hydrogeologic Map and Cross Section of Southern Coyote Spring Valley and Hidden Valley

north-northwest, indicating that the controlling buried faults have the same trend. These faults serve to carry most groundwater beneath Pahranagat Wash and the eastern part of Coyote Spring Valley along a path that generally follows the Wash east, past the northern end of the Arrow Canyon Range and into small Table Mountain basin (Harrill et al., 1988). From there, most of this groundwater continues southeast and east-southeast, partly beneath and partly parallel to, but south of, Nevada Highway 168 along structurally-controlled flow paths to Muddy River Springs, then along structurally-controlled flow paths as underflow beneath the Muddy River to the Overton Arm of Lake Mead. This flow path is described in Sections 4.4.17 and 4.4.21.

It is likely that some of the groundwater beneath Coyote Spring Valley continues southward, parallel to US 93, along faults west of the western side of the Arrow Canyon Range and both east and west of the Elbow Range. A geologic map and cross section (Figure 4-12) shows many north-trending basin-range faults west of the Arrow Canyon Range that may carry groundwater. Groundwater in the vicinity of the cross section is known to be deep (700 to 800 ft), but it would be moving in Cambrian to Permian carbonate rocks that are locally heavily fractured along the faults, creating many likely flow paths. Perhaps the most important of these conduits shown on the cross section is the large western frontal fault of the Arrow Canyon Range, which would allow access of groundwater from southern Coyote Spring Valley into Hidden Valley.

4.4.8 Cherry Creek Range

The high Cherry Creek Range is in northern White Pine and southern Elko Counties. The range is a large horst of gently west-dipping Precambrian through Permian sedimentary rocks. Basin-range faults separate it from Butte Valley on the west and from Steptoe Valley on the east; the bigger fault is on the east.

A thin sliver of bedrock cored by a Tertiary intrusion connects the Cherry Creek Range with the northern Egan Range. A northeast-striking oblique-slip fault, left-lateral and down-to-the-west, cuts through the southern end of this sliver. Despite the suggestion of Harrill et al. (1988), it is unlikely that this fault provides an avenue for minor groundwater to flow from Butte Valley South to Steptoe Valley (Figure 4-9). This pluton, along with Precambrian and Cambrian quartzite into which it was intruded, form a likely barrier to groundwater flow north of the fault. The west dip of the rocks in the Cherry Creek Range would facilitate flow of recharge westward toward Butte Valley.

4.4.9 Northern Egan Range

Like the Cherry Creek Range to the north, the Egan Range is a high, north-trending horst of Precambrian through Permian rocks, unconformably overlain by Tertiary volcanic 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 mi in White Pine County, then another 40 mi in Lincoln County. In the northern end of the range, the rocks dip westward and are intruded by Tertiary stocks. The Snake Range decollement is present here as a thin skin of Paleozoic rocks at the crest of the range and along its western slope (Plates 4 and 8, Cross Section X—X'). The decollement is a Tertiary denudation/attenuation fault that transported rocks as old as Middle Cambrian eastward and placed them on top of older rocks. Butte Valley is to the west and Steptoe Valley is to the east of the northern Egan Range.

About 20 mi south of the northern end of the Egan Range, the range becomes considerably wider and lower as the Butte Mountains join it from the west and Butte Valley closes. Here the range is broken into a series of horsts and grabens (Plates 4 and 8, Cross Section W—W'). The downthrown areas on the western side of the Egan Range are underlain by Tertiary volcanic rocks that form low ridges and hills that connect with the southeastern Butte Mountains. The towns of Ely and Ruth, Nevada, occur in this broad, low, heavily faulted part of the Egan Range, in areas called Copper Flat and Smith Valley. A major mining district, the Robinson district, was developed on a series of east-trending ore deposits of copper, molybdenum, lead, zinc, silver, and gold associated with a middle Cretaceous pluton. Barren Eocene rhyolite plutons and volcanic rocks also are present in the area and extend to Ely on the eastern side of the Egan Range adjacent to Steptoe Valley (Brokaw and Shawe, 1965; Brokaw and Heidrick, 1966; Brokaw and Barosh, 1968; Brokaw, 1967, Brokaw et al., 1973; Jones, 1996; Gans et al., 2001; Tingley et al., 2010). Southwest of the mining district, a series of low hills extends southwest to the White River caldera of the White Pine Range. These hills provide the southeastern margin of Jakes Valley and the north-northwestern margin of White River Valley (Figure 2-1).

South of the Robinson mining district, the Egan Range continues southward for almost 30 mi to the latitude of Lund as a single, high horst of east-dipping Cambrian through Permian rocks that together are more than 30,000 ft thick (Plates 4 and 8, Cross Section V—V') (Kellogg, 1963 and 1964; Taylor et al., 1991). Patches of volcanic rocks overlie the Paleozoic rocks on the eastern edge of the range. Several small plutons also are exposed. Major faults of the horst separate the Egan Range from the White River Valley to the west and southern Steptoe Valley to the east. Steptoe Valley is a deep graben containing as much as 8,000 ft of basin-fill sediments. Thus, it is one of the deepest grabens in the central Great Basin.

4.4.10 Southern Egan Range

At the latitude of Lund, Nevada, a narrow ridge of Cambrian to Permian rocks extends southeastward from the main part of the Egan Range to the Schell Creek Range to the east. This ridge, at Bullwhack Summit, forms the southern end of Steptoe Valley and the northern end of Cave Valley. The Egan and Schell Creek Ranges continue southward, with Cave Valley between them. Along the western side of Cave Valley (Plates 4 and 8, Cross Section U—U'), the Egan Range is a complexly faulted horst of east-dipping Cambrian to Permian rocks, overlain by Tertiary volcanic rocks. White River Valley is west of the Egan Range. Halfway southward down Cave Valley, at a latitude about 20 mi south of Lund, a northeast-striking oblique-slip fault passes through the Egan Range at Shingle Pass (Plates 4 and 8, Cross Section R—R') to join the western range-front fault of the Egan Range. Farther south, the Egan Range remains an east-tilted horst of Cambrian through Tertiary rocks, then bends southeast to join the southern end of the Schell Creek Range. Here Cave Valley terminates where the Egan and Schell Creek ranges join each other in a complex of north-northeast- and north-northwest-striking normal and oblique-slip faults. Farther south, the combined Egan and Schell Creek ranges become a low, narrow, north-northwest-striking horst of faulted Paleozoic sedimentary rocks and Tertiary volcanic rocks (Plates 4 and 8, Cross Section Q—Q') that topographically continues southward to the northern end of the North Pahroc Range.

Cave Valley consists of two distinct but connected portions, separated by the oblique-slip fault at Shingle Pass. One of these portions, northern Cave Valley, is a narrow graben containing mostly east-dipping Cambrian rocks at shallow depth overlain by relatively thin volcanic rocks and in turn basin-fill sediments (Plates 4 and 8, Cross Section U—U'). Gravity data (Scheirer, 2005) and oil test well logs (Hess, 2004) indicate that the base of the combined basin-fill sediments and volcanic rocks is about 3,000 ft below the valley floor of northern Cave Valley.

The fault at Shingle Pass likely provides a conduit for groundwater flow from northern Cave Valley into White River Valley (Figure 4-9). Shingle Pass is formed by the intersection of several major faults, but primarily it is defined by a northeast-striking, oblique-slip (left lateral and normal) fault zone (Figure 4-13). At the western end of Shingle Pass, this fault zone cuts through upper Paleozoic limestone on its northern side and lower Paleozoic limestone on its southern side. These rocks are brittle so the faults could be conduits to southwestward flow.

Southern Cave Valley is in Lincoln County and south of where the valley narrows to about 2 mi wide. The narrowing is due to a northeast-trending tilt block bounded on the northwest by the fault at Shingle Pass and striking northeast across most of Cave Valley. The block is buried but continues in the subsurface to the northeast to the large north-trending range-front fault zone that uplifts the Schell Creek Range (Plates 4 and 8, Cross Section R—R'). To the southwest, the tilt block swings into the main north-trending part of the Egan Range, which continues to the south. The tilt block consists of southeast-dipping Cambrian through Mississippian rocks that includes the Mississippian Chainman Shale, which is buried along the southeastern edge of the block. These relationships are supported by oil-test-well drilling, gravity surveys, seismic surveys and AMT profiles (Hess, 2004; McPhee et al., 2005, 2006a and b; Mankinen et al., 2006; Scheirer, 2005). Details are provided in Sections 5.1.4, 5.2.3, and 5.3. Despite the narrowing of the valley, a groundwater connection between northern and southern Cave Valley is considered certain because of flow along the north-striking, western range-front fault of the Schell Creek Range. Southern Cave Valley generally contains less than 3,000 ft of basin-fill sediments and volcanic rocks. In a narrow, central, north-trending axial part of the valley, however, these Cenozoic rocks are 6,000 ft or more thick. McPhee et al. (2005 and 2007) provided information on faults on the eastern side of the basin based on AMT profiles.

At the southern end of Cave Valley, a series of north-northwest-trending right-lateral oblique-slip faults and north-northeast-trending, left-lateral oblique-slip faults forms the boundary between southern Cave Valley, northern Pahroc Valley, and northern Dry Lake Valley. These faults provide likely and permissible groundwater pathways out of southern Cave Valley (Figure 4-9) into northern Pahroc Valley, and then potentially into northern Dry Lake Valley. A geologic map and cross section (Figure 4-14), oriented parallel to the basin boundary and perpendicular to flow, show several faults that may be conduits to southward flow through the Cave Valley boundary. The range-front, oblique-slip fault (left-lateral and normal) zone at the eastern end of the cross section juxtaposes Devonian dolomite against intrusive rocks. These rocks are brittle; they fracture easily and may form a significant fault conduit. The two faults farther west in the cross section cut through upper Paleozoic limestone, largely overlain by a relatively thin veneer of Tertiary ash-flow tuffs; such rocks also are brittle and would form permissible fault conduits.

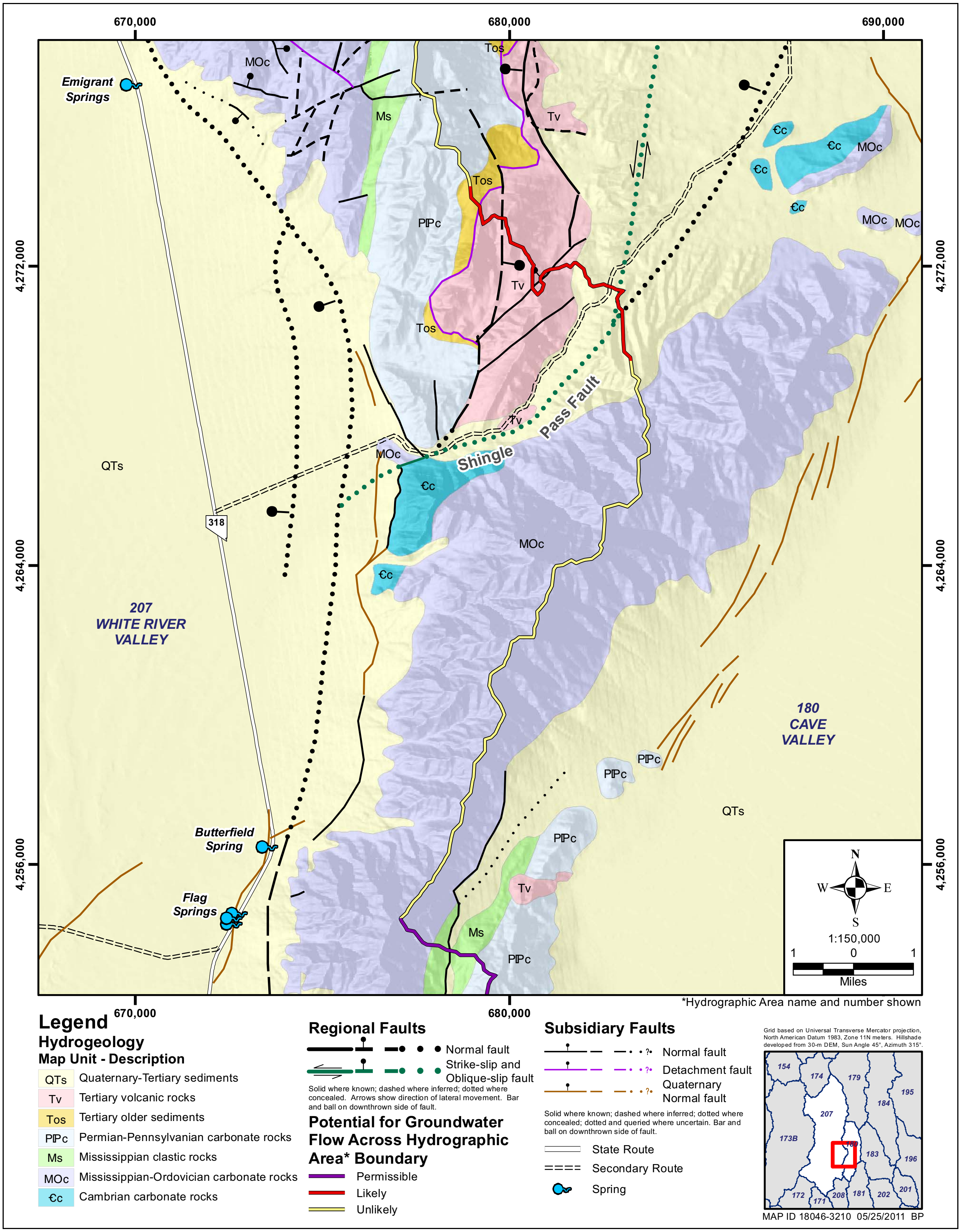


Figure 4-13
Hydrogeologic Map and Basin Boundaries of Shingle Pass Area

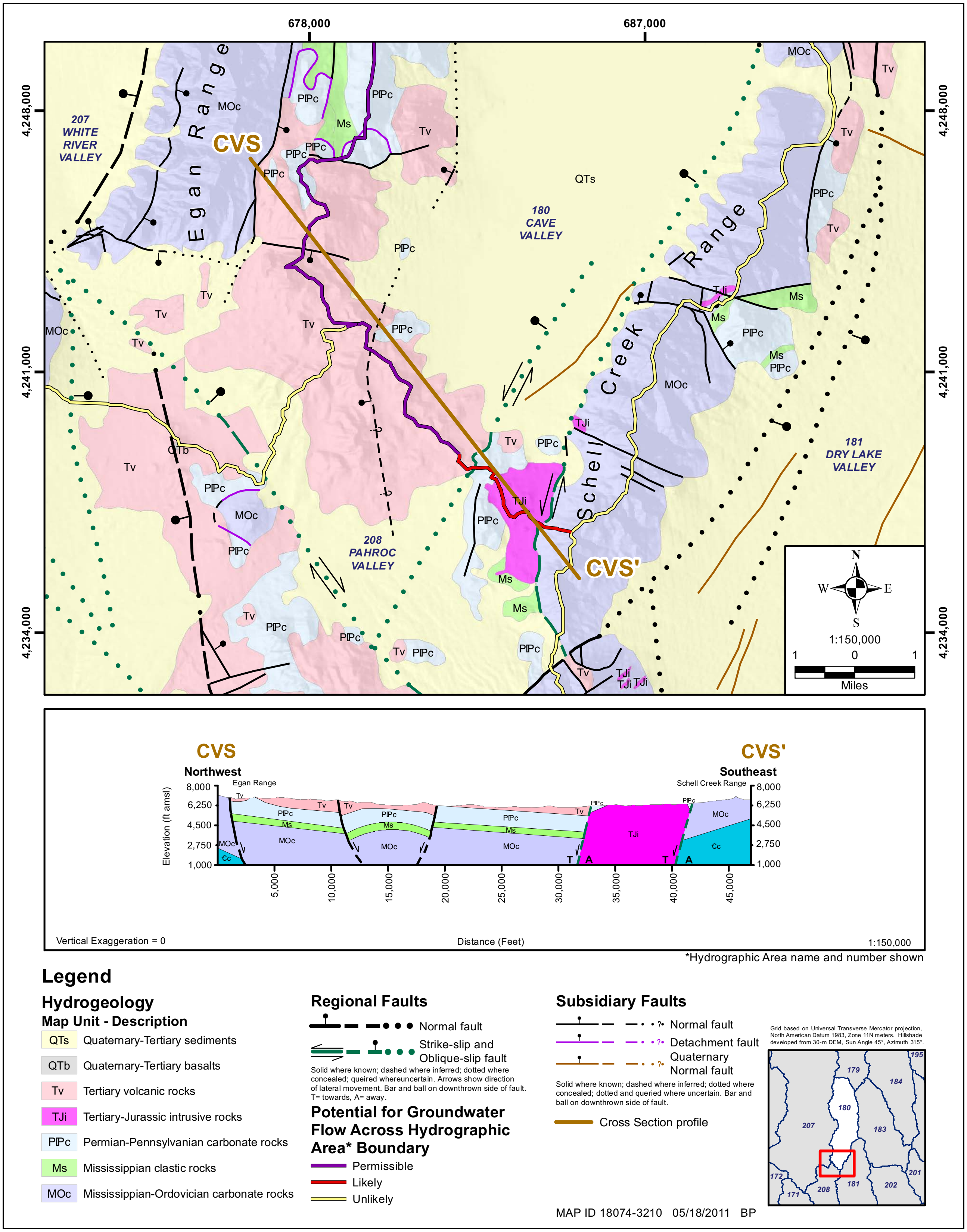


Figure 4-14
Hydrogeologic Map and Cross Section of Southern Cave Valley and Vicinity

4.4.11 Seaman Range

The 35-mi-long, heavily-faulted Seaman Range, located in Nye and Lincoln counties, is a horst that trends north and northwest and joins the Golden Gate Range at the northern end of both ranges (Section 4.4.6). Coal Valley, between the two ranges, is a graben containing several thousand feet of basin-fill sediments (Plates 4 and 8, Cross Section T—T'). The valley is bounded on the south by the Timpahute Range. At its northern end, the Seaman Range is low and bounds the southern end of the White River Valley. In Nye County, the Seaman Range is made up of Devonian to Pennsylvanian sedimentary rocks, overlain unconformably by Tertiary volcanic rocks (duBray and Hurtubise, 1994). In Lincoln County, the Seaman Range is made up of gently west-dipping Ordovician to Pennsylvanian rocks that are unconformably overlain by Tertiary volcanic rocks. The Tertiary volcanic rocks include the dacitic to rhyolitic Seaman volcanic center of flows, subordinate tuffs, and a central plug (duBray and Hurtubise, 1994). It is likely that northwest-trending faults along Seaman Wash (southern end of the range) form conduits for movement of groundwater between Coal Valley and Pahroc Valley (Figure 4-9).

4.4.12 North Pahroc, South Pahroc, and Hiko Ranges

The North Pahroc Range extends south for 40 mi from the junction with the southern Egan and Schell Creek ranges. It is separated from the smaller South Pahroc Range by east-trending belt of faulted rocks of low relief formed by the east-striking Timpahute transverse zone. This zone of faulted rocks is also the boundary between Dry Lake Valley to the north and Delamar Valley to the south. The Seaman (Section 4.4.11) and the North Pahroc are separated by Pahroc Valley but the ranges join together at their southern ends; the Hiko Range continues south of this intersection. The Hiko Range is a small range parallel to and west of the South Pahroc Range and east of northern Pahranagat Valley. The South Pahroc Range is south of the North Pahroc Range and forms the western boundary of Delamar Valley. The South Pahroc Range connects with the Hiko Range at their southern ends to form the eastern boundary of southern Pahranagat Valley. The ephemeral channel of the White River is present along the western side of the North Pahroc Range. The channel is deeply incised through Tertiary volcanic rocks at White River Narrows, then enters the Pahranagat Valley north of the town of Hiko, where the ephemeral channel is called Pahranagat Wash. Pahranagat Valley (Section 4.4.6) is a graben west of the Hiko Range that contains volcanic and Paleozoic bedrock at shallow depth (Plates 4 and 8, Cross Sections S—S', O—O', and N—N').

The North Pahroc, South Pahroc, and Hiko ranges are complex horsts. The North Pahroc Range consists of upper Paleozoic rocks overlain by Tertiary volcanic rocks. These rocks dip west off major faults along the eastern side of the range. The South Pahroc Range is a series of west-tilted blocks of volcanic rocks; the main faults are on the eastern side of the range. The Hiko Range consists of Devonian rocks and overlying volcanic rocks that dip east off the normal fault that separates the range from the floor of Pahranagat Valley. The South Pahroc and Pahranagat ranges terminate to the south against the east-northeast-trending PSZ, which also terminates Pahranagat and Delamar valleys.

Dry Lake Valley is a deep graben (Plates 4 and 8, Cross Sections T—T', P—P', and S—S') east of the southern Schell Creek Range and North Pahroc Range that contains, in most places, 3,000 to 5,000 ft of basin-fill sediments (Mankinen et al., 2006; Dixon and Rowley, 2007d) but locally along the axis of the graben as much as 10,000 ft of sediments and underlying downfaulted volcanic and carbonate rocks (Scheirer, 2005). Delamar Valley, just south of Dry Lake Valley, is a southward-deepening graben with a general maximum thickness of more than 3,000 ft of basin-fill sediments east of the South Pahroc Range (Mankinen et al., 2006; Dixon and Rowley, 2007d) but locally as much as 5,000 ft of sediments and underlying downfaulted volcanic and carbonate rocks (Scheirer, 2005). AMT profiles that show some details of the faults in Dry Lake and Delamar valleys are given in Sections 5.2.4 and 5.2.5, respectively.

Groundwater flow is southward in Dry Lake and Delamar valleys (Harrill et al., 1988; Brothers et al., 1996; Dixon and Rowley, 2007d). The basin boundary between Dry Lake Valley and Delamar Valley is so low as to be imperceptible to a person standing on the ground. Here US 93 runs east-west along the boundary, traversing what appears to be a continuous north-trending valley. Bedrock made up of east-striking fault blocks of Tertiary ash-flow tuffs and lava flows are exposed along the basin boundary both west (Scott and Swadley, 1992; Scott et al., 1995) and east (Swadley and Rowley, 1994) of the valley, and regional tectonic studies (Rowley, 1998; Rowley and Dixon, 2001) indicate that the buried Timpahute transverse zone passes beneath the valley beneath US 93 and is exposed to the east and west of the valley. The depth-to-basement map (Figure 5-13) shows that the thickness of basin-fill sediments and volcanic rocks along the basin boundary is from 2,500 to 6,500 ft thick. This thickness at the basin boundary, as well as continuation through the basin boundary between Dry Lake Valley and Delamar Valley of north-trending basin-range that bound the ranges on either side of the combined valleys, indicate that any basin boundary is indeed superficial and that most groundwater continues on its southerly route across the boundary into Delamar Valley.

To shed more light on the likely path between Dry Lake Valley and Delamar Valley, a boundary-flow profile (geologic cross section), oriented crudely parallel to the basin boundary and perpendicular to the likely flow paths, is given in Figure 4-15. The geologic map and profile show range-front faults on either side of the combined valley and other major faults internal to the valley, all of which are likely conduits for groundwater flow from north to south.

The southern end of Delamar Valley is structurally complicated. It is defined by the northeast-trending PSZ (Ekren et al., 1977; Scott et al., 1995), which has at least 5 parallel, left-lateral faults, spread across a width of about 10 mi. Three of these faults enter southern Delamar Valley, where they pass into north-trending normal faults (Figure 4-11). In addition, other north-trending normal faults, some feeding into faults of the shear zone, define the east and west sides of Delamar Valley; some continue southward into Coyote Spring Valley. Harrill et al. (1988) expressed the complex nature of the faults when he showed three southward flow paths out of southern Delamar Valley. Two of the fault zones of the PSZ that enter southern Delamar Valley are the Delamar Lake fault to the north and the Maynard Lake fault to the south. The Maynard Lake fault continues southwestward to define the southern end of Pahranagat Valley and the Pahranagat Range and the northern end of the Sheep Range, then the fault enters Tikaboo Valley. AMT profiles made across both faults in southern Delamar Valley show (Section 5.2.5, Figures 5-27 and 5-28, respectively) that both are large subvertical faults that exhibit high conductivity. Flow along both faults is geologically classified as likely. Of these flow paths, the most significant is along or north of the larger fault, the Maynard Lake fault. Near Maynard Lake, some of the fractures in the fault zone served as vents for late Cenozoic basalt lava flows, so in addition to its central gouge zone, the fault is likely a barrier in most places to flow to the south. Thus the fault creates a natural dam that impounds southern Pahranagat Lake, in the southern end of Pahranagat Valley. In addition, the fault barrier allows some

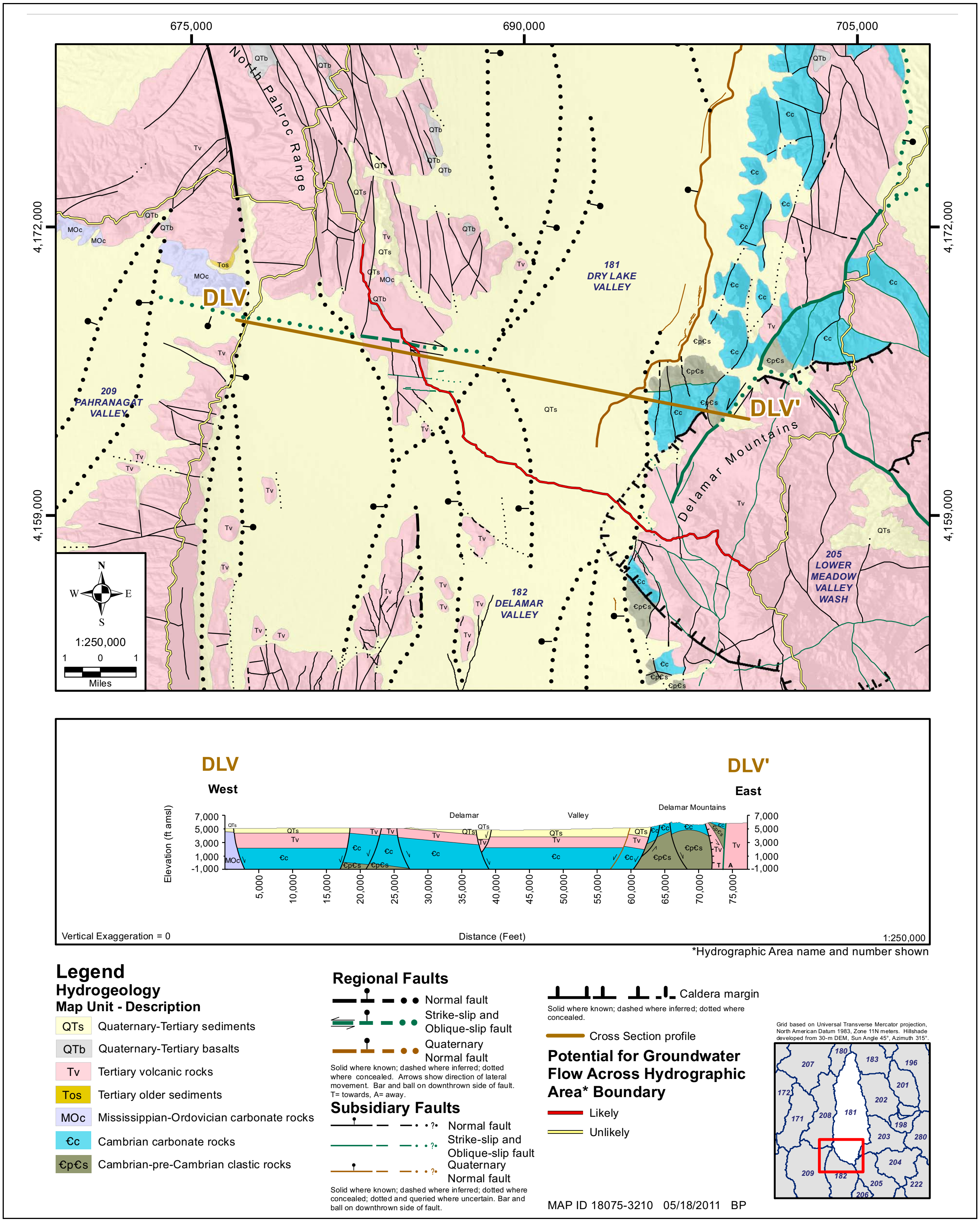


Figure 4-15
Hydrogeologic Map and Cross Section of Southern Dry Lake Valley and Northern Delamar Valley

groundwater to pass along its northwest side into Tikaboo Valley (Section 4.4.6). Nonetheless, significant groundwater from Delamar and Pahranagat valleys passes southward through the Maynard Lake fault and along other left-lateral or normal faults into Coyote Spring Valley, although the exact multiple paths have yet to be determined (Rowley and Dixon, 2001, 2004; Johnson, M. 2007a).

4.4.13 Schell Creek Range

The northern end of the Schell Creek Range is just south of the northern border of White Pine County. The range continues south for 120 mi, mostly as a high, narrow, north-striking horst. Steptoe and Cave valleys are on the west, and Spring Valley, northern Lake Valley, and northern Dry Lake Valley (Muleshoe Valley) are on the east. The northern part of the Schell Creek Range is made up of a west-dipping sequence of Precambrian through Permian rocks (Lumsden et al., 2002), with overlying Tertiary volcanic rocks along the faulted western flank of the range (Plates 4 and 8, Cross Section X—X'). Small Tertiary intrusions are exposed locally along the range. The main bounding basin-range fault is on the eastern side of the range. The Snake Range decollement is locally exposed at the crest of the Schell Creek Range. This denudation/attenuation fault transported Middle Cambrian and younger rocks westward and eastward over Lower Cambrian and older rocks (Figure 4-8). About 10 mi northeast of Ely, two north-northeast-striking faults form a graben, Duck Creek Valley, in the range (Plates 4 and 8, Cross Section W—W'). The southern half of the Schell Creek Range along Cave Valley contains a narrow, heavily faulted sequence of Precambrian through Tertiary rocks that dips east. Here the dominant fault is on the western flank of the range. West of the Geyser Ranch (Johnson, M. 2007b) (Plates 4 and 8, Cross Section U—U') the rocks are mostly Neoproterozoic and Cambrian quartzite (Van Loenen, 1987), but farther south the rocks are dropped down along an east-trending fault at Patterson Pass and are mostly of middle to upper Paleozoic and Tertiary age (Plates 4 and 8, Cross Section R—R'). Where the Schell Creek Range joins the Egan Range, a Tertiary pluton has mineralized adjacent carbonate rocks at the Silver King Mine (Plates 4 and 8, Cross Section Q—Q').

Spring Valley is a broad, deep graben. On the southwestern side of Spring Valley, a thin ridge of gently northeast-dipping Pennsylvanian and Permian carbonate rocks extends southeast from the central Schell Creek Range to the Fortification Range; here the low pass traversed by US 93 is called Lake Valley Summit. Spring Valley continues southeast on the eastern side of the Fortification Range. South of the thin carbonate ridge is Lake Valley (Johnson, M. 2007a), between the Schell Creek Range and the Fortification Range. Lake Valley contains at least 2,000 ft of basin-fill sediments throughout its 60-mi length but locally the sediments may be much thicker (Plates 4 and 8, Cross Sections U—U', R—R', and Q—Q') (Scheirer, 2005). At the thin bedrock ridge between the Fortification Range and the Schell Creek Range, the combination of carbonate rocks here and a north-south fault cutting through would seem to create the potential for significant groundwater flow between southern Spring and northern Lake valleys, but the Chainman Shale, at shallow depth beneath the thin ridge, probably creates a barrier to flow, and we consider flow through the ridge unlikely. Water levels, in fact, suggest that the ridge is a groundwater divide (Burns and Drici, 2011). In contrast, Knochenmus et al. (2007) considered flow to be possible through it. The Schell Creek Range forms the northwestern boundary of Lake Valley for about 20 mi southward until it bends south-southwest to join the Egan Range.

Because much of the Schell Creek Range is covered by Precambrian to Cambrian quartzite, the range forms a barrier to flow between much of Steptoe Valley and Spring Valley. Knochenmus et al. (2007) and Welch et al. (2007), however, proposed two flow routes east through the Schell Creek Range from southern Steptoe Valley (see Section 6.0). Gravity data analyzed in Section 5.1.3 provide no support for these hypotheses.

On the eastern side of northern Cave Valley, the Schell Creek Range is cored by Precambrian to Cambrian quartzite, creating a likely barrier to flow between northern Cave Valley and Lake Valley (Figure 4-9). Farther south, at Patterson Pass, the quartzite sequence is down-faulted and carbonate and volcanic rocks and cross faults are present, but it is unlikely that groundwater flows between southern Cave Valley and Lake and northern Dry Lake valleys. Range-front faults on both sides of the southern Schell Creek Range further inhibit this flow.

Northern Dry Lake Valley, also known as Muleshoe Valley, lies east of the southern Schell Creek Range. This valley contains at least several thousand feet of basin-fill sediments (Plates 4 and 8, Cross Section Q—Q'), and gravity surveys (Scheirer, 2005) indicate that about 3,000 to more than 6,000 ft of basin-fill sediments plus underlying downfaulted volcanic rocks underlie most of the valley. A seismic profile across the valley is discussed in Section 5.3. It is permissible that some groundwater flows southward from Lake Valley through fault conduits at Muleshoe Pass, between the Schell Creek Range and the northern Fairview Range (Figure 4-9). Fault conduits provide pathways for groundwater flow from northern Dry Lake Valley to the south and into Delamar Valley.

4.4.14 Fairview, Bristol, West, Ely Springs, Highland, Black Canyon, Burnt Spring, and Chief Ranges, and Pioche Hills

From north to south, the Fairview, Bristol, Highland, and Chief Ranges are a 60-mi-long group of north-trending, heavily faulted ranges of mostly east-dipping rocks. These in-line horsts and tilt blocks lie west of Lake and Panaca (Meadow) valleys. From north to south, the West, Ely Springs, Black Canyon, and Burnt Spring ranges are small horsts along the western side of the Bristol, Highland, and Chief ranges. Northern Dry Lake (Muleshoe) Valley is west of the Fairview Range, and the rest of Dry Lake Valley is west of the West, Ely Springs, Black Canyon, and Burnt Spring ranges. The Pioche Hills, which extends southeast from the eastern side of the southern Bristol Range, separates Lake Valley on the north from Panaca (Meadow) Valley on the south. All the ranges are uplifted by normal and oblique-slip (left-lateral and right-lateral, normal) faults.

The Fairview Range touches the Schell Creek Range across Muleshoe Pass, through which runs the range-front faults for both the Schell Creek and Fairview Ranges. 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. The low pass between the Fairview Range and the Bristol Range is cut by numerous east-striking faults of the Blue Ribbon transverse zone, which crosses the entire Great Basin at about this latitude (Rowley, 1998; Rowley and Dixon, 2001).

The Bristol Range is a horst that consists mostly of an east-dipping sequence of Cambrian carbonate rocks. The range is cored by a Tertiary pluton on the northern end that is associated with silver deposits of the Jackrabbit and Bristol districts. A low angle, west-dipping denudation or gravity-slide fault that placed Devonian rocks on Cambrian rocks is exposed in the northwestern part of the range (Page and Ekren, 1995). The Highland Range, the southward continuation of the Bristol Range, consists of east-dipping Cambrian carbonate rocks, underlain by Precambrian and Cambrian quartzite. A moderately west-dipping, down-to-the-west fault on the western side of the range, the breakaway part of the Highland detachment fault, placed the younger carbonate rocks on the older quartzite. The Chief Range, south of the Highland Range, is made up of east-dipping Precambrian and Cambrian quartzite that is unconformably overlain by Tertiary volcanic rocks and cut by a Tertiary pluton that controls the small Chief gold district (Rowley et al., 1994). The faults that lift the range on the western side consist of an oblique-slip fault (right lateral and normal) and the west-dipping Highland detachment fault.

The small West Range, to the west of the northern Bristol Range, consists of Devonian sedimentary rocks and Tertiary volcanic rocks on which Devonian rocks are emplaced by a low-angle fault that can be interpreted as either a denudation fault or a gravity-slide plane (Plates 4 and 8, Cross Section T—T') (Page and Ekren, 1995). The Ely Springs Range, south of the West Range and northwest of the Highland Range, consists of Cambrian through Silurian rocks, overlain by Tertiary volcanic rocks. The Black Canyon Range, south of the Ely Springs Range and southwest of the Highland Range, consists of Cambrian sedimentary rocks and Tertiary volcanic rocks (Plates 4 and 8, Cross Section P—P'). The Burnt Springs Range, southwest of the Black Canyon Range, is made up of Cambrian sedimentary rocks unconformably overlain by Tertiary volcanic rocks (Plates 4 and 8, Cross Section S—S').

The Pioche Hills consists of Cambrian sedimentary rocks unconformably overlain to the northeast by Tertiary volcanic rocks (Dixon and Rowley, 2007b). The hills contain the major Pioche lead-zinc-silver mining district, which is controlled by its proximity to the margin of the Indian Peak caldera complex. The margin includes caldera-collapse megabreccia and caldera ring dikes. Panaca (Meadow) Valley, south of the Pioche Hills, is probably at least 5,000 ft deep (Plates 4 and 8, Cross Section P—P') and is filled with Pliocene to upper Miocene basin-fill sediments of the Panaca Formation (Rowley and Shroba, 1991).

The presence in the Bristol, Highland, and Chief ranges of near-surface Neoproterozoic to Cambrian quartzite results in a barrier to groundwater flow between Lake, Patterson (southern Lake) and Panaca (Meadow) valleys to the east and Dry Lake Valley to the west (Figure 4-9). Across the Fairview Range, a barrier to flow results from the Indian Peak caldera complex due to probable subsurface intracaldera intrusions and their contact metamorphic and hydrothermal products. A permissible fault conduit from Lake to Dry Lake valleys exists for flow through Muleshoe Pass at the northern end of the Fairview Range (Figure 4-9).

4.4.15 Delamar Mountains

The Delamar Mountains extends southward for 40 mi from the Burnt Springs Range, forming the western side of Delamar Valley and continuing to Coyote Spring Valley. The boundary between the Delamar and Burnt Spring ranges is the northern caldera wall of the Caliente caldera complex, here controlled by the east-trending Timpahute transverse zone (Ekren et al., 1976; Swadley and Rowley, 1994; Rowley, 1998). The eastern side of the northern Delamar Mountains is bounded by the perennial, south-flowing Meadow Valley Wash, which drains Panaca (Meadow) Valley, passes south through Caliente, Nevada, and then creates beautiful Rainbow Canyon that separates the Delamar Mountains from the Clover Mountains to the east (Dixon and Rowley, 2007c; Tingley et al., 2010). The stream becomes ephemeral at the southern end of Rainbow Canyon, but in the Pleistocene it was part of through-flowing drainage that joined the Muddy River at Glendale, Nevada, and from there to the Colorado River. The eastern side of the southern Delamar Mountains is Kane Springs Valley, to the east of which is the Meadow Valley Mountains.

The Delamar Mountains consists of east-dipping Neoproterozoic to Cambrian rocks and Tertiary volcanic rocks. The range, however, is dominated by Tertiary caldera complexes. The western end of the Caliente caldera complex is in the northern part of the range, and the Kane Springs Wash caldera complex is in the central part of the range (Plates 4 and 8, Cross Sections N—N', D—D', and C—C') (Rowley et al., 1995; Scott et al., 1995 and 1996; Dixon et al., 2007b). The main bounding fault of the Delamar Mountains is the down-to-the-west normal fault on the western side, and this is joined from the southwest by several splays of the left-lateral and normal PSZ (Ekren et al., 1977). In Kane Springs Valley, the bounding fault is the oblique (left-lateral and normal down-to-the-west) Kane Springs Wash fault zone (Swadley et al., 1994). Flow from southern Delamar Valley is likely through the PSZ and north-striking normal faults into Pahranagat and Coyote Springs valleys (see Figure 4-9 and Figure 4-12).

Neoproterozoic to Cambrian quartzite and shale and Tertiary caldera complexes form an effective barrier to groundwater flow between Delamar Valley and valleys to the east (Figure 4-9). The calderas are barriers primarily because of their underlying intracaldera intrusions and both hydrothermal clays and contact-metamorphic rocks formed by emplacement of the intrusions into intracaldera tuffs. North- and northeast-striking basin-range faults just west of the calderas provide geologically likely conduits for groundwater to southern Pahranagat and northern Coyote Springs valleys.

4.4.16 Meadow Valley Mountains

The Meadow Valley Mountains constitutes a narrow, generally low, north-northeast-trending range about 40-mi-long. The northern 30 mi of the range consists mostly of outflow ash-flow tuffs and part of the Kane Springs Wash caldera complex (Plates 4 and 8, Cross Section C—C'). The southern end of the Meadow Valley Mountains, just east of Coyote Spring Valley, is made up of mostly thrust-faulted and normally faulted Paleozoic rocks (Plates 4 and 8, Cross Sections C—C', Plates 5 and 9, Cross Sections B—B', E—E', and F—F') (Pampeyan, 1993; LVVWD, 2001). The Meadow Valley Mountains is separated from the Delamar Mountains on the west by Kane Springs Valley, a shallow valley underlain along the eastern side by the oblique-slip (normal, left-lateral) Kane Springs Wash fault zone (Swadley et al., 1994; Harding et al., 1995; Scott et al., 1996). The broad, deep valley of Meadow Valley Wash lies east of the Meadow Valley Mountains and west of the Mormon Mountains (Schmidt, 1994).

The Kane Springs caldera, north-northeast-striking oblique faults, and thrusts likely prevent groundwater flow between Kane Springs Valley and the valley of Meadow Valley Wash.

4.4.17 Arrow Canyon Range

The Arrow Canyon Range is a sharp, narrow, north-trending range consisting of a syncline of Cambrian to Mississippian carbonate rocks. It is uplifted along its western side by normal faults of the Arrow Canyon Range fault zone (Plates 5 and 9, Cross Section I—I') (Schmidt and Dixon, 1995; Page and Pampeyan, 1996; Page, 1998). The trace of the north-striking Dry Lake thrust, which carries Cambrian rocks over Silurian through Permian carbonate rocks, is exposed and projected north just east of the range (Page and Dixon, 1992; Schmidt and Dixon, 1995; LVVWD, 2001). East of the Dry Lake thrust, the Silurian through Permian rocks form a series of low, unnamed, north-trending hills. These hills are controlled by north-striking normal faults, along some of which are Pleistocene carbonate spring-mound deposits that indicate that the faults formerly carried significant groundwater (Schmidt and Dixon, 1995).

Coyote Spring Valley, on the western side of the range, is underlain by thin basin-fill sediments, generally less than 1,000 ft thick (Plates 5 and 9, Cross Sections L—L', E—E', F—F', and G—G'; Section 5.2). Groundwater moves south beneath Coyote Spring Valley (Section 4.4.7). A major part of that groundwater flows southeast, between the northern end of the Arrow Canyon Range and the southwestern end of the Meadow Valley Mountains (Figure 4-16; Harrill et al., 1988). Here it flows past the MX-4 and high-yield (3,400 gpm) MX-5 wells, drilled in the 1980s by the military adjacent to Pahranagat Wash during the MX Missile Program (Buqo, 2007). Pahranagat Wash is currently an intermittent stream but was perennial after White River Valley was integrated with the Colorado River, at least ten thousand years ago. Some groundwater also may flow through the Arrow Canyon Range in its carbonate rocks. It is well known that the southeast-flowing groundwater is the principal source of many large springs in the Muddy River Springs area, which currently create the surface flow in the perennial part of the Muddy River below the springs (Schmidt and Dixon, 1995; Donovan et al., 2004; Buqo, 2007; Donovan, 2007; Johnson, J. 2007).

The details of the groundwater flow to Muddy River Springs were determined in part from the geologic mapping by Page and Pampeyan (1996), Schmidt et al. (1996), and Donovan et al. (2004), and the geophysics of Scheirer et al. (2006). The mapping recognized that, following stream integration during the late Pleistocene, ancestral Pahranagat Wash flowed southeast—as it does now—through a small basin (Table Mountain basin) just east of the northern Arrow Canyon Range that is underlain by the Muddy Creek Formation and younger Holocene to late Miocene surficial and basin-fill sediments. Many of the younger sediments were deposited from spring discharge. From that basin, the ancestral river continued southeast, parallel to and south of Nevada Highway 168, through an unnamed ridge of north-trending, east-dipping, upper Paleozoic carbonates. The ridge is the southward continuation of the southeastern prong of the Meadow Valley Mountains. Here the ancestral stream cuts spectacular Arrow Canyon, which is currently dry; at Muddy River Springs, dry Pahranagat Wash becomes the Muddy River.

Additional geologic mapping by SNWA showed that the bedrock ridge continues, although locally buried, for 20 mi south of Arrow Canyon to become the Dry Lake Range (Plates 2 and 5, Cross Sections F—F', G—G', H—H', and I—I'). The bedrock ridge is uplifted on both sides by north-trending basin-range faults, the largest being on the western side. These faults, plus others that parallel them on the east, served as groundwater conduits that carried groundwater southward, forming several upper Pleistocene spring mounds north of I-15 and west of the railway stop of Ute.

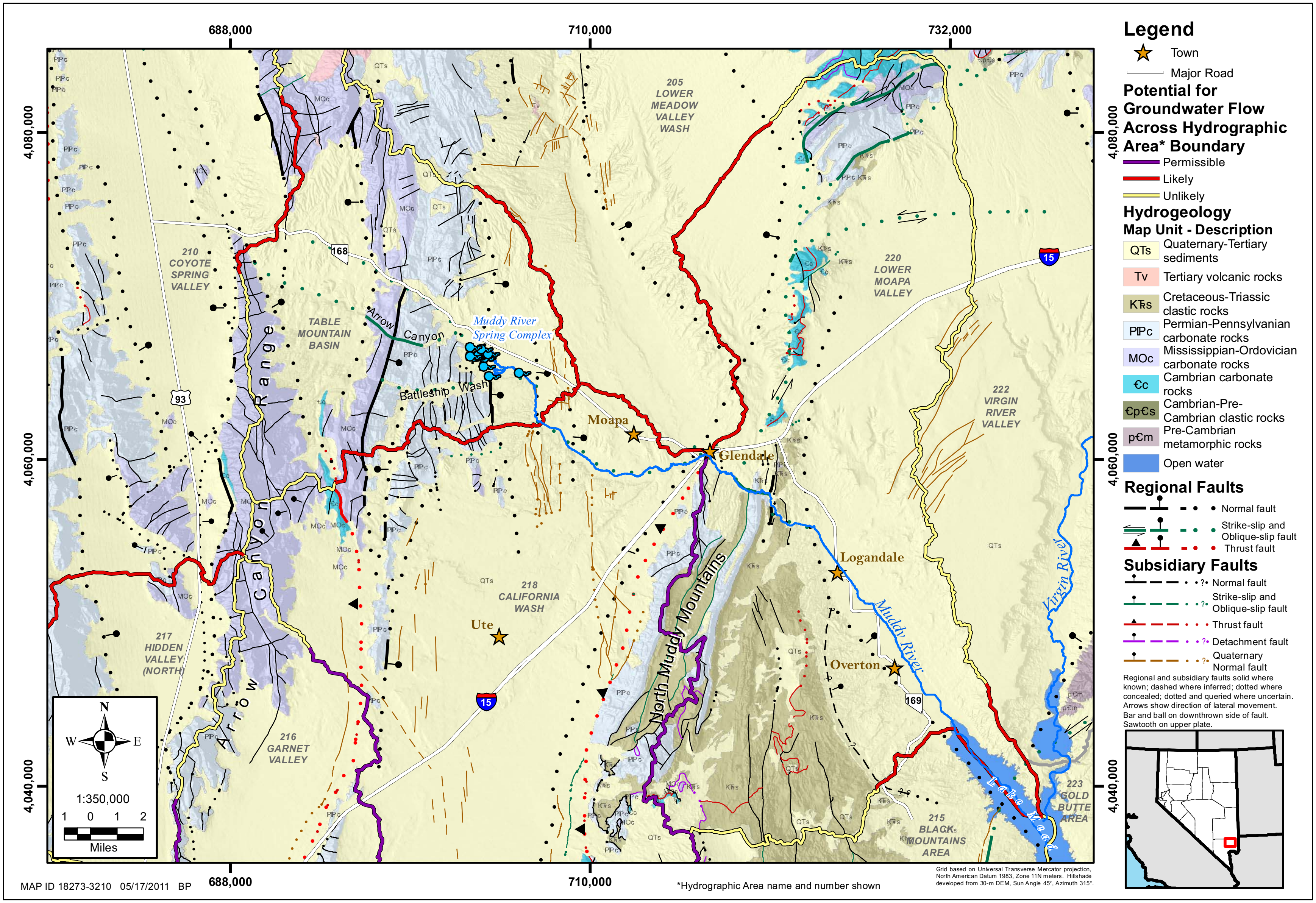


Figure 4-16
Hydrogeologic Map of Coyote Spring Valley to Lake Mead

Within the bedrock ridge, east-trending faults are abundant, including some that control Arrow Canyon and Battleship Wash just to the south. These faults act as conduits that allow groundwater to pass eastward through the ridge to Muddy River Springs. In addition, mapping suggests that a west-northwest-trending fault zone, probably with right-lateral motion, formed a broad canyon now followed by Highway 168 that was probably another large ancestral stream that carried surface water, with groundwater beneath it. The geologic map presented on Figure 4-17 shows these details. The large, north-trending, down-to-the-east, normal fault at the western end of the cross section is the main control on Muddy River Springs. Virtually all springs in the Muddy River Springs complex are at fault intersections of east-, north-, and northwest-trending faults. Locally the faults created abrupt Pleistocene scarps, some of which failed as landslides (Donovan et al., 2004). White, post-Muddy Creek Formation (Pliocene) sediments were deposited by spring discharge east-southeast of Muddy River Springs, in upper Moapa Valley. Current groundwater flow continues southeast of Muddy River Springs as underflow beneath the Muddy River. The new mapping indicated that west- to northwest-trending faults appear to control nearly the entire course of the Muddy River between Muddy River Springs and Logandale (Figure 4-16), including the course of the river through the North Muddy Mountains (at Jackman Narrows). At Glendale, groundwater beneath Meadow Valley Wash combines with that beneath the Muddy River, then continues through The Narrows to Logandale, and from there to Overton and Lake Mead (Harrill et al., 1988). The passage through the North Muddy Mountains to Logandale is interpreted to be as surface flow and underflow in fractures beneath the fault-controlled passageway at and east of The Narrows. As described in Section 4.4.21, north-northwest-trending faults probably controlled the course of the Muddy River from Logandale to Overton, as well as the Overton Arm of Lake Mead (Figures 4-16 and 4-18).

Some of the faults suggested by new mapping between Table Mountain basin and Lake Mead are buried by surficial sediments. To test the likelihood of faults in these areas, Scheirer and Andreasen (2008) interpreted gravity data that they collected along traverses oriented perpendicular to buried parts of some of the possible faults. The gravity data supported faults beneath Pahranagat Wash in Table Mountain basin (gravity line 2 of Scheirer and Andreasen, 2008), along Nevada 168 in Table Mountain basin (gravity lines 1 and 2) and perhaps north of Muddy River Springs (gravity line 3), perhaps at Muddy River Springs (gravity line 3), beneath the Muddy River south of Moapa (gravity line 4se), and perhaps in three places near Overton (gravity line 12).

4.4.18 Fortification Range, Wilson Creek Range, and White Rock Mountains

The Fortification Range is a narrow, locally high, north-northwest-trending range about 20-mi-long. The range is a horst bounded on both sides by normal faults. Northern Lake Valley is on the west, and the southern end of Spring Valley is on the east. The northern half of the Fortification Range is a series of faulted, upper Paleozoic carbonate rocks including, at the northern end, a narrow, low, north-northwest-trending, northeast-dipping cuesta that joins the eastern side of the Schell Creek Range. This low ridge, which separates Spring Valley on the northeast from Lake Valley on the southwest, is a groundwater divide, as noted in Section 4.4.13. Geological reasons for the ridge being a groundwater divide are that the ridge is bounded on the northeastern side by a northwest-striking fault and the ridge is underlain by the Chainman Shale, which is probably more than 1,000 ft thick (Plates 4 and 8, Cross Sections U—U'). The northern Fortification Range is complexly faulted and contains repeated sections of the Chainman Shale beneath the surface. The presence of the Chainman in the fault blocks likely prevents groundwater flow through the northern half of the range.

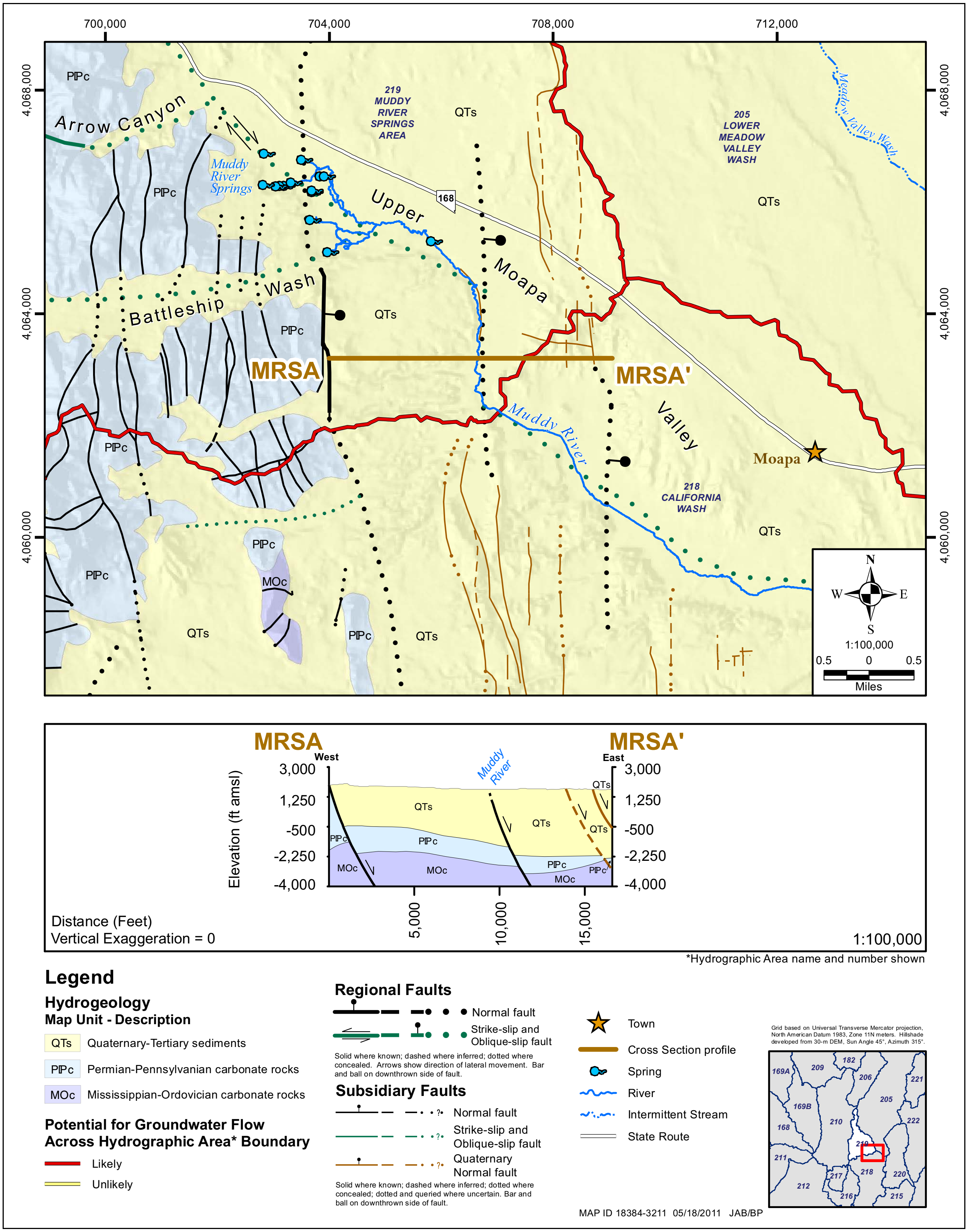


Figure 4-17
Hydrogeologic Map and Cross Section of the Muddy River Springs Area

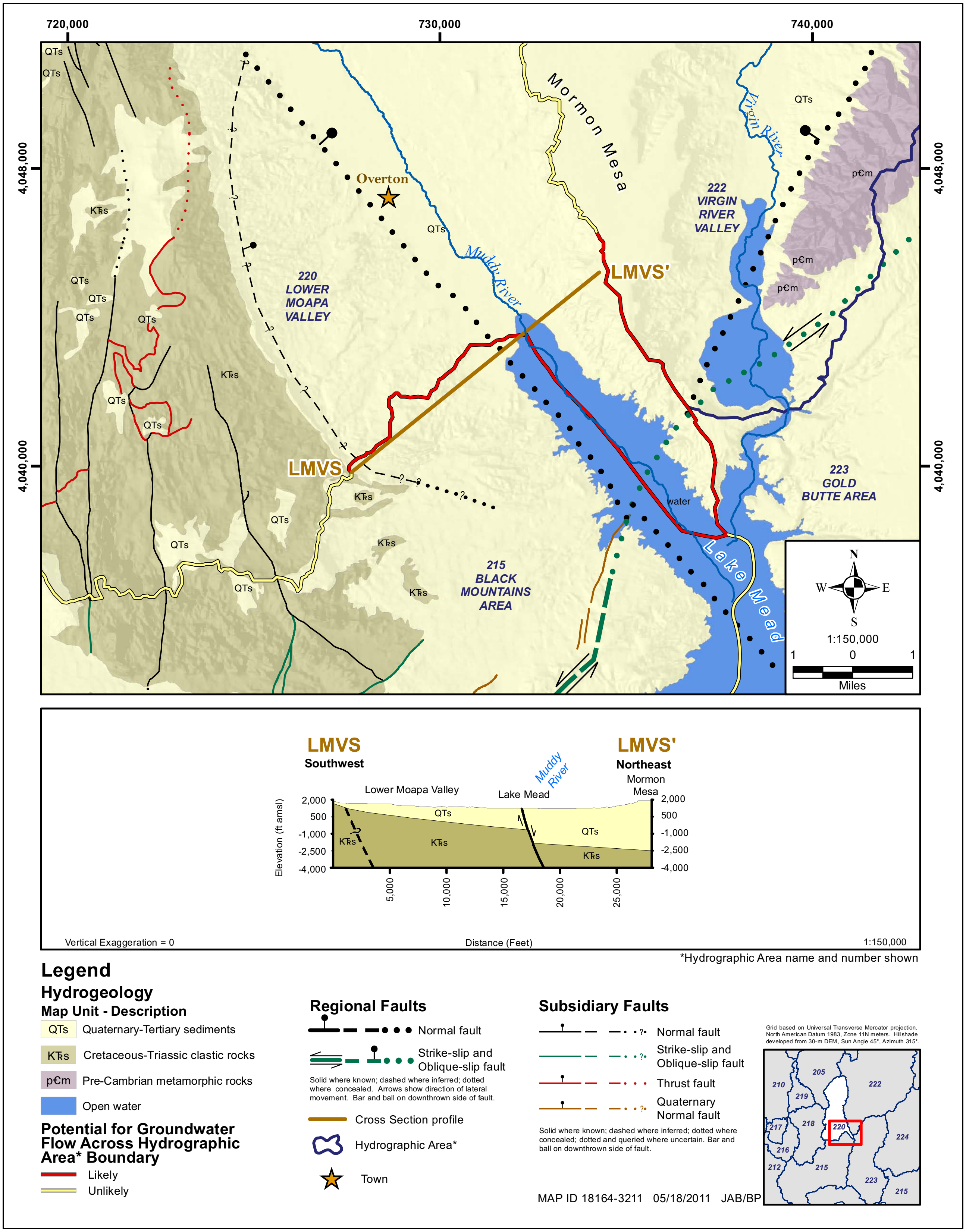


Figure 4-18
Hydrogeologic Map and Cross Section of the Lower Moapa Valley

The southern half of the Fortification Range consists of east-dipping volcanic rocks (Loucks et al., 1989), part of which are interpreted to be intracaldera rocks of the Indian Peak caldera complex. Due to the Chainman Shale in the northern part of the range and the caldera in the southern part, the entire range likely is a barrier to groundwater flow. The Fortification Range connects at its southern end with the broad Wilson Creek Range beyond a low pass. This pass, at the mining town of Atlanta, Nevada, is partly underlain by an east-striking fault, which may permit groundwater flow.

The Wilson Creek Range is a complexly faulted, north-northwest-trending range that forks southward, with the continuation of the Wilson Creek Range on the west and with the White Rock Mountains on the east. A small central valley (graben), named Spring Valley, separates the two ranges. This valley is called “little” Spring Valley in this report to distinguish it from the much larger Spring Valley to the north. The Wilson Creek Range and White Rock Mountains are each about 35-mi-long and consist entirely of intracaldera volcanic rocks, probably floored by an unexposed intracaldera (resurgent) intrusion of the Indian Peak caldera complex (Willis et al., 1987; Best et al., 1989c). The western side of the Wilson Creek Range is bounded by its main normal fault. The valleys to the west of the range are northern Lake and Patterson (southern Lake) valleys; the southern half of northern Lake Valley and all of Patterson Valley are within the Indian Peak caldera. The White Rock Mountains is a horst, with its main fault on the eastern side. The southern ends of the Wilson Creek Range and White Rock Mountains pass into a series of mostly unnamed, generally low fault blocks of intracaldera volcanic rocks (Best and Williams, 1997; Williams et al., 1997). These fault blocks continue southward for 10 mi to the southern wall of the Indian Peak caldera. The fault blocks of the southern end of the White Rock Mountains extend eastward to join the southern Needle Range (Indian Peak Range), thereby closing off Hamlin Valley east of the White Rock Mountains. More fault blocks extend southward another 15 mi as outflow volcanic rocks to the Clover Mountains, which is underlain by the Caliente caldera complex. Panaca Summit, traversed by Nevada State Route (SR) 319 and 10 mi east of Panaca, is a pass through these hills of outflow volcanic rocks.

Because of its assumed underlying intracaldera intrusions, the Indian Peak caldera complex probably is a low-permeability unit with limited groundwater flow through it. However, north-south faults, particularly the range-front faults along Lake, Patterson, and Hamlin valleys, likely provide conduits for southward (Lake and Patterson valleys) and northward (Hamlin Valley) groundwater flow (Figure 4-9).

4.4.19 Clover Mountains and Bull Valley Mountains

The Clover Mountains, Bull Valley Mountains, and northern Delamar Mountains represent a poorly defined, broad, east-trending, 60-mi-long series of low mountains made up of heavily faulted volcanic rocks. North-south Rainbow Canyon is a narrow erosional cut made by Meadow Valley Wash near the western part of the mountains. The Clover Mountains extends from Rainbow Canyon on the west for about 30 mi to the Utah/Nevada border on the east and from the Panaca (Meadow) Valley on the north to about 25 mi to the Tule Desert on the south. The Bull Valley Mountains extends eastward about 20 mi from the Utah/Nevada border and is about 20 mi north to south. The entire east-trending mountain mass passes into north-trending ranges on all sides. This massif gets its unusual easterly trend because it is cored by the 50-mi by 20-mi Caliente caldera complex (Ekren et al., 1977; Rowley et al., 1995), one of the largest calderas in the United States.

The east-elongated Caliente caldera complex is bounded on the north and south by east-trending transverse zones, the Timpahute on the north and the Helene on the south. Locally, the transverse zones are caldera margins. These transverse zones facilitated differential east-west growth (spreading) of the caldera, driven by east-west extension and caldera eruptions. Rowley and Anderson (1996) referred to the complex as a syntectonic caldera. The caldera complex is floored by an intracaldera intrusion of batholithic dimensions, but it is exposed in few places (Plates 4 and 8, Cross Sections N—N' and D—D'). South of the caldera complex, the Clover Mountains is underlain by Paleozoic carbonate rocks cut by a Sevier thrust fault and many high-angle normal faults, but these rocks are blanketed by a thick cover of outflow ash-flow tuff, and they are remote and poorly studied and mapped.

The batholith and the east-trending faults present a likely barrier to southward groundwater flow, but the entire mountain mass is heavily cut by north- and northwest-trending faults, so it is geologically permissible that these provide conduits to some flow. Rainbow Canyon allows surface water to move southward via Meadow Valley Wash.

4.4.20 Mormon Mountains

The Mormon Mountains is a nearly circular range, about 18 mi across, east of lower Meadow Valley Wash. The Mormon Mountains represents a dome of mostly Cambrian to Permian rocks, underlain by Paleoproterozoic crystalline metamorphic rocks. East-verging Sevier thrust faults placed Cambrian rocks above Cambrian to Mississippian rocks. The range subsequently underwent major uplift, and it now is underlain by prominent positive aeromagnetic and gravity anomalies. Wernicke et al. (1985) interpreted the range to contain west-verging detachment faults that resulted from late Tertiary extension above a metamorphic core complex. Wernicke et al. (1985) suggested that these detachment faults followed thrust faults within the mountains. Anderson and Barnhard (1993) disputed the detachment hypothesis, and they instead emphasized footwall deformation along normal and oblique-slip, generally high-angle faults that flatten upward and formed during the major domal uplift. Carpenter and Carpenter (1994a) also disputed the detachment hypothesis, partly on seismic data unavailable to Wernicke and colleagues. Carpenter and Carpenter (1994a and b) argued for Tertiary extension along high-angle normal faults and explained Wernicke’s low-angle structures as representing gravity slides. Walker et al. (2007) discussed data that supported the gravity-slide concept. These interpretations based on the findings since 1985 have been largely adopted by Page et al. (2005a), Scheirer et al. (2006), Anderson et al. (2010), and by this report.

The broad valley of Meadow Valley Wash, to the west and northwest of the Mormon Mountains, is underlain by three geophysical sub-basins, the northern two of which contain basin-fill sediments and underlying volcanic rocks as thick as 6,000 ft, whereas the southern geophysical basin contains basin-fill and volcanic rocks as thick as 9,000 ft (Scheirer et al., 2006). Well logs suggest that the component of basin-fill sediments in these sub-basins is as much as 3,000 ft (Plates 5 and 9, Cross Section E—E'). Northwest of the Mormon Mountains, two buried thrust faults have been hypothesized (Plates 4 and 8, Cross Section C—C'). Southwest of the Mormon Mountains, buried Paleozoic carbonate rocks may be present beneath Meadow Valley Wash (Plates 5 and 9, Cross Section B—B'). A band of hills continuing southward from the Mormon Mountains is underlain by Paleozoic sedimentary rocks that are cut by Sevier thrust faults, including the Glendale/Muddy Mountains thrust (Plates 5 and 9, Cross Sections E—E' and F—F').

The Mormon Mountains represents a barrier to groundwater flow between the eastern side of Meadow Valley Wash and the Tule Desert to the east. However, a low divide north of the Mormon Mountains might allow minor volumes of such eastern flow. Southwest of the Mormon Mountains, flow is likely from lower Meadow Valley Wash to California Wash at Glendale, Nevada (Section 4.4.21).

4.4.21 North Muddy Mountains, Muddy Mountains, and Dry Lake Range

The southeastern corner of the geologic study area contains the North Muddy Mountains and, to the south, the Muddy Mountains (Plates 5 and 9, Cross Sections H—H', I—I', and K—K') (Bohannon, 1983). The North Muddy Mountains separates the California Wash area on the west from the Mesquite basin (Virgin River Valley) on the east. The Muddy Mountains occupies the northern side of Lake Mead. West of the Muddy Mountains, the map area includes the small Dry Lake Range east of Apex. This range is made up mostly of Bird Spring carbonate rocks. A narrow arm of bedrock extending west from Apex connects with the southern Arrow Canyon Range/Las Vegas Range. A thin finger of Quaternary sediments at Apex, just west of the Dry Lake Range, most probably was a pathway for Tertiary and Quaternary basin-fill sediments entering the Las Vegas Valley in the southwestern corner of the map area. The finger also is along the trace of the north-northeast- striking Dry Lake thrust (Page and Dixon, 1992). Basin-fill sediments to the northeast along the I-15 corridor (California Wash area) belong to an east-tilted half graben that reaches depths of 9,000 to 12,000 ft (Langenheim et al., 2001, 2010; Scheirer et al., 2006). The California Wash area does not appear to have been connected with the Las Vegas basin because, based on limited mapping in the area, the basin sediments are not correlated with those in the Las Vegas Valley.

In the Muddy Mountains and North Muddy Mountains, high-angle faults strike north-northeast (Bohannon, 1983; Beard et al., 2007), and the east-west gap between the two ranges, now occupied by Tertiary and Quaternary basin-fill sediments, is also likely underlain by fractures of the same strike. The northern Muddy Mountains and North Muddy Mountains contain significant Jurassic sedimentary rocks (Bohannon, 1983; Beard et al., 2007), including the Aztec Formation. The Aztec Formation and other Jurassic sandstone units have low permeability and thus form a confining zone. The northwestern side of the North Muddy Mountains is made up of upper Paleozoic carbonate rocks, which suggests that it is geologically permissible that they allow southward and southeastward groundwater flow (Figure 4-9) (Eichhubl et al., 2004). Mesozoic sedimentary rocks in the eastern North Muddy Mountains and the Muddy Mountains may also allow southward flow to Lake Mead. A possible flow barrier is provided by east-striking faults of the northern Muddy Mountains. These faults include the northeast-verging Glendale/Muddy Mountains thrust (Figures 4-6 and 4-7) (Bohannon, 1983; Carpenter and Carpenter, 1994b; Beard et al., 2007). Bohannon interpreted this structure as the northern continuation of the Keystone thrust zone, which has been displaced approximately 40 mi right laterally by the LVVSZ (see Section 4.4.7). As with the Keystone/ Glendale/Muddy Mountains thrust zone, the Dry Lake thrust just west of the Keystone/ Glendale/Muddy Mountains thrust has been displaced 40 mi by the same shear zone; its southern equivalent is the Deer Creek thrust in the Spring Mountains. Farther east in the North Muddy Mountains, the Summit/Willow Tank thrust is exposed (Plates 5 and 9, Cross Section J—J') (Bohannon, 1983, 1984, and 1992; Carpenter and Carpenter, 1994b; Beard et al., 2007). At the southeastern end of the Muddy Mountains and northern side of Lake Mead, the LVVSZ passes eastward into the northeast-striking, oblique-slip (left-lateral and normal) Lake Mead fault zone, both part of Quaternary and late Tertiary east-west extension in the area (Anderson and Barnhard, 1993; Workman et al., 2002a and b; Page et al., 2005a and b; Beard et al., 2007, 2010; Langenheim et al., 2010).

Lower Moapa Valley, in the southeastern edge of the geologic study area and northwest of where the Muddy and Virgin rivers enter the Overton Arm of Lake Mead, is clearly an area of groundwater discharge (Harrill et al., 1988). Surficial sediments, dominated by Quaternary and Pliocene river deposits of the ancestral and present Virgin and Muddy rivers and resistant calcretes, respectively, underlie the valley and Mormon Mesa. The surficial deposits are underlain by Pliocene and upper Miocene basin-fill deposits making up the southwestern end of Mesquite basin. Surficial and basin-fill sediments are lumped as the QTa and QTs units in Plates 2 and 7, respectively, but in this area most basin-fill sediments are represented by the Horse Springs and Muddy Creek formations, which are exposed as low hills west of the river lowlands at Longandale and Overton. The Black Mountains and Gold Butte areas, respectively southwest and east of Lake Mead, contain Proterozoic metamorphic rocks that extend northeastward to the southwestern Virgin Mountains. Numerous fault zones have been mapped here and in the north Muddy Mountains. These faults include northeast-striking faults of the Lake Mead fault zone that are discharge points for Rogers and Blue Point springs in the Lake Mead National Recreation Area.

Figure 4-18 shows a geologic map and cross section in the southern part of lower Moapa Valley. Although not distinguished on the map from Tertiary basin-fill deposits, deposits of the ancestral and present-day Virgin and Muddy rivers are likely to be hundreds of feet thick, inasmuch as both rivers have been carrying and depositing sediments since at least the Pliocene. Permeability in the deposits is probably considerably greater than the underlying finer-grained Muddy Creek Formation but probably not the Horse Springs Formation. A large northwest-trending, down-to-the-northeast, normal fault is interpreted to partly control the axis of the basin and the linear nature of Overton arm of Lake Mead. Gravity line 12 (Scheirer and Andreasen, 2008) imaged three density contrasts that might represent splays of the fault, even though density contrasts would be expected to be small between different beds in the underlying basin sediments. This fault downthrows river deposits on the northeast against Muddy Creek Formation on the southwest. Such a fault would provide significant conduits for groundwater flow. Southwest of that fault, the poorly exposed Muddy Creek Formation may be dropped down against the Horse Spring Formation by a queried normal fault. These rock units, as well as underlying Mesozoic rocks west of them, dip northeast into the basin.

4.4.22 Antelope Range, White Pine County

The Antelope Range, in northeastern White Pine County, Nevada, is a relatively small, low range of faulted, Tertiary volcanic rocks that unconformably overlie west-dipping Silurian to Permian sedimentary rocks, dominantly carbonate rocks. It is a horst between the narrow, northern part of Spring Valley on the west, and Tippett Valley (Antelope Valley) on the east. At its northern end, Spring Valley contains about 2,000 ft of basin-fill sediments. Tippett Valley contains at least 1,000 ft of basin-fill sediments, with thick volcanic rocks beneath these sediments; geophysical data indicate that the depth to the pre-volcanic rocks locally is as much as 18,000 ft (5.5 km).

The Antelope Range likely is a barrier to groundwater flow through it (Figure 4-9), for flow in northern Spring Valley appears to head south, whereas flow in Tippett Valley appears to head north

(Harrill et al., 1988). Low passes separate Tippett Valley from northeastern Spring Valley. Some flow is permissible between Spring Valley and Tippett Valley, given the presence of north-trending faults that may be conduits to flow in the low passes, the direction of flow is equivocal. Harrill et al. (1988) suggested minor flow southward, but Knochenmus et al. (2007) suggested minor flow northward. Gans et al. (1989) and Sweetkind et al. (2007a) speculatively showed the caldera source of the largest ash-flow tuff in the area, the 35-Ma Kalamazoo Tuff, to be buried beneath northern Spring Valley just south of the Antelope Range and southwest of the Red Hills. If present here, this feature might retard groundwater flow to or from Tippett Valley. To address groundwater flow in and south of Tippett Valley, detailed gravity data were collected and analyzed by Mankinen and McKee (2011) of the USGS, through a cooperative agreement with SNWA (Section 5.1.1). The gravity anomalies (Figures 5-4 and 5-6) and depth-to-basement data (Figure 5-5) do not corroborate a caldera there, but suggest alternative caldera sites within Tippett Valley (see also Sections 4.4.23 and 5.1.1).

4.4.23 Kern Mountains and Adjacent Small Ranges

The Kern Mountains is a 17-mi-long, east-trending range that was structurally controlled by the Sand Pass transverse zone; east-striking faults occur on both the northern and southern sides of the range (Rowley, 1998; Rowley and Dixon, 2001). The granite core of the Kern Mountains is made up of three separate plutons. These plutons are all biotite-bearing; the largest pluton also contains primary muscovite. The plutons range in age from 75 to 35 Ma (Best et al., 1974; Ahlborn, 1977; Miller et al., 1999). A separate, shallow Tertiary pluton erupted lava flows 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 part of an underlying core complex that formed the Snake and Deep Creek ranges and their attenuation/denudation faults. The Red Hills, a small north-trending range south of the western end of the Kern Mountains, consists mostly of complexly faulted and mineralized Paleozoic rocks. A narrow east-draining valley, Pleasant Valley, separates the Kern Mountains and the Deep Creek Range to the north. This valley may have as much as 3,000 ft of valley fill (Plates 4 and 8, Cross Section X—X'). A broad unnamed valley between the Kern Mountains and the Snake Range contains white, coarse-grained, basin-fill sediments at its eastern end but these rocks appear to be relatively thin.

Because of its core of plutonic rocks, the Kern Mountains forms a likely barrier to groundwater flow through it. However, it is geologically permissible that limited eastward flow takes place along east-striking fault conduits, carbonate rocks, and basin-fill sediments south of the mountain block (Nichols, 2000, Plate 4; Katzer and Donovan, 2003). This flow would have to cross many buried north-south faults across its path, so the path would have to be circuitous. Nichols (2000) noted that water-level data in northern Spring Valley are ambiguous in evaluating the volume he proposed. Gillespie (2008) concluded that water geochemistry and isotopes provide no support for any interbasin flow. Welch et al. (2007), in contrast, suggested a steep eastward gradient and a large flow in carbonate rocks beneath the basin fill (see Section 6.0). In an attempt to shed light on this possible flow path, Mankinen and McKee (2011) of the USGS prepared a detailed isostatic residual gravity map and maxspots of the area (Figure 5-6), as interpreted in Section 5.1.1. This analysis suggests that the Red Hills presents a barrier to interbasin flow from Spring Valley and from Tippett Valley. A boundary-flow profile (geologic cross section) oriented perpendicular to the possible flow path and parallel to the permissible basin boundary is given as Figure 4-19. The thin clastic sediments of the late Cenozoic basin fill (QTs) and the west-northwest fault may allow groundwater to move eastward,

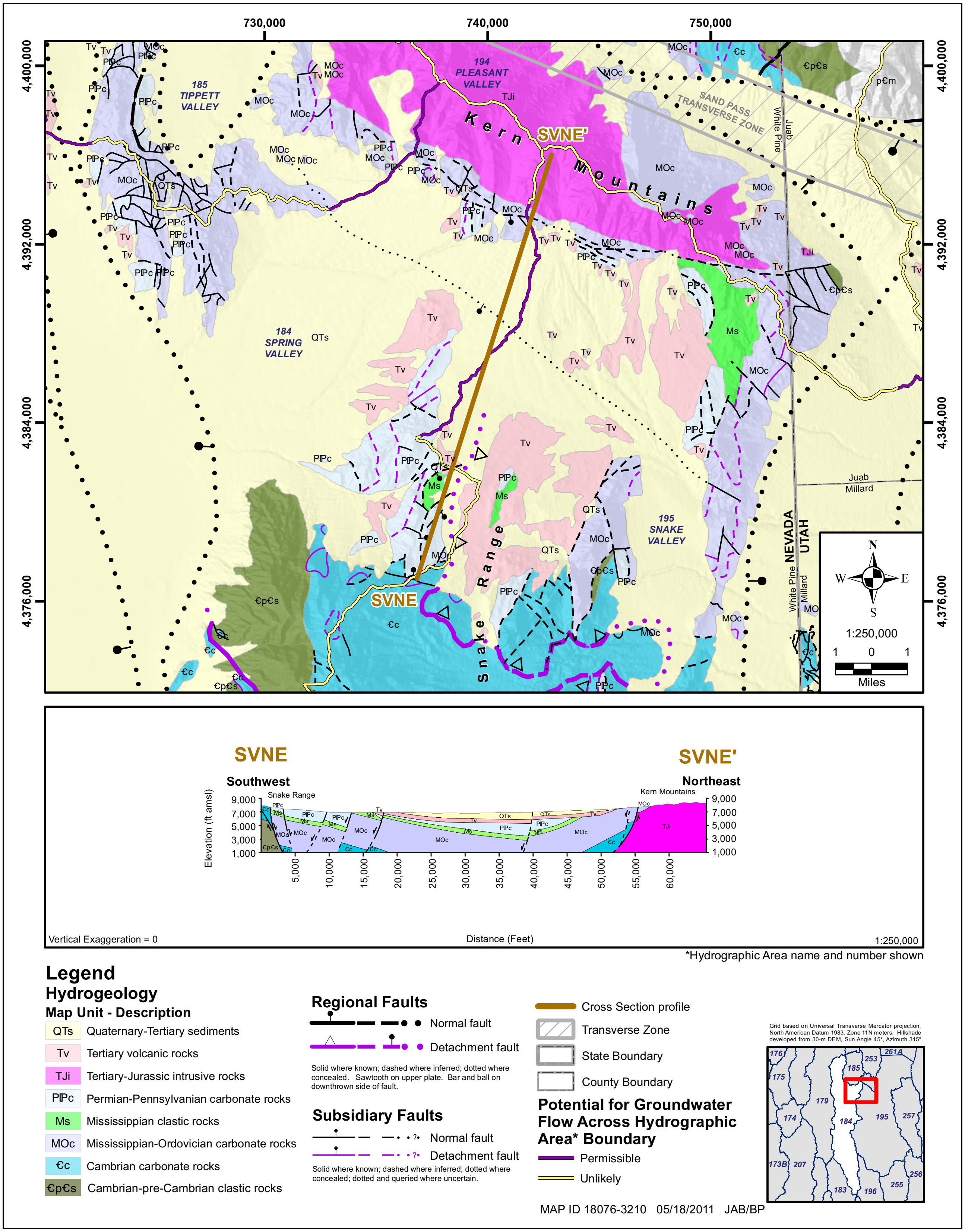


Figure 4-19
Hydrogeologic Map and Cross Section of Northeastern Spring Valley

but possible north-trending fault barriers, which likely are more significant than indicated on the map because they are buried, would present impediments to this flow. It is more likely that any interbasin contribution from Spring or Tippett valleys is small. Probably most groundwater in the shallow basin(s) between the Kern Mountains and the Snake Range (Figure 5-6) is from local recharge, in other words, from precipitation on the Kern Mountains and northern end of the Snake Range. This local recharge would be the source of tritium (modern water) that is found at Gandy Warm Springs in Snake Valley (Acheampong et al., 2009; Kistinger et al., 2009; Section 4.4.25).

4.4.24 Deep Creek Range, Utah

The Deep Creek Range is a high (as much as 12,000 ft altitude), north-trending range about 40-mi-long just east of the Nevada-Utah border and northeast of the Kern Mountains. The Deep Creek Range is a horst bounded by north-striking normal faults on either side that separate it from Deep Creek Valley to the west and northern Snake Valley and the Great Salt Lake Desert to the east. The fault on the eastern side of the Deep Creek Range appears to be the main basin-range fault controlling the range, and has vertical displacement of at least 10,000 ft, based on the height of the range and the Precambrian and plutonic rocks on its crest. The basin-range fault on the western side is also significant, for it drops Deep Creek Valley, which contains as much as 5,000 ft of basin-fill sediments.

Geologic mapping of the Deep Creek Range began with Nolan's (1935) classic report on the Gold Hill mining district at the northern end of the range. Here, Jurassic, Eocene, and Miocene plutons formed gold, tungsten, arsenic, silver, lead, copper, and zinc deposits in limestone of mostly Pennsylvanian and Mississippian age (Nolan, 1935; Robinson, 1993). Nolan mapped many east-striking faults that he called "transverse faults" and recognized that they cut the range in many places. Rocks in the northern part of the mountains dip east and range from Proterozoic to Cambrian quartzite on the east to Devonian dolomite on the west. In the central part of the range, another Tertiary pluton, the Ibapah granite of 39 Ma (Miller et al., 1999) spans the width of the range. The southern part of the range consists of highly deformed Neoproterozoic quartzite and schist of the McCoy Creek and Trout Creek groups. These Precambrian units have a combined thickness estimated at 19,000 ft (Nutt et al., 1990; Hintze and Kowallis, 2009). West of the southern part of the range, Paleozoic sedimentary rocks dip westward. These rocks range from Neoproterozoic and Cambrian quartzite through Cambrian and Devonian carbonate rocks and Mississippian Chainman Shale. They are cut by many low- to high-angle faults subparallel to the north-northeast-striking beds. The faults include detachments that may represent attenuation deroofing of the Deep Creek Range during its uplift (Miller et al., 1999).

The quartzite and plutons that make up the core of the Deep Creek Range form a likely barrier to groundwater flow between Snake and Deep Creek valleys (Figure 4-9). Groundwater flows north in these valleys. In fact, Snake Valley passes northward into the Great Salt Lake Desert at the latitude of the central Deep Creek Range. The Great Salt Lake Desert is the ultimate sink for groundwater in this area (Harrill et al., 1988).

4.4.25 Snake Range and Limestone Hills

The Snake Range is a broad, high, north-trending range. It contains Wheeler Peak, more than 13,000 ft high and within GBNP. The range is about 65-mi-long, nearly all of it in White Pine County, but with the low southern end in Lincoln County. The range is a complexly faulted horst, bounded on both sides by major high-angle normal fault zones. South of the Snake Range, the Limestone Hills is a narrow, low, heavily-faulted cuesta of mostly Devonian carbonate rocks about 20 mi long.

Spring Valley, west of the Snake Range, is a 100-mi-long, broad, deep graben containing about 6,000 ft of basin-fill sediments and defined by basin-range faults of at least 10,000 ft of vertical displacement (McPhee et al., 2005, 2006a and b; Mankinen et al., 2006; Dixon and Rowley, 2007a; Mankinen, 2007; McPhee, 2007) (Plates 4 and 8, Cross Sections X—X', W—W', V—V', and U—U'). Details on the faults bounding and within the valley are given by isostatic residual gravity and maxspots (Figure 5-4) and depth to pre-Cenozoic basement (Figure 5-5), as discussed in Section 5.1.1. About 25 AMT profiles, many of them discussed in Section 5.2.1, locate range-front and subsidiary faults and depth to bedrock (Pari and Baird, 2011).

Snake Valley, east of the Snake Range, is a 95-mi-long, broad, deep graben that passes southward into Hamlin Valley. Basin-fill sediments are locally more than 5,000 ft thick beneath Snake Valley but local holes in the basin contain thicker (10,000 ft) basin-fill and volcanic rocks (Plates 4 and 8, Cross Sections X—X', W—W', and V—V') (Allmendinger et al., 1983; Saltus and Jachens, 1995; Davis, 2005; Kirby and Hurlow, 2005). Seismic sections (Alam, 1990; Alam and Pilger, 1991) and logs of five deep oil wells in Snake Valley support these thicknesses (Herring, 1998a and b; Herring et al., 1998; Schalla, 1998; Hintze and Davis, 2002a; Hess, 2004; UDOGM, 2008). Additional information on faults is given from gravity data (Section 5.1.1) and AMT profiles (Section 5.2.2). Surficial sediments of Spring Valley and northern Snake Valley are dominated by deposits of late Pleistocene lakes (Currey, 1982).

Hamlin Valley, southeast of the Snake Range and south of, and tributary to, Snake Valley, is about 55 mi long. Gravity data indicate that the maximum thickness of basin-fill deposits and underlying volcanic rocks beneath Hamlin Valley is about 10,000 ft (Mankinen and McKee, 2009), with the basin-fill deposits being at least 4,000 ft thick. Seismic profiles and oil-test boreholes provide details to these interpretations (Alam, 1990; Alam and Pilger, 1991; Hess, 2004).

Except for the southern end, the Snake Range is cored by Neoproterozoic to Cambrian quartzite that is intruded by a massive composite batholith formed apparently by multiple episodes of intrusion in Middle and Late Jurassic and Tertiary time (Whitebread, 1969; Miller et al., 1994, 1995 and 1999; Gans et al., 1999a and b; Lee et al., 1999a, b, and c; Miller and Gans, 1999; Gans, 2000b). The range was uplifted along its high-angle faults and the roof stretched apart so that its rocks failed along bedding planes in the Pioche Shale and moved down the flanks of the range as the Snake Range decollement (Section 4-8). The decollement places complexly faulted Middle Cambrian carbonate and younger rocks over a lower plate of Middle Cambrian carbonate rocks, Lower Cambrian clastic rocks, and older rocks. Most development of the decollement was synchronous with basin-range extension (Miller et al., 1999; Gans, 2000a). The decollement is exposed on the top and eastern side of the northern half of the range (Tingley et al., 2010) (Plates 4 and 8, Cross Section W—W'). 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. Allmendinger et al. (1983) and Kirby and Hurlow (2005) suggested that the eastern frontal fault of the Snake Range, separating the range from Snake Valley, is the low-angle Snake Range decollement. Geophysics (Mankinen and McKee, 2009; McPhee et al., 2009) and the straight range front argue instead for our interpretation of a high-angle normal fault that bounds the eastern side of the range (Plates 1 and 6). Rodgers (1987), Alam (1990), Smith et al. (1991), Alam and Pilger (1991), McGrew (1993), and Miller et al. (1999, Figure 10) also showed such a high-angle basin-range fault that is younger than, and thus cuts, the decollement (Plates 4 and 8, Cross Section W—W').

The central part of the Snake Range is narrower and becomes progressively lower southward, and detachment faults are not exposed. Where U.S. Highway 6 (US 6)/US 50 crosses over Sacramento Pass, north-striking, east-dipping listric normal faults drop down to the east Miocene basin-fill sediments that are about 6,500 ft thick (Gans et al., 1989; Miller et al., 1994, 1995, and 1999). The area south of Sacramento Pass includes GBNP (Sweetkind, 2007b), the centerpiece of which is Wheeler Peak, the second highest mountain in Nevada. The northern part of the Park was geologically mapped by Whitebread (1969) at 1:48,000 scale. In his mapping, he recognized the Snake Range decollement, which he left unnamed but referred to it not as a thrust but as a low-angle fault that placed younger rocks on older rocks. He considered all faults in the area to be of low angle and of the same structural event, although it is not clear whether he considered it of Sevier or Tertiary age. This mapping was compiled at 1:250,000 scale by Hose and Blake (1976). Following comprehensive detailed mapping in mostly the northern Snake Range (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) summarized the geology of the Snake Range decollement. Miller and her colleagues continued their mapping southward to include the entire Park, resulting in an unpublished, unauthored, and unreviewed draft digital 1:24,000-scale geologic map of the park, on file in 2008 with the National Park Service (NPS). It compiled, with some modifications, and expanded the mapping of Whitebread. Because the emphasis of their project was the Snake Range decollement, their mapping—as with Whitebread (1969)—of surficial (Quaternary) and basin-fill (Quaternary to Miocene) deposits was superficial, and high-angle basin-range normal faults that define and uplift the range and also are abundant within the range were not recognized. Updating the geology of the Snake Range on Plates 1 and 6 required examination of 1:40,000-scale aerial photos and Google Earth images as well as limited field work and a review of more recent publications, including those on young and active high-angle faults in the area (Black et al., 2003). Many previously unrecognized high-angle, generally north-trending, basin-range faults, some cutting Quaternary and Pliocene surficial and basin-fill deposits, were added to the map.

The southern end of the Snake Range is a low series of tilt-block cuestas of Devonian and Mississippian sedimentary rocks faulted against Tertiary volcanic rocks (Plates 4 and 8, Cross Section U—U'). These tilt blocks become progressively lower in elevation to the south, and the eastern tilt blocks plunge beneath the valley fill. The western tilt blocks continue southward to become the Limestone Hills, which consists mostly of east-dipping Devonian carbonate rocks bounded by normal faults on the western and eastern sides. The Limestone Hills continues southward into the Wilson Creek Range (Section 4.4.18). The southern end of the Limestone Hills forms part of the northern wall of the Indian Peak caldera complex. Here the Atlanta silver-gold mining district is in Silurian to Ordovician carbonate rocks along the east-striking caldera margin.

Because of its core of plutons and quartzite, the Snake Range is a groundwater barrier to east or west flow for nearly its entire length. In the Sacramento Pass area in the center of the range, however, it is geologically conceivable that minor groundwater might flow eastward through the range along an east-striking fault and adjacent carbonate and volcanic rocks. But we consider such flow unlikely because any flow would have to be at least 1,500 ft below the surface to surmount the pass.

Spring Valley is made up of at least two geophysical sub-basins (Figure 5-5), as indicated by gravity data discussed in Section 5.1.1. The northern of these is about 90 mi long. It is structurally deepest at its northern end, west of the Antelope Range, where it is also a separate small basin. Harrill et al. (1988) suggested that water from this part passes southward. The southern end of the northern geophysical sub-basin is near the northeastern end of the Fortification Range, where depth-to-basement data (Figure 5-5) shows a shallow buried east-west bedrock ridge connecting the northern Fortification Range with the southern Snake Range. Near the central part of this northern geophysical sub-basin, just south of where US 6/50 crosses Spring Valley, Rattlesnake Knoll protrudes above the valley. This Knoll, investigated by Mankinen et al. (2006), may be the surface expression of another, but narrower (Figure 5-5), buried east-west ridge whose hydrologic significance is unknown.

Groundwater seems to pool in the northern geophysical sub-basin (Harrill et al., 1988). Some flow, however, is permissible to or from Tippett Valley (Section 4.4.22) or to Snake Valley between the southern Kern Mountains and northern Snake Range, although the Red Hills would seem to block flow out of Spring Valley (Section 4.4.23).

The southern geophysical sub-basin is about 20 mi long, between the Fortification Range and the Limestone Hills (Section 5.1.1). It is part of the same surface-drainage basin as the northern geophysical sub-basin, with surface flow northward into the low part of the northern sub-basin.

It has long been suggested that the faulted carbonate rocks that form the low Limestone Hills and its adjacent passes provide the only significant likely pathway for groundwater flow from Spring Valley; this flow goes eastward to northern Hamlin Valley (Harrill et al., 1988) (Figure 4-9). Yet, north-south faults bound the Limestone Hills on its east and west sides, so these present partial barriers to eastward flow. Therefore, flow along this route was estimated to be only 4,000 afy by Hood and Rush (1965), Rush and Kazmi (1965), Harrill et al. (1988), Brothers et al. (1994), and Katzer and Donovan (2003). Nichols (2000) suggested a flow of between 8,000 and 12,000 afy if one uses a greater hydraulic conductivity value for carbonate rocks in the area. Gillespie (2008) found that any interbasin flow "cannot be confirmed or rejected based on the current data and modeling constraints." Welch et al. (2007), however, suggested a volume of 33,000 afy (see Section 6.2.1.4).

To test the hypothesis that groundwater moves from Spring Valley to Hamlin Valley via the Limestone Hills, Figure 4-20 gives a boundary-flow profile (cross section) drawn parallel to the basin boundary and perpendicular to the possible flow direction. The cross section suggests that flow is likely at both the northern and southern ends of the Limestone Hills, with permissible flow in between. The geologic map shows that the Limestone Hills is a horst, defined on either side by two north-trending basin-range, range-front faults that lifted the horst up with respect to the basins on either side. Both faults probably are partial barriers to easterly flow through them. At the northern likely flow route, two regional faults are shown cutting through the lowest pass along the basin

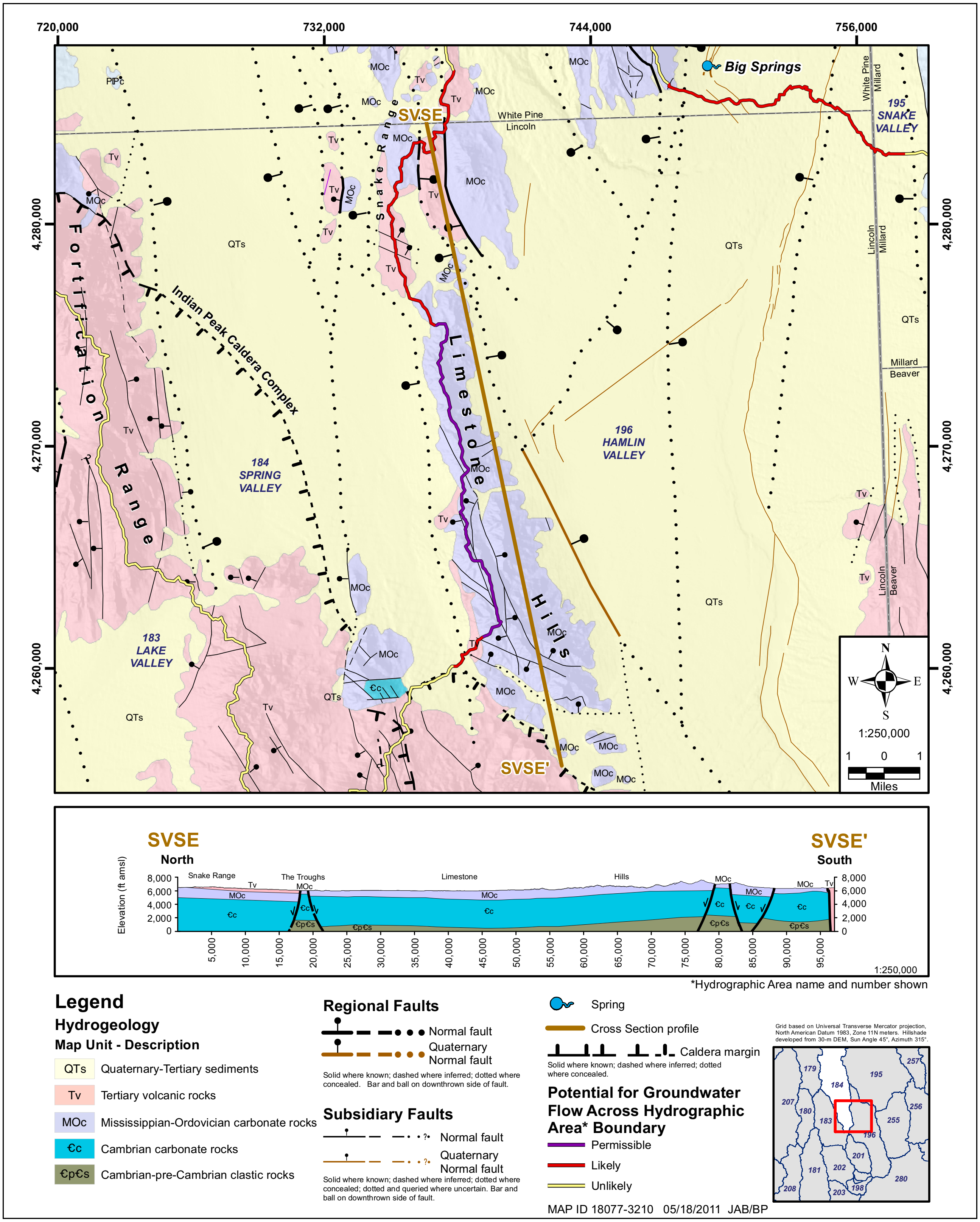


Figure 4-20
Hydrogeologic Map and Cross Section of the Southern Snake Range and Limestone Hills and Vicinity

boundary, known as The Troughs (see also Figures 5-7 and 5-20). Both are splays of the eastern range-front fault of the Limestone Hills and are possible conduits in one of two areas considered likely for groundwater to move through the Limestone Hills. Two subsidiary, west-northwesterly-trending faults are shown on the map just west of The Troughs. East-trending faults, too small to be mapped at this scale, may cut entirely through the narrow horst of the Limestone Hills at various places, including the area of The Troughs.

The southern likely flow path through the Limestone Hills would be at the southern part of the Hills. Here two west-northwest-trending faults cut through lower Paleozoic carbonate rocks just north of where the parallel-trending margin of the Indian Peak caldera complex separates the Limestone Hills to the north from the White Rock Mountains to the south. The southern of the two faults underlies a low pass at that locality, so it may be a small conduit for flow. All rocks shown in the cross section, except those at great depth, are aquifers, amenable to flow through them. Therefore interbasin flow is considered likely or permissible, although no evidence yet supports a flow that is large. Whatever the flow is, the southern geophysical sub-basin of Spring Valley, west of the Limestone Hills, would seem to be the only source for the groundwater.

From northern Hamlin Valley, groundwater passing through the Limestone Hills combines with north-flowing groundwater from southern Hamlin Valley, then flows northward into Snake Valley (Davis, 2005) then farther northward to the Great Salt Lake Desert (Harrill et al., 1988; Knochenmus, 2007). Groundwater in Snake Valley flows northward along mostly high-angle, north-striking normal faults in both the basin-fill and carbonate-rock aquifers. Not only is the valley bounded on both sides by range-front faults, forming a graben, but the interior part of the valley itself and its basin-fill sediments are cut by innumerable faults (Mankinen and McKee, 2009; McPhee et al., 2009; Rowley et al., 2009), few of which have been shown in previous mapping and only some of which can be shown on Plates 1 and 4 because of scale.

Several springs in Hamlin and Snake valleys owe their presence to faults. Big Springs occurs on the southeastern flank of the Snake Range at the edge of northwestern Hamlin Valley (Figures 4-20 and 5-7). Like most other springs in the Great Basin, it is controlled by north-trending basin-range faults (Sections 5.1.1 and 5.2.2), which allow groundwater to move to the surface from the underlying water table.

4.4.26 Confusion Range, Conger Range, Burbank Hills, and Tunnel Spring Mountains

The Confusion Range and small ranges of similar rocks form the entire eastern (Utah) side of Snake Valley. The area includes hills (Middle Range) connected to and east of the northern end of the Confusion Range. The Confusion Range proper is 60-mi-long, with a general northerly trend. Tule Valley is east of the Confusion Range. The Conger Range is a 15-mi-long, southwest-diverging fork in the southern Confusion Range, located northeast of the small communities of Baker, Nevada, and Garrison, Utah. The Burbank Hills is a 15-mi-long range south of the Conger Range and southeast of Baker and Garrison. The Burbank Hills is separated from the Conger Range by a northwest- trending valley known as the Ferguson Desert; the Desert may contain several thousand feet of basin-fill deposits (Plates 1 and 6, Plates 4 and 8, Cross Section V—V'). The Tunnel Spring Mountains is a narrow, 20-mi-long range southeast of the Burbank Hills and east of northern Pine Valley. Northern Pine Valley connects with the southeastern end of the Ferguson Desert.

All of these ranges consist almost entirely of north-striking, folded, thrusted, and attenuated, middle to upper Paleozoic rocks and Triassic rocks that together form a synclinorium, in other words a combination of synclines and anticlines that overall appear as a broad syncline (Plates 1 and 6, Plates 4 and 8, Cross Sections W—W' and V—V') (Hose, 1977; Hintze and Davis, 2002a and b, and 2003). The Mississippian Chainman Shale, 1,000 to 2,000 ft thick in the area, is repeated and thus exposed on both sides of and beneath all these ranges because it is deformed into north-striking folds (Hintze and Davis, 2002a and b, and 2003). Tertiary regional ash-flow tuffs formerly covered most of the area to a thickness of as much as 500 ft, but erosion has left only patches of these tuffs, notably the Oligocene Needles Range Group, derived from the Indian Peak caldera complex (Best et al., 1989a and b). Basin-range faults cut all these ranges, but most are of small displacement so individual stratigraphic units are remarkably coherent and continuous over this large area. The most significant basin-range fault is the northerly-trending fault zone that defines the eastern side of Snake Valley. Basin-range faults that separate the Confusion Range from Tule Valley have moderate vertical offset.

The Chainman Shale underlies, at shallow depth, all of these areas except the southern Confusion Range. The entire area is underlain at shallow depth by north-striking thrust faults. The folded Chainman, and perhaps the thrusts, probably are significant barriers to groundwater flow to the east or west. Other barriers to east or west flow are the north-striking basin-range faults. The only flow from west to east that is permissible is in the southern Confusion Range, where lower Paleozoic carbonate rocks are exposed and the range is low (Harrill et al., 1988). East-trending transverse faults of the Sand Pass transverse zone were mapped in the central and eastern Middle Range and through Sand Pass, but none extended westward to Snake Valley. The available water- level data suggest that most groundwater flow in Snake Valley and Tule Valley, and perhaps in the Confusion and related ranges, is northward, most likely along the north-striking faults and north-striking beds.

4.4.27 Needle Range and Wah Wah Mountains

The Needle Range, just east of the Nevada-Utah state line, is about 50-mi-long and consists of two subranges, the Mountain Home Range to the north and the Indian Peak Range to the south. The Mountain Home Range merges with the Burbank Hills to the north. Hamlin Valley, to the west, separates the Needle Range from the southern Snake Range, Limestone Hills, and White Rock Mountains to the west. To the east of the Needle Range is Pine Valley and to the south is the Escalante Desert. The Wah Wah Mountains is a parallel tilt block of similar length to, and located east of, the Needle Range, east of the geologic study area. The Wah Wah Mountains is the southward continuation of the Confusion Range. Wah Wah Valley is east of the Wah Wah Mountains and west of the San Francisco Mountains.

The northern part of the Needle Range consists of folded, middle to upper Paleozoic rocks (Hintze and Davis, 2002b). Locally, lower Paleozoic carbonate rocks are thrust 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 southeastern 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 separating Hamlin Valley from the Needle Range (Plates 1 and 6, Cross Sections U—U' and Q—Q'). Hamlin Valley contains at least 4,000 ft of basin-fill sediments (Plates 4 and 8, Cross Sections U—U' and Q—Q'). The basin-fill sediments in the southern half of Hamlin Valley are underlain by the Indian Peak caldera complex (Plates 4 and 8, Cross Section Q—Q'). A significant basin-range fault separates the eastern side of the Needle Range from Pine Valley.

The northern Wah Wah Mountains, like the southern Confusion Range just to the north, consist of gently folded and locally thrusted, lower to middle Paleozoic carbonate rocks. Farther south, east-dipping Neoproterozoic to Cambrian quartzite and overlying Cambrian carbonate rocks form most of the range (Hintze and Davis, 2002b; Rowley et al., 2009, Plate 1). An oil well drilled by Hunt Oil Company in the southern Wah Wah Mountains was spudded in the Prospect Mountain Quartzite and penetrated 12,500 ft of rocks, including several thrust zones (Erskine, 2001). Other thrust faults that place lower Paleozoic rocks over middle and upper Paleozoic rocks are well exposed and unconformably overlain by east-dipping, Tertiary ash-flow tuffs (Abbott et al., 1983). Near the southern end of the range, other Sevier thrusts place Cambrian rocks above the Jurassic Navajo Sandstone (Best et al., 1987c). The southeastern part of the Indian Peak caldera complex cuts the southwestern end of the Wah Wah Mountains (Williams et al., 1997). As with the Needle Range, the dominant structure controlling the range is a basin-range fault zone on the western margin, beneath Pine Valley. Pine Valley is a graben underlain by basin-fill sediments perhaps as much as several thousand feet thick but generally less (Davis, 2005). The southern ends of both the Needle Range and Wah Wah Mountains merge with each other (Best et al., 1987c) and, still farther southwest, these merge with the White Rock Mountains. These southern range margins form the northern margin of Escalante Desert and the southern margin of the Indian Peak caldera complex (Best, 1987).

4.4.28 Fish Springs and House Ranges

The 20-mi-long Fish Springs Range, near the northeastern edge of the geologic study area, extends south from the Great Salt Lake Desert. The southward continuation of the Fish Springs Range is the 60-mi-long House Range. The two ranges form the eastern boundary of Tule Valley, which is just east of the study area and contains basin-fill sediments that in most places are 1,000 to 2,000 ft thick but have been estimated to be locally more than 6,000 ft thick (Davis, 2005). The surficial deposits in Tule Valley consist largely of lacustrine deposits of Lake Bonneville and of alluvial fans (Sack, 1990).

The Fish Springs Range is a highly faulted but generally gently west-dipping horst consisting of Middle Cambrian to Middle Devonian carbonate rocks that rest on Lower Cambrian siliciclastic rocks (Plates 4 and 8, Cross Section X—X') (Kepper, 1960; Hintze, 1980a and b; Morris, 1987; Hintze et al., 2000; Hintze and Kowallis, 2009). The range is bounded by large basin-range faults on its western and eastern sides, with the main fault being the one on the eastern side. This fault is still active and has components of Holocene and Pleistocene movement (Oviatt, 1991; Black et al., 2003). East-striking, oblique-slip faults have been mapped throughout the range (Hintze, 1980a and b). Some of them partly control the Fish Springs zinc-lead-silver-tungsten mining district on the northwestern side of the range (Oliveira, 1975; Christiansen, 1977); a newly discovered, buried Eocene quartz monzonite pluton also controls this district (Puchlik, 2009). A concentrated series of east-striking faults occurs at Sand Pass, which separates the southern end of the Fish Springs Range from the northern end of the House Range. This east-trending fault zone is part of the Sand Pass transverse zone, which extends intermittently as far to the east as the Wasatch front and as far to the west as the Kern Mountains (Stoeser, 1993; Rowley, 1998; Rowley and Dixon, 2001). At Sand Pass, the transverse zone contains small intrusions (Chidsey, 1978) and causes profound structural differences (the rocks have opposite dips and the main fault is on opposite sides) between the two ranges, as in some other transverse zones (Faulds and Varga, 1998).

The high House Range is a tilt block, bounded on the western side by a major basin-range fault beneath eastern Tule Valley and on the eastern side by a fault of lesser displacement. The faults uplift the range and tilt it several degrees east (Hintze and Davis, 2002a; Rowley et al., 2009, Plate 1). Like the main bounding fault zone of the Fish Springs Range, the main fault zone of the House Range is an active fault zone of large displacement that includes Holocene and Pleistocene movement (Sack, 1990; Black et al., 2003), but this fault zone is on the western side of the House Range. The range, famous among paleontologists for its trilobites, consists mostly of Cambrian strata, which include clastic sedimentary rocks at the western base of the range and carbonate rocks above. The central part of the range is intruded by the Notch Peak quartz monzonite pluton of Jurassic age.

Neoproterozoic to Cambrian quartzite along the western side of the Fish Springs and House ranges forms a likely eastward groundwater barrier between Tule Valley and the valleys to the east, including the Sevier Desert. Northward flow, of course, likely dominates in this entire area in conduits provided by basin-range faults, including the fault zone along the western sides of the Fish Springs and House ranges (Stephens, 1977).

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5.0 GEOPHYSICS

In an effort to provide additional data to interpret the subsurface of the geologic framework, SNWA contracted with the USGS Geophysical Unit at Menlo Park, California to collect and analyze geophysical data in the geologic study area. The analysis of geophysical measurements throughout the project area defines the overall shape and thickness of basins, identifies buried faults that may be either barriers or conduits to groundwater flow, provides estimates of the depth to pre-Cenozoic basement rocks, helps characterize interbasin flow as to likely, unlikely, or permissible interbasin flow, and assists in describing aquifers.

5.1 Gravity Surveys

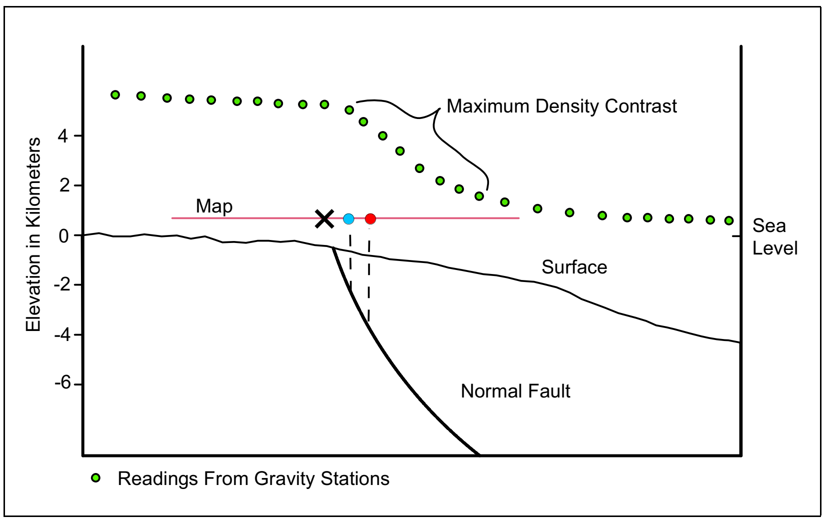
For hydrogeology, the most critical type of geophysical information is data on the gravity of rocks measured at the surface. Within the geologic study area, more than 5,000 gravity measurements (Snyder et al., 1981 and 1984; Bol et al., 1983; Ponce, 1992 and 1997) had previously been made, but more detail was needed in many areas. In 2000, the USGS collected 224 gravity stations along 5 profiles in Coyote Spring Valley (Phelps et al., 2000). Between 2003 and 2007, the USGS collected another 1,632 gravity stations and issued analysis reports (Scheirer, 2005; Mankinen, 2007; Mankinen et al., 2006, 2007, 2008). In 2002, with funding from the Virgin Valley Water District, NPS, and the USGS, the USGS collected 344 gravity stations in Meadow Valley Wash basin and California Wash basin and, just east of the map area, in the Tule Desert (Scheirer et al., 2006). In 2008, Mankinen and McKee (2009) collected 206 gravity stations, primarily in Snake Valley and, just east of the geologic study area, in Tule Valley and Fish Springs Flat, and interpreted the anomalies. In the fall of 2010, additional gravity data (99 new gravity stations) were measured in several key areas in and adjacent to Spring Valley by Mankinen and McKee (2011) and their analysis is included here. The sections below summarize the geophysical results for each basin, discussed from north to south. A brief analysis of gravity data from California Wash Basin and lower Meadow Valley Wash, which have less significance for the four Project Basins, are discussed in Sections 4.4.20 and 4.4.21. At gravity stations on bedrock, samples were collected for density and magnetic-susceptibility properties. In this section, we use metric measurements because they were used in the USGS studies.

New gravity stations were collected within coverage gaps of the prior data, especially within and adjacent to the Project Basins. Values of observed gravity at the new stations were calculated by accounting for fluctuations related to tidal accelerations and for instrument drift constrained at the beginning and end of each day. Gravity observations were processed to account for the predictable effects of latitude, elevation, and terrain variations. 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-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 km using a minimum curvature algorithm (Webring, 1985). Gravity data were reduced using standard gravity corrections (Blakely, 1995) to produce the complete Bouguer gravity anomaly. A regional isostatic field was subtracted from the Bouguer anomaly, thus removing long-wavelength variations in the gravity field that are inversely related to topography. The resulting isostatic gravity field is a reflection of local density distributions in the middle and upper crust. Gravity lows (cool colors) generally indicate low-density sedimentary basin-fill deposits and volcanic rocks in the basins; gravity highs (warm colors) generally reflect pre-Cenozoic basement rocks in the basins.

Gridded isostatic gravity anomaly data were used to guide the gravity analysis in two modes: (1) to detect significant lateral density interfaces in the subsurface using a maximum horizontal gradient technique (Blakely and Simpson, 1986) and (2) 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, in turn, involves two steps: (a) to separate contributions to the isostatic gravity anomaly that arise from Cenozoic sedimentary and volcanic deposits and those from pre-Cenozoic rocks and (b) to convert the contributions from the lower density deposits into a model of basin depth (Jachens and Moring, 1990). In other words, the isostatic residual gravity field 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 basin fill. Because upper Cenozoic sedimentary alluvial fill and underlying Tertiary volcanic rocks have similar densities, they cannot be geophysically discriminated from each other, so geophysically (in this section only) they are lumped together as “basin fill” within an area. The accuracy of thickness estimates derived by the gravity inversion technique is dependent on (1) the assumed density-depth relation of the Cenozoic basin fill and (2) the initial density assigned to the basement rocks. Density of basement rocks is generally assumed to be 2.67 mg/m^3, and this value is considered appropriate in this area, where major exposures consist of Neoprecambrian 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.

Gravity data can be enhanced in a number of ways (e.g., Blakely, 1995) to better characterize causative sources of their anomalies. Gravity anomalies can be analytically upward-continued by 1 to 3 km (Hildenbrand, 1983) to de-emphasize surface and near-surface features and enhance the contribution from deeper sources. Horizontal gradients can then be calculated for the long-wavelength gravity anomalies identified by the upward-continued data (e.g., Cordell, 1979; Blakely, 1995). When calculated for two-dimensional (2D) data grids, horizontal gradients will place narrow ridges, called “maxspots,” over significant changes in gravity. The method of Blakely and Simpson (1986) was used to calculate maximum values of these gravity and magnetization gradients, the locations of which tend to overlie the edges of causative bodies with abrupt, near-vertical contacts. For non-vertical contacts between geologic units of contrasting properties, maximum values of the horizontal gradients will be displaced down-dip and away from the edges of the body. These maxima, along with the gradient "ridges" containing them, identify density contrasts that can help delineate deep-seated crustal structures, primarily faults, separating major tectonic domains. Zones between these domains can potentially locate Cenozoic tectonic features and, indeed, many examples can be seen where the maxspots closely track faults that have been mapped at the surface. Where lines of maxspots from deeper levels are displaced from each other toward the basin, a basin-dipping fault is suggested (Figure 5-1). In other words, when progressively deeper maxspots are projected vertically (that is, upward continued) to the surface, onto the map of the isostatic residual gravity field, they are progressively farther on the downdip side of a fault than the actual surface trace of the fault (see Figure 5-5 and others). The less a fault dips, the farther apart are the maxspots from the various depths, as opposed to a vertical fault, where the maxspots that are upward continued from different depths are on top of each other.



Note: X at surface, blue dot from 2 km depth, red dot from 3 km depth.

Figure 5-1
Geologic Cross Section of a Normal Fault Interpreted from a Gravity Profile across It (Black Dots), Showing Upward-Continued Maxspots Projected onto a Map

5.1.1 Gravity Data for Spring and Snake Valleys

Mankinen et al. (2006) interpreted the gravity data in Spring and Snake valleys (Figure 5-2), including 545 new gravity stations (Figure 5-3) collected primarily in Spring Valley, the northern Limestone Hills, northern Hamlin Valley, and southern Tippett (Antelope) Valley. The isostatic gravity field for Spring and Snake valleys is shown on Figure 5-4. The depth to basement, calibrated by 11 oil and gas wells, is shown on Figure 5-5. The topographic contour interval in these figures is 400 m. Later, Mankinen et al. (2007) collected additional data in Tippett Valley and Spring Valley as well as areas to the south; and Mankinen and McKee (2009) reinterpreted the gravity data in Snake Valley, Hamlin Valley, and areas farther east of the geologic study area based on 206 new gravity stations in these regions. In the fall of 2010, additional gravity data were collected by Mankinen and McKee (2011) in northern Spring Valley, Tippett Valley, and the unnamed valley between the Kern

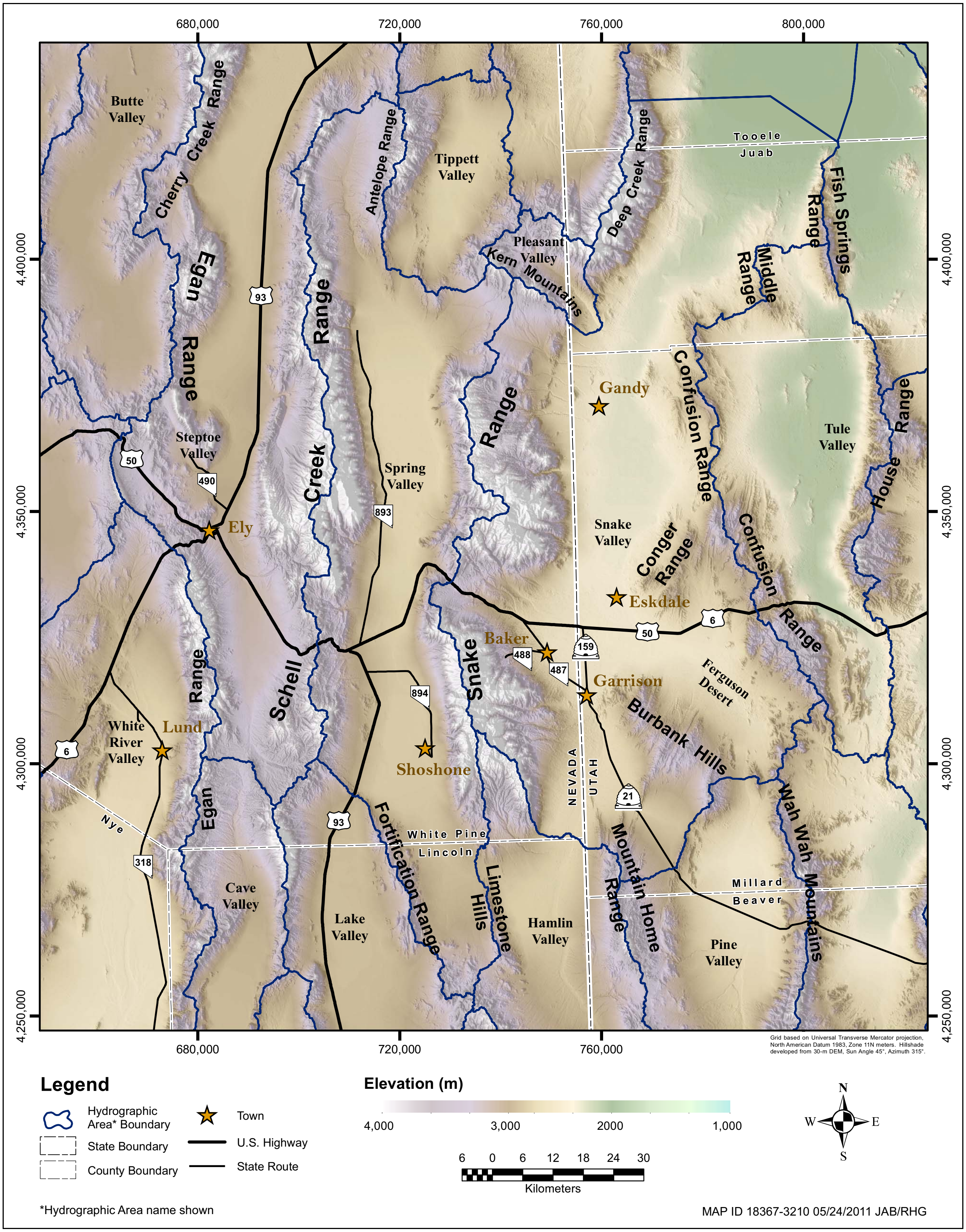


Figure 5-2
Shaded Relief Map of Spring and Snake Valleys and Vicinity, Nevada and Utah

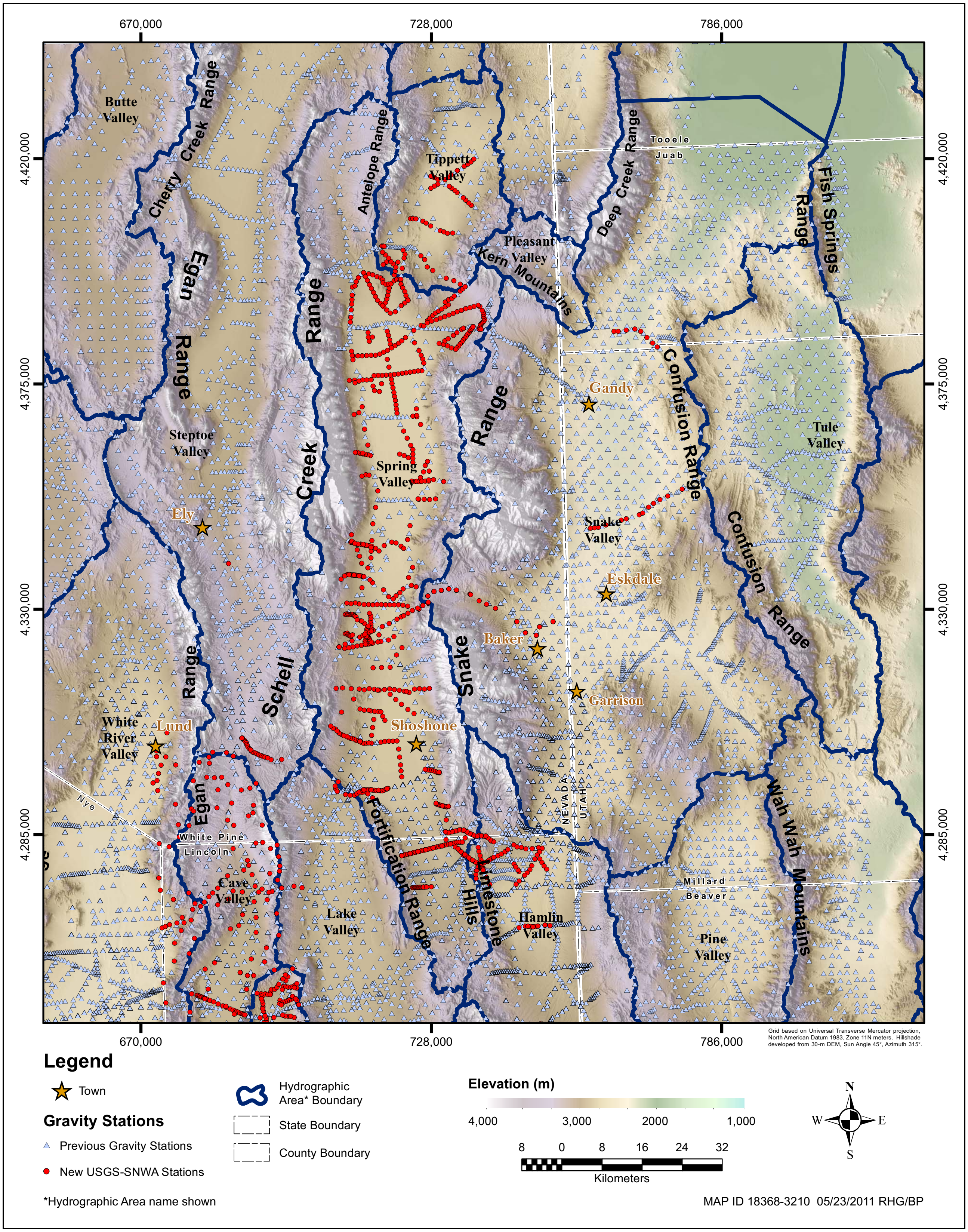
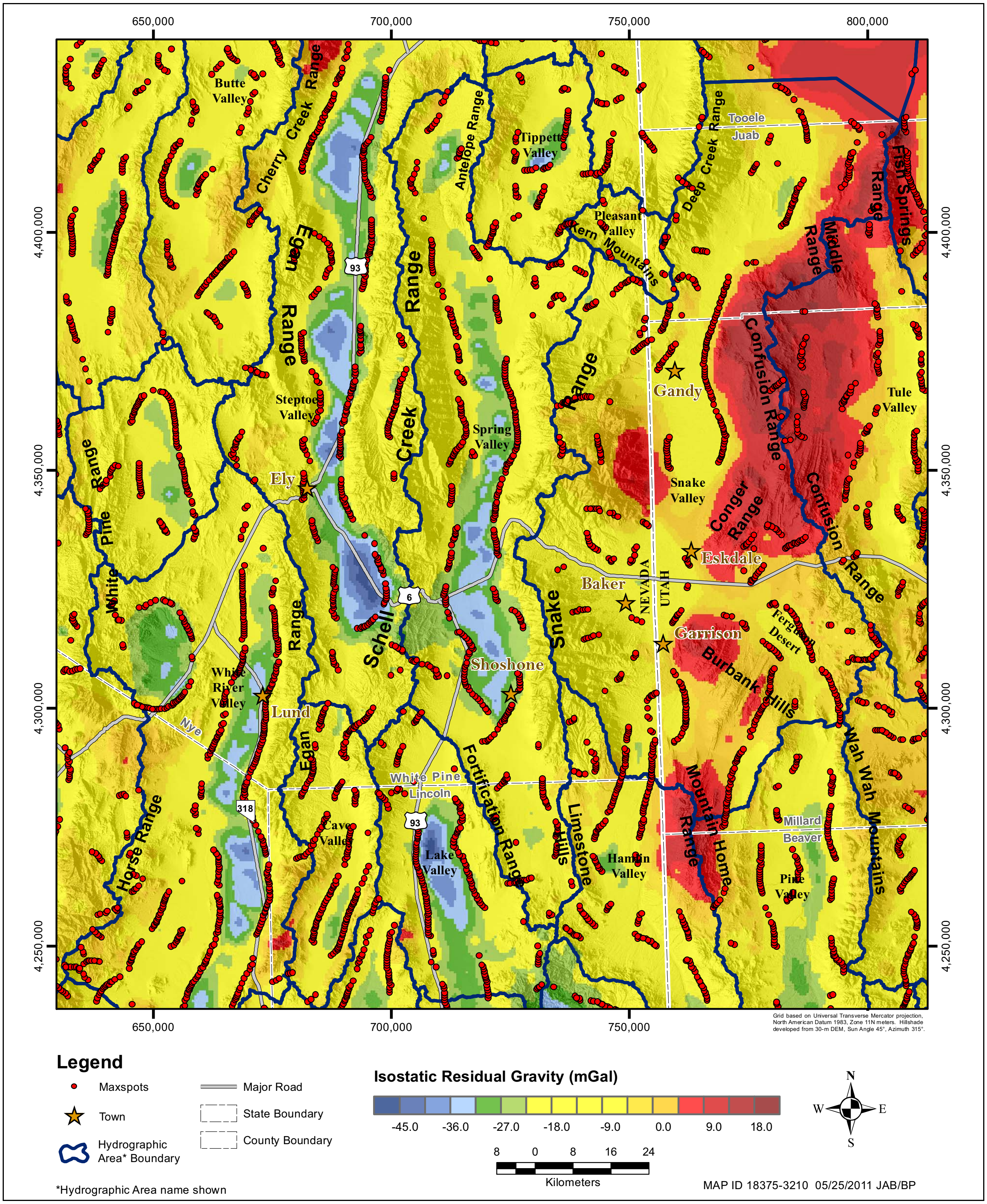


Figure 5-3
Gravity Stations in Spring and Snake Valleys and Vicinity, Nevada and Utah



Note: Maxspots calculated from the 3-km upward-continued gravity grid.

Figure 5-4
Isostatic Residual Gravity Field and Maxspots in Spring and Snake Valleys and Vicinity, Nevada and Utah

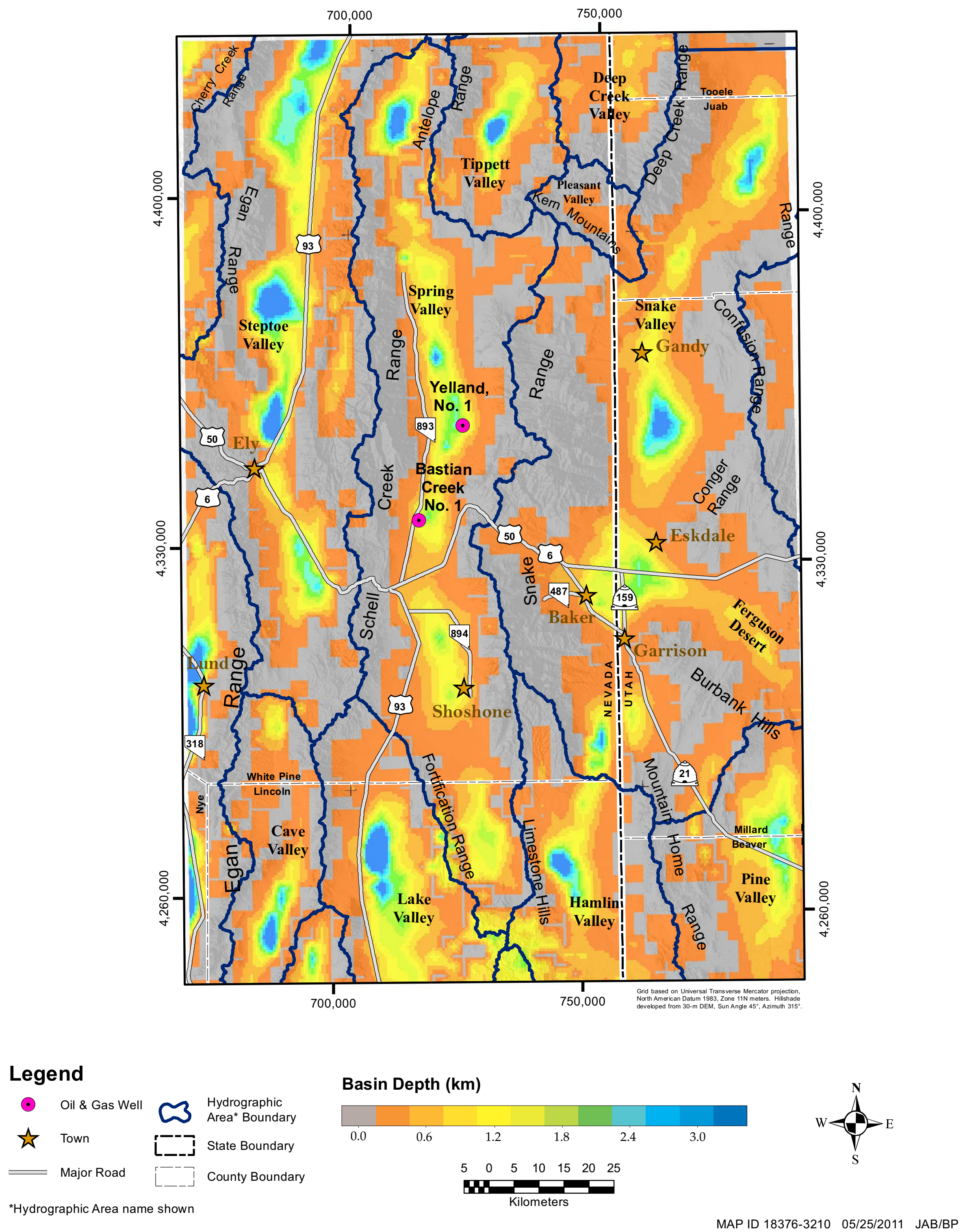


Figure 5-5
Depth to Pre-Cenozoic Basement in Spring and Snake Valleys and Vicinity, Nevada and Utah

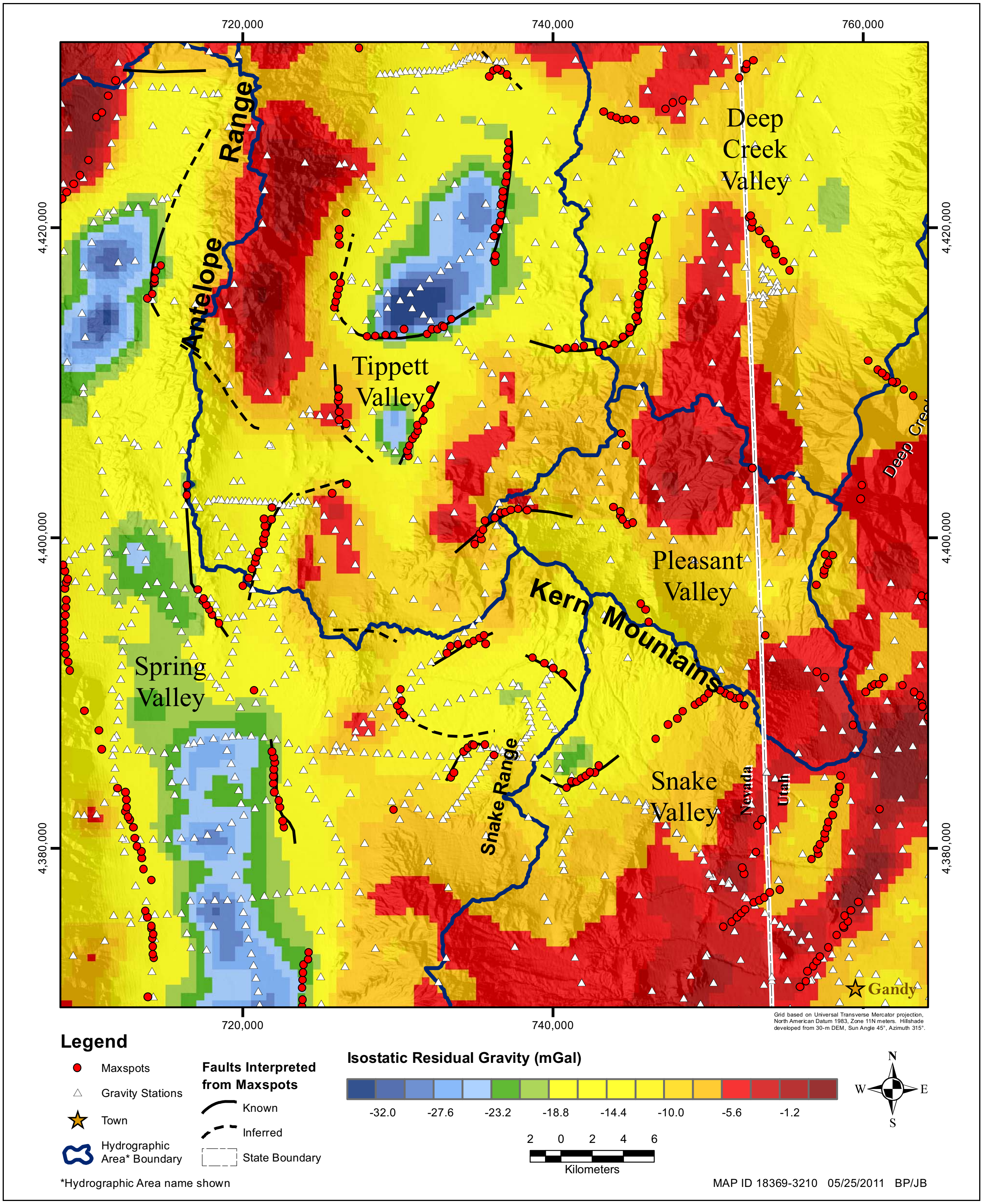
Mountains and Snake Range. Our discussion below and all figures include these new data, although the final USGS reports giving them will soon be released.

The gravity inversion method indicates that the maximum thickness of basin fill (alluvium and volcanic rocks) in the principal valleys of interest is generally 2 km or more (Figure 5-5). Note, however, that the deepest areas of Spring and Hamlin valley are much narrower than the deepest areas in both Steptoe and Snake valleys. Absolute values of basin depths are estimated using a density-depth profile calibrated by deep oil and gas wells, some of which penetrated pre-Cenozoic basement. Maximum depths to pre-Cenozoic basement in Spring, Steptoe, and Hamlin valleys are interpreted to be between 3 and 3.5 km, except for the northernmost parts of Steptoe and Spring valleys (39°45′ N to 40°N), which appear to 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 (Antelope Valley), where depths appear to be generally greater than 3 km, and in some areas these depths max extend to between 5 and 5.5 km.

Depth-to-basement data (Figure 5-5) indicate that Spring Valley has a maximum depth (basin-fill sediments plus volcanic rocks) of almost 4 km west of the Antelope Range, but elsewhere is generally 1.5 to 2 km deep, and locally 3 km (Mankinen et al., 2006). Two oil test wells (Yelland No. 1 and Bastian Creek No. 1) in northern Spring Valley give depths to basement of 1.5 and 1.2 km, respectively (Hess, 2004). Figure 5-5 also suggests two geophysical sub-basins to Spring Valley. The northern geophysical sub-basin extends from west of the Antelope Range southward to just northeast of the Fortification Range. In its northern part, just south of the Antelope Range, Gans et al. (1989) and Sweetkind et al. (2007a) suggested that the caldera source of the Kalamazoo Tuff was buried beneath the valley here. However, the relatively high gravity at this location would tend to argue against this hypothesis inasmuch as most calderas are marked by substantial gravity lows. In the central part of the northern geophysical sub-basin, where the valley is crossed by US 6/US 50, a small hill (Rattlesnake Butte) made up of bedded volcanic breccia protrudes from near the middle of the valley and is the site of a former fluorspar mine. Mankinen et al. (2006) collected gravity, ground magnetic, and paleomagnetic data here that suggests a narrow and subtle, buried east-west bedrock ridge that connects with the Snake Range to the east (Figure 5-5).

The southern geophysical sub-basin of Spring Valley is south of an inter-valley bedrock ridge that is entirely buried by basin-fill alluvium. This interpreted ridge has no bedrock at the surface but has an obvious expression in the gravity data as a broad ridge at less than 0.4 km depth (Figure 5-5) that appears to extend entirely across Spring Valley between the northern Fortification Range and the southwestern Snake Range. The southern sub-basin located west of the Limestone Hills, has a maximum depth of about 1.6 km.

During data collection, special attention was paid to several boundaries to Spring Valley where groundwater-flow volumes or directions were poorly known or in debate. These included (1) Tippett Valley, (2) the area between Tippett Valley and Spring Valley, (3) the area between the Kern Mountains and the Snake Range, and (4) the area of and north of the Limestone Hills. For area #1, #2, and #3, Figure 5-6 shows the isostatic gravity, including maxspots, from Mankinen and McKee (2011). Two deep lows in Tippett Valley are shown here, both marked by curved structures on their southern sides that clearly define the lows. The curved lines in either area could be faults



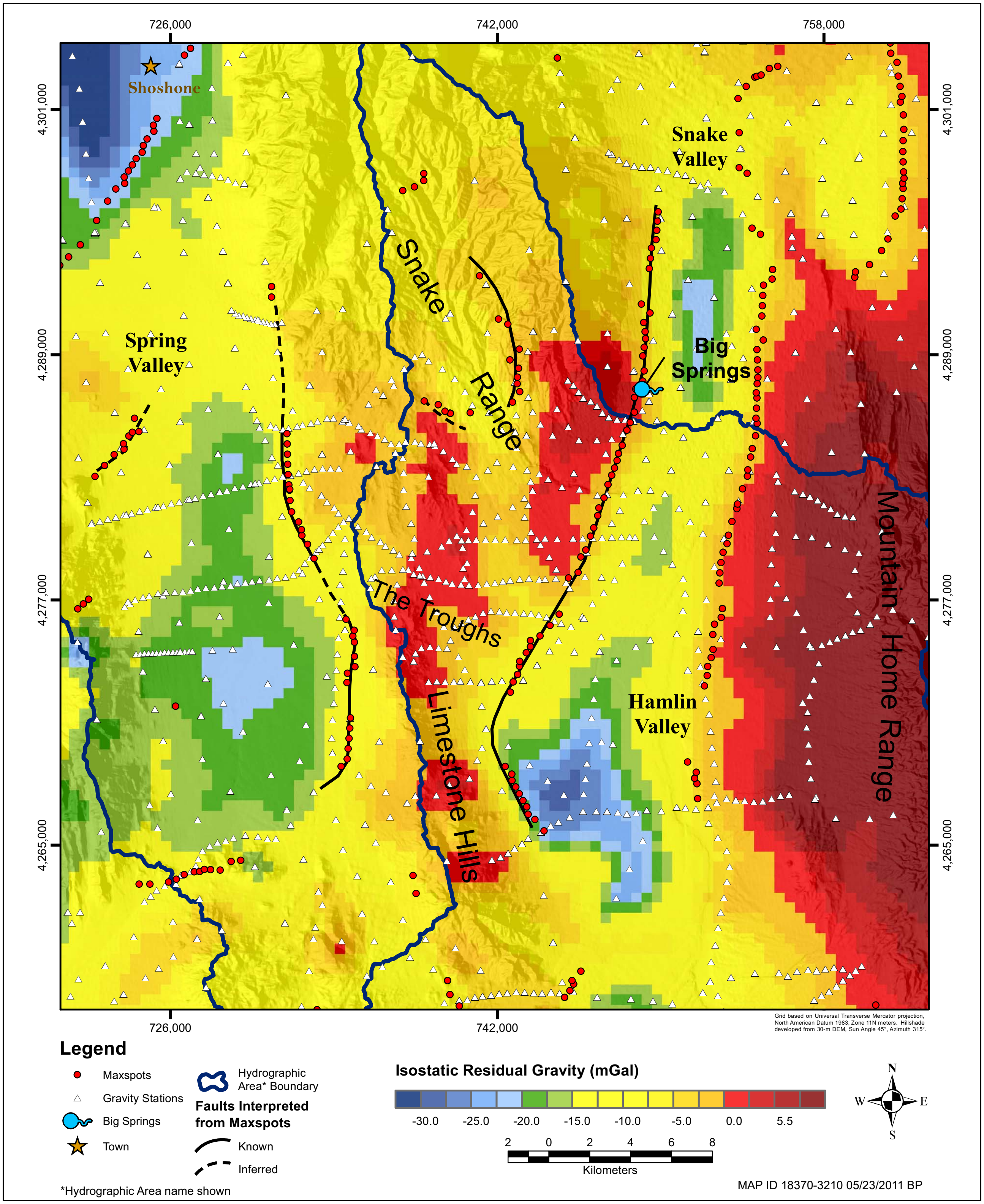
Note: Red maxspots are upward-continued from 3 km depth. Black lines are faults interpreted from maxspots.

Figure 5-6
Isostatic Residual Gravity Field and Maxspots in Tippett Valley, Western Kern Mountains, and Vicinity, Nevada

downthrown into the center of the basin or the boundaries of the caldera that erupted the Kalamazoo Tuff. Maxspots on these curved lines and on the north-trending structure on the northeastern side of the larger, northern low clearly define structures that dip into the basins; the one on the northeastern side of the northern low is a major down-to-the-west basin-range fault. In the western part of the map area, gravity data define two segments of the main, north-trending, mostly west-dipping, graben-bounding fault on the eastern side of Spring Valley and another north-to-northeast-trending range-front fault that bounds the western side of the central to northern Antelope Range; the three faults probably connect with each other.

Farther south, the east-central part of the map area (Figure 5-6) shows the western end of the Kern Mountains, including an east-trending fault defined by gravity data on the northern side. South of the Kern Mountains, the western part of the basins between the Kern Mountains and Snake Range (southeastern part of the map area) was downthrown along faults that have east-northeast and west-northwest components but result in one or two east-west basins. The low range southwest of the Kern Mountains is the Red Hills, whose western and eastern sides are defined by north-trending basin-range faults. Isostatic gravity data show that these north-trending faults not only define the Red Hills but appear to continue as buried faults that define shallow bedrock both north and south of the range. It might be argued that groundwater could move eastward from Spring Valley south of the Red Hills, but the isostatic gravity data suggest that buried pre-Tertiary rocks underlie the area south of the Red Hills and likely constitute a barrier for such a flow path. In conjunction with the depth-to-basement map (Figure 5-5), it seems more reasonable that any interbasin contribution of groundwater to the basin(s) between the Kern Mountains and Snake Range would be small or nil.

Figure 5-7 shows the isostatic gravity map and maxspots for area #4, from Mankinen and McKee (2011). The map shows the northern Limestone Hills and southern Snake Range, and the low pass between them that is south of the center of the map (contour interval is 400 m). The high-gravity areas (red) are underlain by exposed Devonian carbonate rocks, whereas the basins of Spring Valley on the west and northern Hamlin Valley on the east (yellow to blue) are underlain by upper Cenozoic alluvium and basin-fill deposits and in turn by volcanic rocks (compare with the geologic map, Plates 1 and 6). The two main north-trending, range-front, basin-range faults are shown by gravity data on either side of the Snake Range and Limestone Hills. The ranges are intensely internally broken, especially by north-trending faults, as indicated by Plates 1 and 6, but few of these faults are discriminated by gravity. One that is discriminated separates the large eastern high from the large central to southern high to the west, with a small graben of alluvial-fan and underlying volcanic rocks between the two highs of carbonates; this fault clearly continues south and probably joins the main eastern range-front fault. At the low pass (i.e., The Troughs) between the southern Snake Range and the Limestone Hills, the large central gravity high (red) has a northwest-trending embayment on its eastern side. This embayment probably marks an east-trending or northwest-trending fault that displaces the gravity high. This structure may provide a pathway for groundwater to flow from Spring Valley to northern Hamlin Valley. In the northeastern part of the map area, Big Springs is a large local spring controlled by a north-trending Quaternary fault subsidiary to the main range-front fault due west.



Note: Red maxspots are upward-continued from 3 km depth. Black lines are faults interpreted from maxspots.

Figure 5-7
Isostatic Residual Gravity Field and Maxspots in the Southern Snake Range and Northern Limestone Hills, Nevada

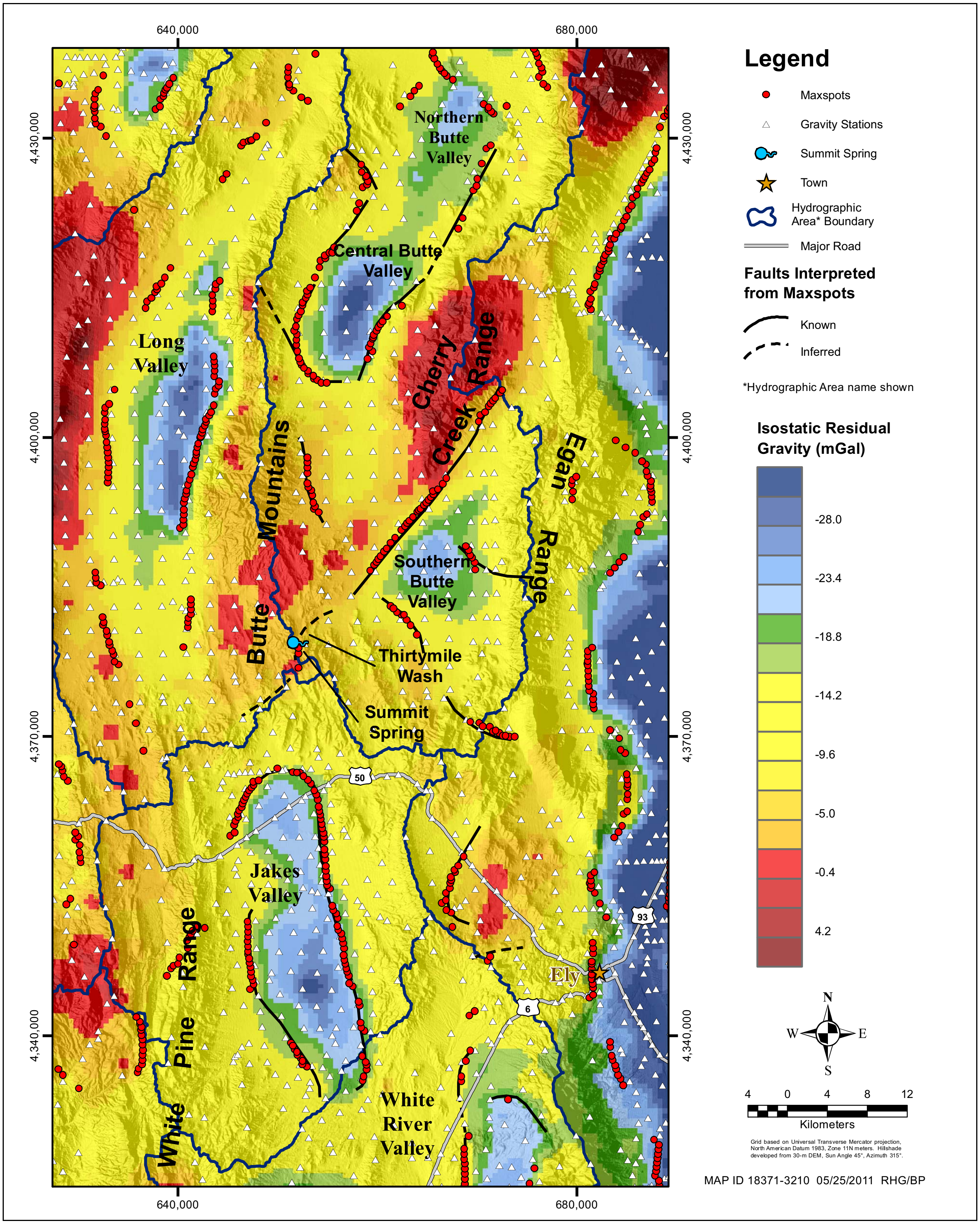
5.1.2 Gravity Data for Butte Valley and Jakes Valley

In order to help better understand the boundary conditions between south Butte and Jakes valleys, we analyzed the isostatic gravity in these two valleys and the low hills between them (Figure 5-8). Butte Valley consists of three deep gravity low areas (blue), or geophysical sub-basins, two that trend northeast and are joined in the northeastern part of the figure, and the other a deep low 20 km to the south, just south of the southwestern-extending end of the Cherry Creek Range, and also trending largely northeast. The two northern geophysical sub-basins are defined on both sides by major, northeast-striking normal basin-range faults, and the northwestern side of the southern sub-basin is similarly defined by a major northeast-striking normal fault. These faults are interpreted from maxspots. Gravity data show that the fault controlling the southern geophysical sub-basin, located between the sub-basin and the Cherry Creek Range, continues southwestward beneath southern Butte Valley. Clearly the bedrock in the southwestern end of the Cherry Creek Range also continues as a buried ridge beneath Butte Valley, and connects with the southeastern Butte Mountains on the western side of the valley.

The northeast-striking basin-bounding fault that defines the southern geophysical sub-basin (Figure 5-8) is dashed to the southwest along the southeastern edge of the Butte Mountains and low hills of volcanic rocks just to the southeast of the Butte Mountains. The fault is dashed because the change in gravity across it is considerable but the data (gravity stations) are not closely spaced here to constrain the gradient, which therefore is not as obvious or as significant as the gradient farther northeast where it bounds the sub-basin. The dashed part of the geophysically-determined fault is also shown by a mapped fault on the geologic map (Figure 4-10). A gravel road between Butte and Jakes Valley (its eastern part follows Thirtymile Wash) parallels the fault, with Summit Spring along the road controlled by the fault near the low pass between the Butte Mountains and the hills to the southeast.

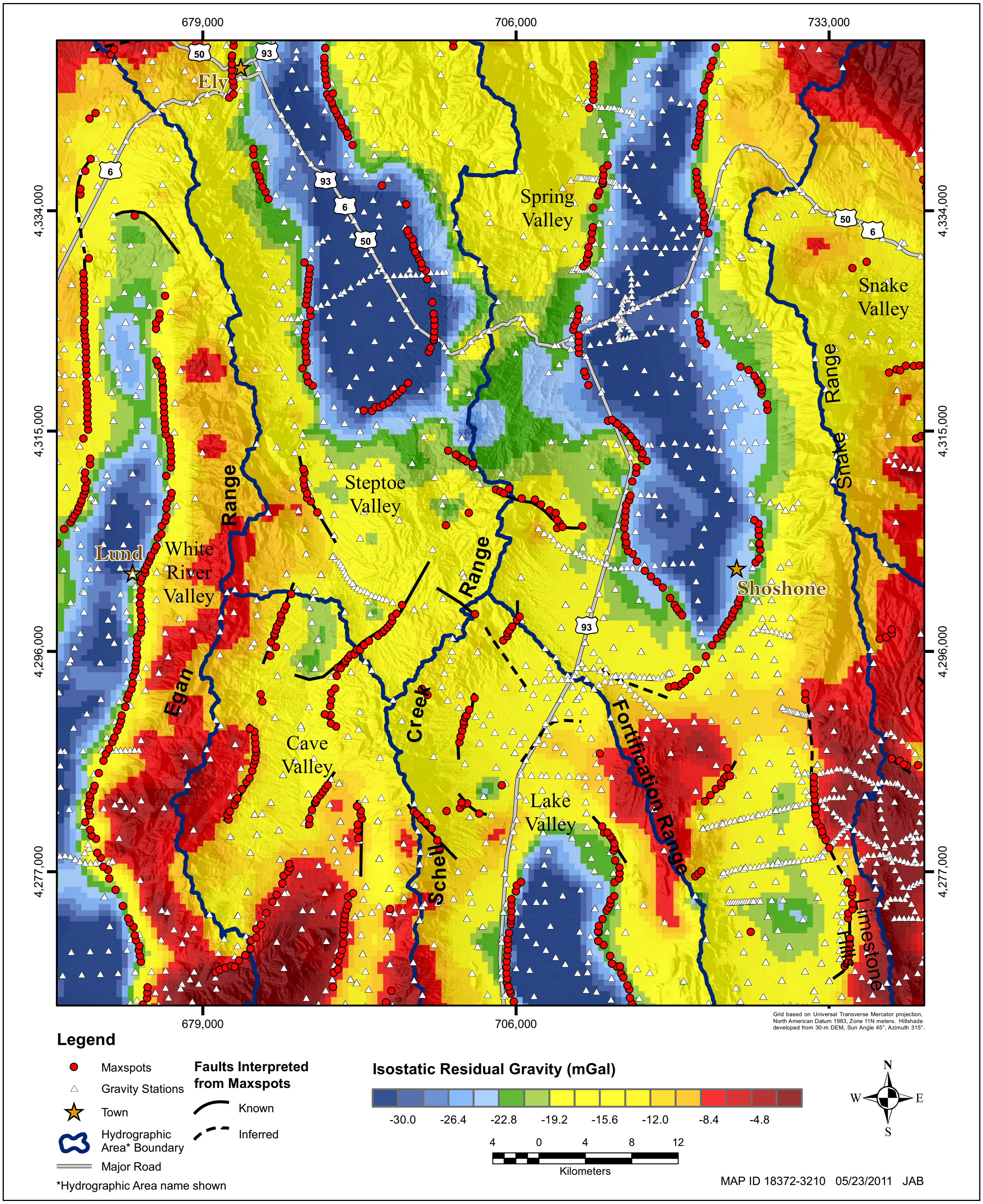
5.1.3 Gravity Data for the Southern End of Steptoe Valley

In an attempt to look for possible outlets for groundwater flow from southernmost Steptoe Valley, Mankinen and McKee (2011) compiled detailed gravity data for the area consisting of southern Steptoe Valley, southwestern Spring Valley, northern Cave Valley, and northern Lake Valley. Figure 5-9 illustrates the isostatic gravity anomalies for this area. Southernmost Steptoe Valley, shown as green in the northwestern corner of the map, appears to be relatively shallow. In fact, in the middle of Steptoe Valley about 5 km north of the map area, oil test well Titan Federal No. 1 penetrated basin-fill sediments and volcanic rocks to a depth of 940 m (Hess, 2004). Southwestern Spring Valley in the northeastern part of the map and northern Lake Valley in the southeastern part of the map are significantly deeper, as indicated by blue. Only a small sub-basin of Cave Valley, at and south of the low pass, called Bullwhack Summit, which separates Steptoe Valley from Cave Valley, appears to contain significant basin-fill sedimentary rocks or volcanic rocks, whereas basin-fill and volcanic rocks are thin in more southern parts of Cave Valley on the map (see also Figure 5-5). Maxspots in Figure 5-9 show that this northern sub-basin to Cave Valley is defined on its southern side by a northeast-trending, northwest-dipping normal fault. This fault continues northeast and it and its northeast continuation (green northwest of it, and yellow southeast of it) may partly uplift the Schell Creek Range. To the east, other north- to northeast-trending normal faults that dip east to southeast mark another prominent fault zone that defines the eastern side of the Schell Creek Range.



Note: Red maxspots are upward-continued from 3 km depth. Black lines are faults interpreted from maxspots.

Figure 5-8
Isostatic Residual Gravity Field in Butte and Jakes Valleys and Vicinity, Nevada



Note: Red maxspots are upward-continued from 3 km depth. Black lines are faults interpreted from maxspots.

Figure 5-9
Isostatic Residual Gravity Field and Maxspots in Southern Steptoe Valley and Vicinity, Nevada

The main mass of the range, between these faults marking its east and west sides, are made up of relatively high-gravity rocks (yellows, with some reds) that correlate on the geologic map (Plate 1) with heavily faulted Paleozoic carbonates and the Chainman Shale.

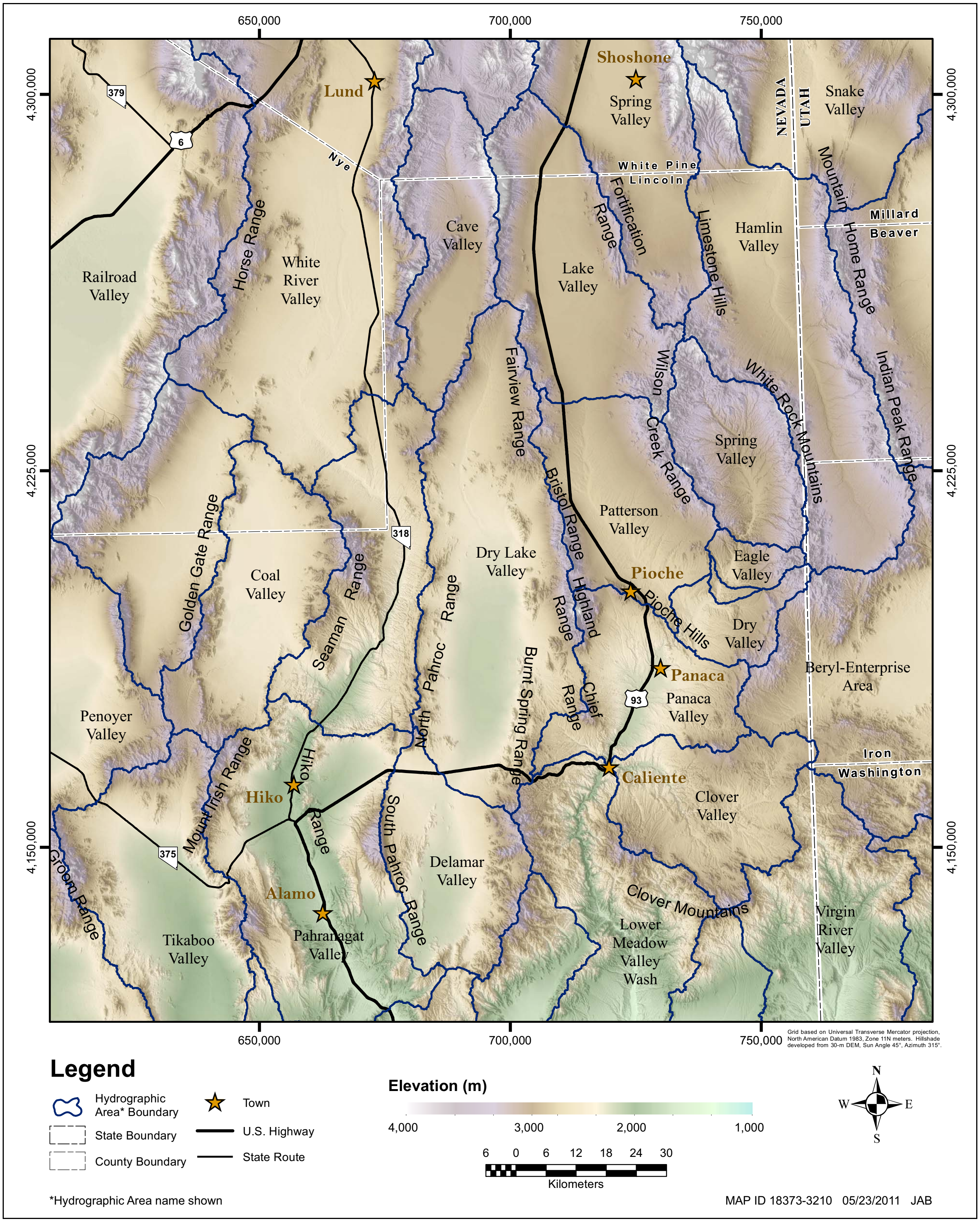
5.1.4 Gravity Data for Cave, Dry Lake, and Delamar Valleys

In 2003 and 2004, with support from SNWA, Scheirer (2005) collected 468 new gravity stations in Cave, Dry Lake, and Delamar valleys to supplement about 3,500 stations in the area that had been previously collected (Snyder et al., 1981 and 1984; Bol et al., 1983; Ponce, 1992 and 1997). Scheirer's study was updated in 2006 with the collection of 434 additional stations in Spring and northern Dry Lake valleys (Mankinen et al., 2007). In 2007, another 185 gravity stations in central to southern Dry Lake and Delamar valleys (Mankinen et al., 2008) were obtained.

The figures and some of the interpretations of the gravity anomalies in the three valleys follow that of Mankinen et al. (2008). Figures 5-10 and 5-11 (Figures 1and 3, respectively, of Mankinen et al., 2008) provide, respectively, the shaded relief index map and the isostatic gravity field. Figure 5-12 (Figure 4 of Mankinen et al., 2008) shows maxspots on the isostatic gravity field. The calculated maximum values of the horizontal gradients are given as small crosses, whereas colored dots are maximum values of the horizontal gradients after analytically upward-continuing the observed anomalies to 2 km.

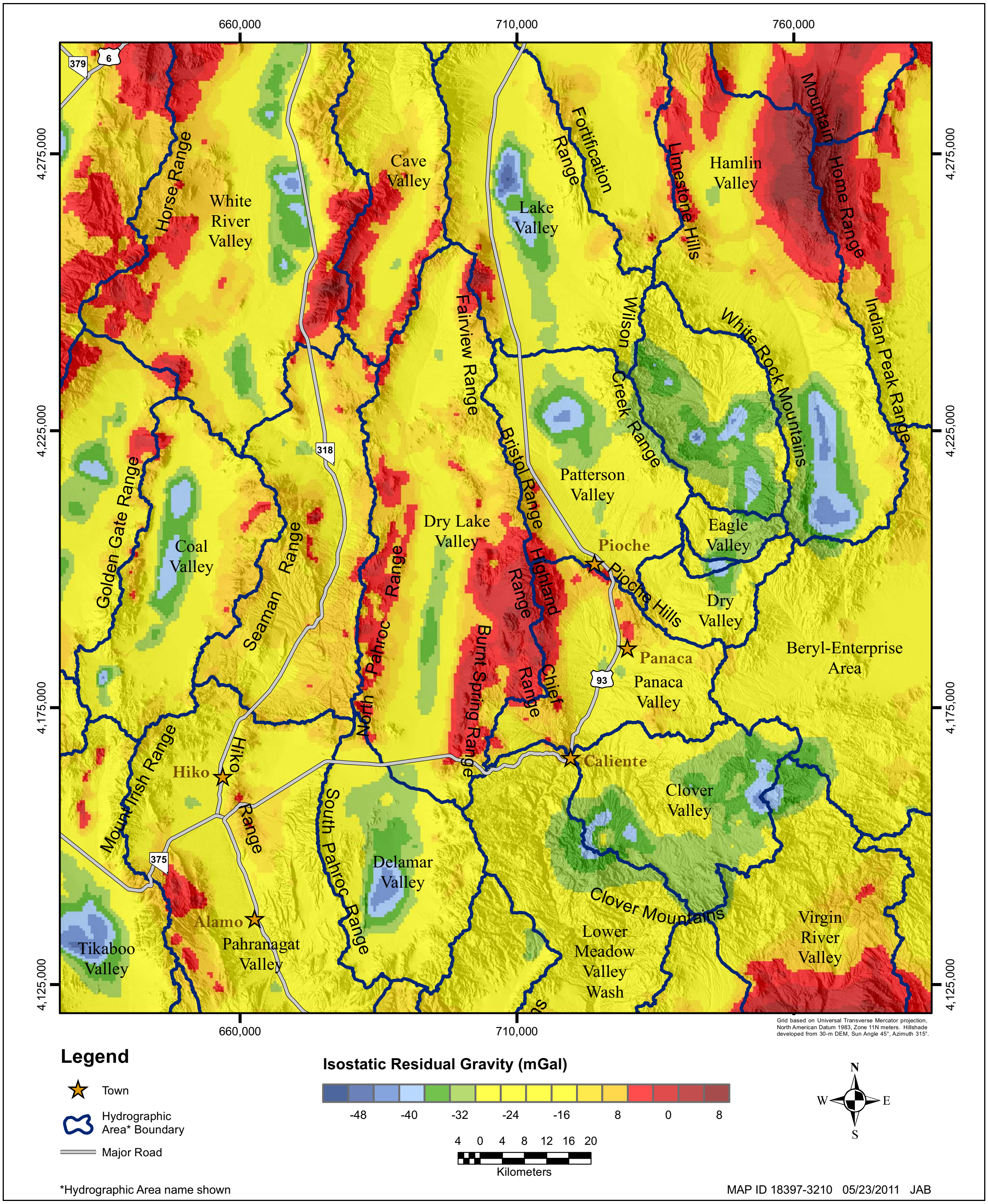
Figure 5-13 (Figure 7 of Mankinen et al., 2008), the depth to pre-Cenozoic basement, shows that all basins are asymmetrical in cross section and in their placement beneath the valley, reflecting basin-range extension that is rarely symmetrical in time and space. Dry Lake Valley is characterized by a slot-like graben in its center, whereas the deep portions of Cave and Delamar valleys are more bowl-shaped. The figure shows that southern Cave Valley (south of the Shingle Pass fault) is significantly deeper than Cave Valley north of the Shingle Pass fault and that the deepest parts of Dry Lake and Delamar valleys are in their southern parts. Northern Dry Lake Valley (Muleshoe Valley) is relatively shallow compared to the rest of Dry Lake Valley, and the buried bedrock ridge separating them, along the east-trending Blue Ribbon transverse zone, is apparent in the depth-to-basement data (Figure 5-13). Using the depth-to-basement algorithm, the general depth of the basin beneath southern Cave Valley extends down to 3 to 5 km, that beneath northern Dry Lake (Muleshoe) Valley to 2 km, that beneath southern Dry Lake Valley to 3 to 5 km and perhaps locally to 6.5 km, and that beneath southern Delamar Valley to 2 to 3 km (Scheirer, 2005; Mankinen et al., 2008). The ranges surrounding Dry Lake and Delamar valleys are dominated by volcanic rocks that may produce lower-density basin infill, which, in turn, would make the maximum depth estimates somewhat less. Significant parts of the basins are shallow (less than 1 km deep).

The east-trending Timpahute transverse zone shows up well in gravity data (Figure 5-12) across Dry Lake Valley and east and west of it, but a possible bedrock ridge that might separate southern Dry Lake Valley from northern Delamar Valley is indeed subtle, in the depth-to-basement data (Figure 5-13). In contrast, a buried north-trending bedrock ridge between the North Pahroc and South Pahroc ranges is obvious (Figure 5-13).



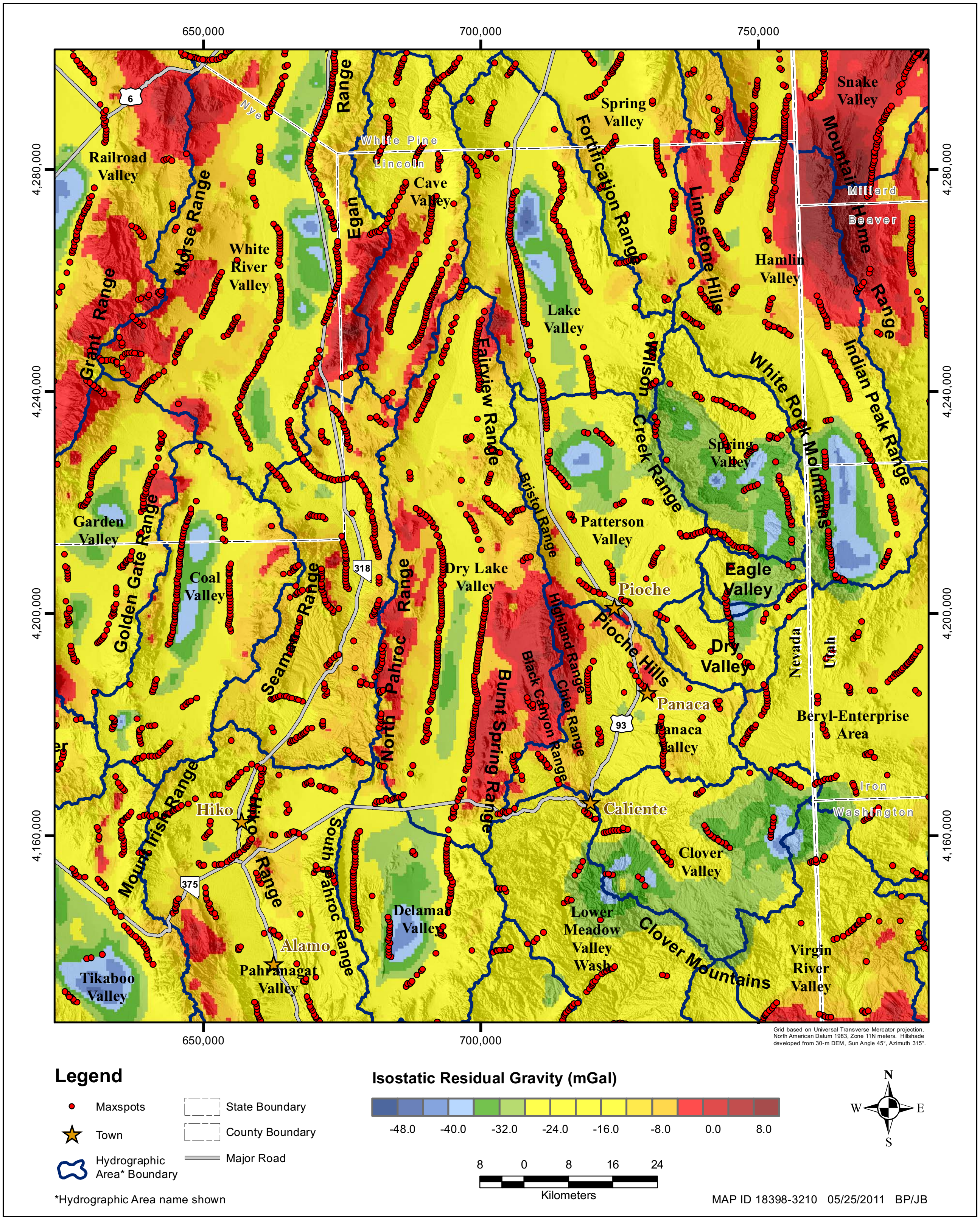
Source: Mankinen et al. (2008)

Figure 5-10
Shaded Relief Map of Cave, Dry Lake, and Delamar Valleys and Vicinity, Nevada



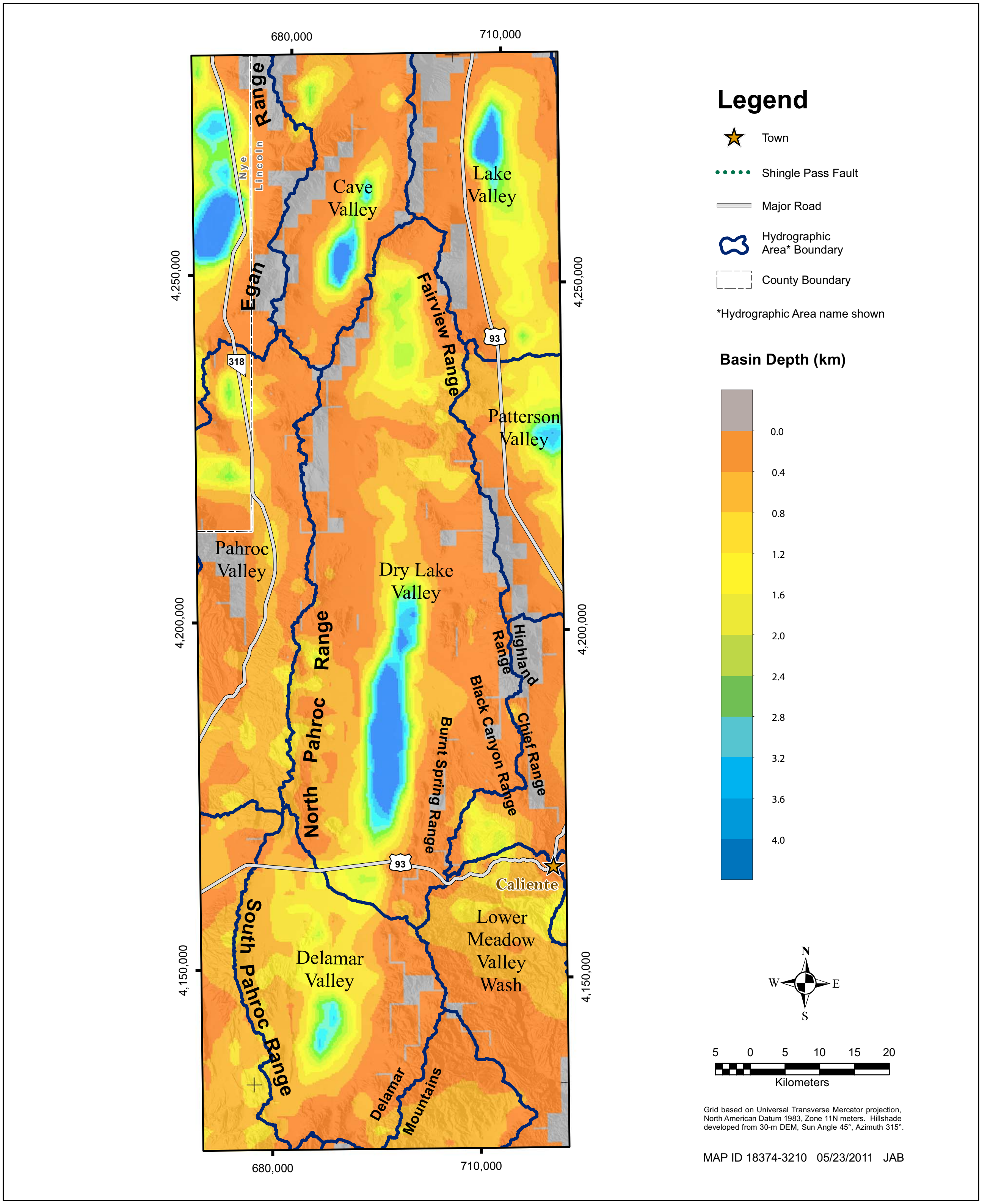
Source: Mankinen et al. (2008)

Figure 5-11
Isostatic Residual Gravity Field of Cave, Dry Lake, and Delamar Valleys and Vicinity, Nevada



Source: Mankinen et al. (2008)

Figure 5-12
Isostatic Residual Gravity Field Showing Maxspots



Source: Mankinen et al. (2008)

Figure 5-13
Depth of pre-Cenozoic Basement of Cave, Dry Lake, and Delamar Valleys and Vicinity, Nevada

5.2 Audiomagnetotelluric Studies

In conjunction with the gravity studies, AMT surveys were performed targeting faults and stratigraphy within the valleys, as well as estimates of depth to pre-Cenozoic basement. AMT technology detects variations in shallow, subsurface electrical resistivity, which is largely dependent on the fluid content, porosity, density, fractures, and conductive mineral content of the subsurface geology. The results are presented as a cross section along a linear profile, providing information on the third dimension in the geologic framework.

Under funding from SNWA, the USGS (McPhee, 2007; McPhee et al., 2005, 2006a and b) concluded that the technology serves as a valuable tool for mapping subsurface faults and lithology at shallow depths in basins (above about 300 m). In addition, when compared to the basement-surface estimates derived from the inversion of gravity data (Section 5.1), AMT technology proves successful in estimating the depth to bedrock. That the AMT data are consistent with the gravity data enhances confidence in both depth estimates. Dixon et al. (2007a) reproduced and interpreted three of the profiles of McPhee and her colleagues. The results of some of these later studies were published by McPhee et al. (2007, 2008, 2009), whereas other profiles have been and are being prepared by SNWA, which also interpreted the profiles (Pari and Baird, 2011).

AMT uses the magnetotelluric (MT) method, a geophysical technique that applies the earth's natural electromagnetic fields as an energy source to investigate the electrical resistivity structure of the subsurface (Telford et al., 1990; Vozoff, 1991). Within the earth's upper crust, the resistivity of geologic units is largely dependent upon their fluid content, porosity, density, degree of fracturing, temperature, and conductive mineral content (Keller, 1987). Saline fluids within pore spaces and fracture openings can reduce bulk resistivity by several orders of magnitude relative to dry rock. Resistivity can also be lowered by the presence of conductive clay minerals, graphite, and metallic sulfide mineral deposits. Tables of electrical resistivity for a variety of rocks, minerals, and geological environments may be found in Keller (1987) and Palacky (1987). For example, marine shale, mudstone, Pleistocene lake beds, and clay-rich alluvium are normally conductive, having values of a few to tens of ohm-m (ohm-meters). Fault zones can appear as low-resistivity (i.e., high-conductivity) units of less than 100 ohm-m when they are composed of rocks fractured enough to host fluids and clay alteration minerals (Eberhart-Phillips et al., 1995). Carbonate and clastic rocks are moderately to highly resistive, having values of hundreds to thousands of ohm-m depending on their fluid content, porosity, fractures, and impurities. Unaltered, metamorphic, nongraphitic rocks are moderately to highly resistive. Unaltered, unfractured igneous rocks normally are resistive and have values greater than 500 ohm-m or greater.

Using the same principles as the MT method, the AMT method estimates the electrical resistivity of the earth over depth ranges of a few meters to about one kilometer, depending upon site conditions, using a high-frequency range (Zonge and Hughes, 1991), whereas MT typically uses a lower frequency range. In areas where the resistivity distribution does not change rapidly from station to station, resistivity soundings provide a reasonable estimate of the resistivity layering beneath the site.

AMT data were collected using a Geometrics Stratagem EH4 system, which applies both natural- and controlled-source electromagnetic signals to obtain a continuous electrical sounding of the earth beneath the measurement site (Geometrics, 2007; McPhee et al., 2006a and b). Profiles were from

0.7 to 12.7 km long, with station spacing between 100 and 400 m. They are discussed below in basins generally from north to south, then west to east. The first AMT studies in the project area were done by McPhee et al. (2005, 2006a and b) along two profiles in southern Spring Valley, both of which (Profiles A and B) are reproduced below.

5.2.1 AMT Data for Spring Valley

A total of twenty-five, generally east-trending, AMT profiles (2D inversion models) were completed in Spring Valley to define faults, interpret the stratigraphy, and aid in siting drill hole locations. The work was done by the USGS, SNWA, and Layne GeoSciences. All profiles are discussed by Pari and Baird (2011). Only some of the profiles, however, are displayed here; the locations of these are shown on Figures 5-14.

About 8 km north of US 6/US 50 and just east of SR 893, the AMT data for Profile POD 54011 (abbreviated as POD 54011) were collected by Layne Geosciences (2009) along a line 1.6 km long in order to determine the geologic framework at SNWA point of diversion (POD) well application 54011. The geophysical data were reprocessed and interpreted by Pari and Baird (2011). Figures 5-15 presents the geologic map and interpreted profile. The profile reveals two buried interbasin basin-range normal faults, which are east of the main range-front fault west of SR 893. The two faults in the profile displace basin-fill sediments down to the east between stations S2 and S3 and near station S7. The highly conductive nature of the sediments suggests that they are lake sediments.

Profile 10 consists of two profiles about 10 km south of US 6/US 50 and separated by the main north-south highway here, US 93. Profile 10 West (SVN10West) is 3.2 km long, passing along the northern side of several large hills of carbonate rocks (the high resistivity material in the profile) dropped down along multiple large, north-trending, down-to-the-east normal faults that define the east side of the Schell Creek Range. The profile was collected by Layne Geosciences (2009) and reprocessed and interpreted by Pari and Baird (2011). The geologic map and interpreted profile (Figure 5-16) shows a complicated series of normal faults.

AMT data in Profile B (SVNB) were collected on a line about 3 km east of where US 93 crosses a low pass (Lake Valley Summit) that separates Spring Valley from Lake Valley to the south. The data in Profile B (SVNB) were published by McPhee et al. (2006a) and interpreted by McPhee et al. (2005) and SNWA, as shown in Figure 5-17. The low, northwest-trending ridge (in the southwest part of the map) is made up of Permian rocks and Pennsylvanian Ely Limestone that strike northwest and dip northeast; the ridge connects the southern Schell Creek Range with the northern Fortification Range. SNWA test well 184W103, just north of the western end of the line, was drilled to a depth of 310 m in the Ely Limestone. The AMT profile, about 2.3 km long, images a prominent west-northwest-trending, range-front fault that defines the low ridge and is the southeastward continuation of the fault zone that defines the eastern side of the Schell Creek Range.

Profile A (SVNA) is 12.7 km long, spanning southern Spring Valley between the eastern edge of the Fortification Range and the western edge of the Limestone Hills (McPhee et al., 2005, 2006a and b). The 2D inversion model and its geologic interpretation are shown in Figure 5-18. Two SNWA monitoring wells are shown on the geologic map; the western one is projected to the profile. SNWA

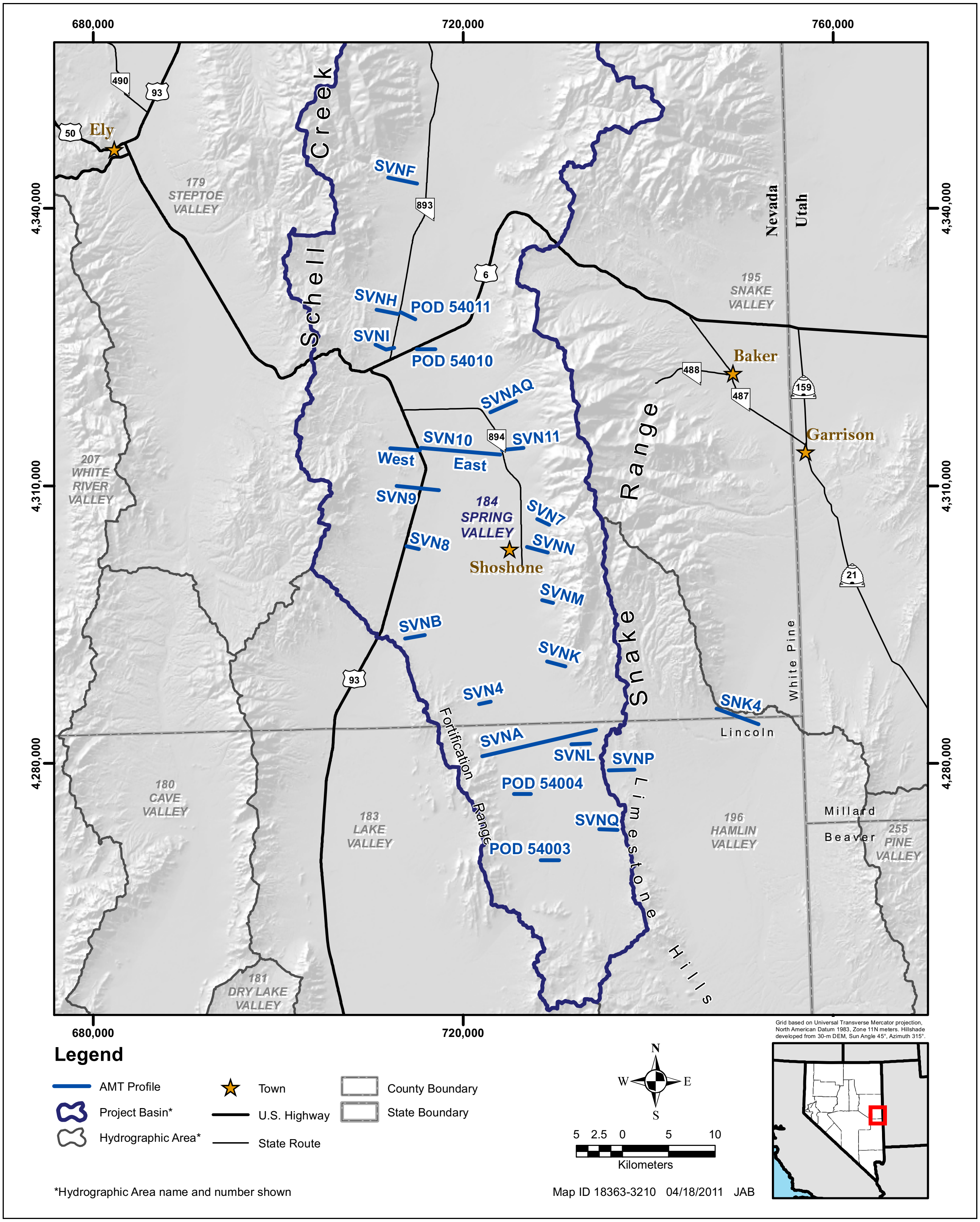
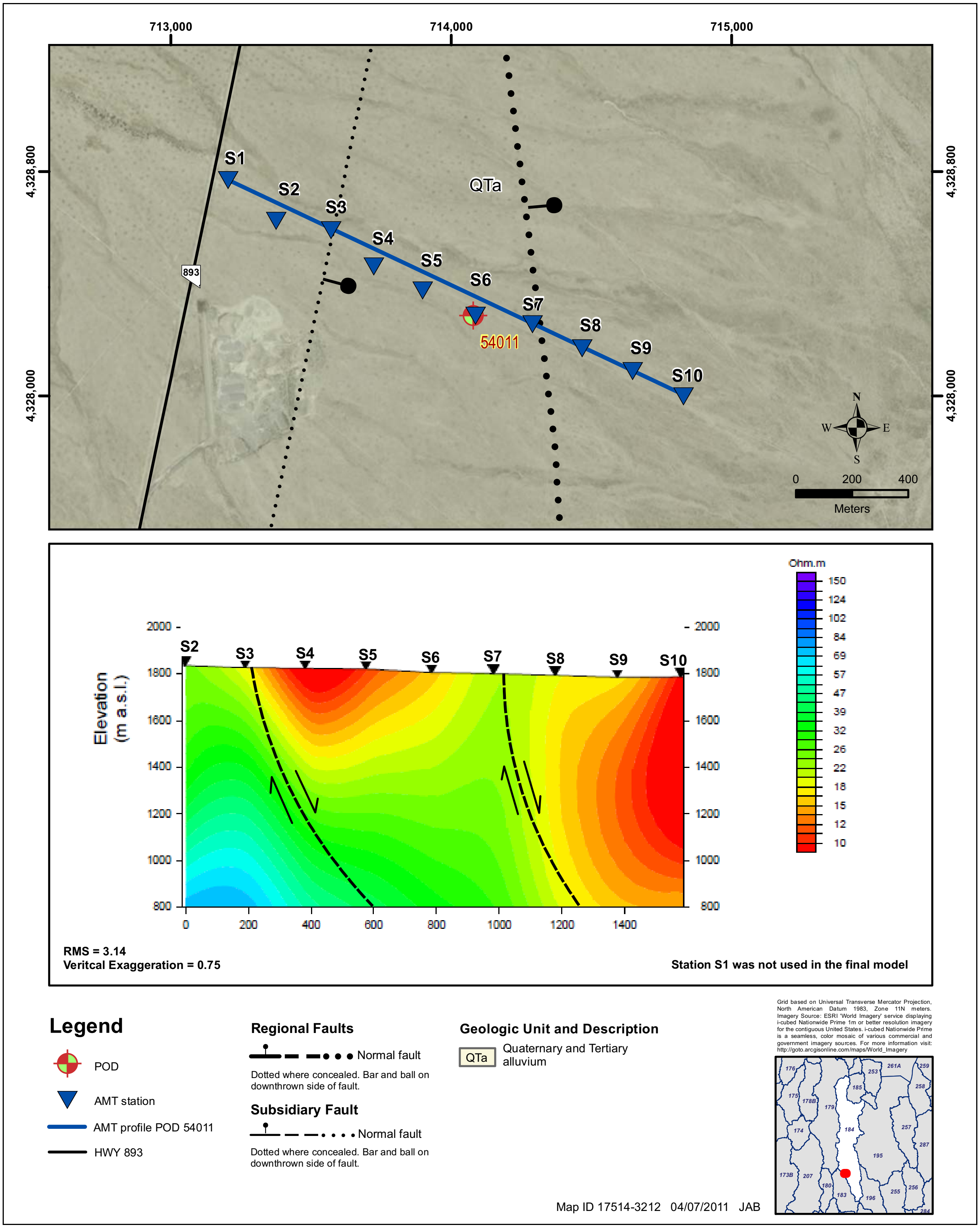
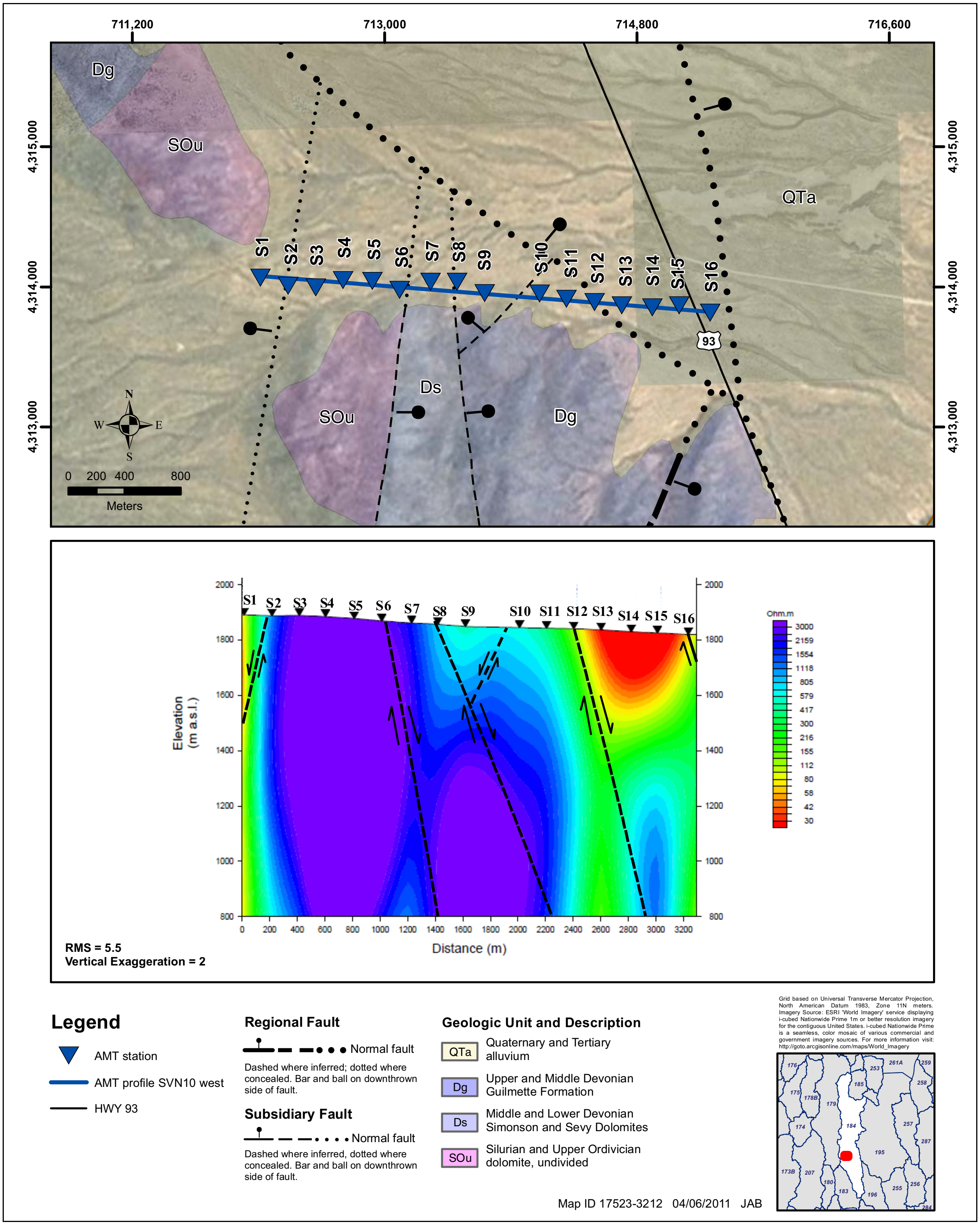


Figure 5-14
Map of Spring Valley and Vicinity, Nevada
Showing Locations of AMT Profiles



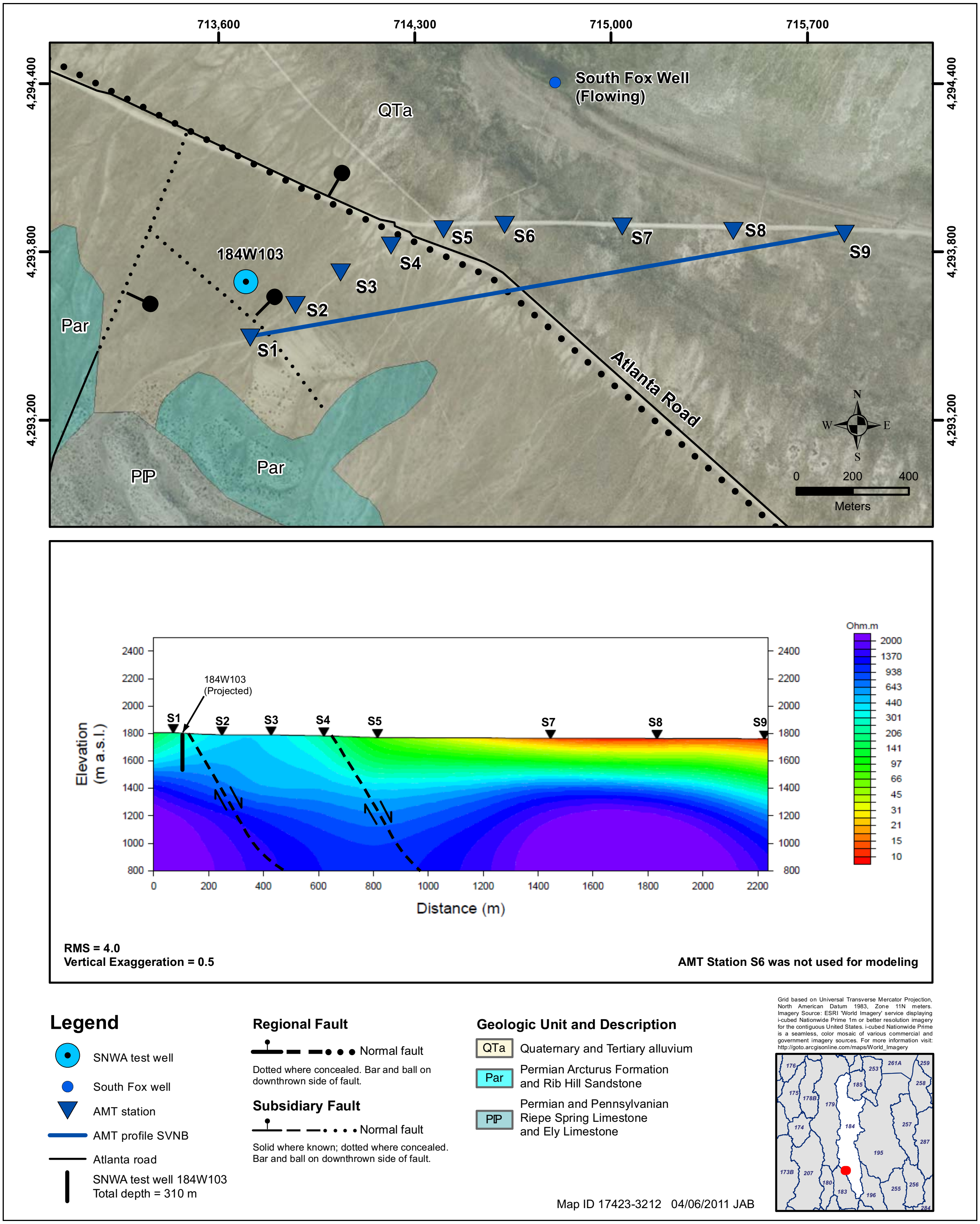
Source: Pari and Baird (2011)

Figure 5-15
Map and 2D Model of Area of POD 54011



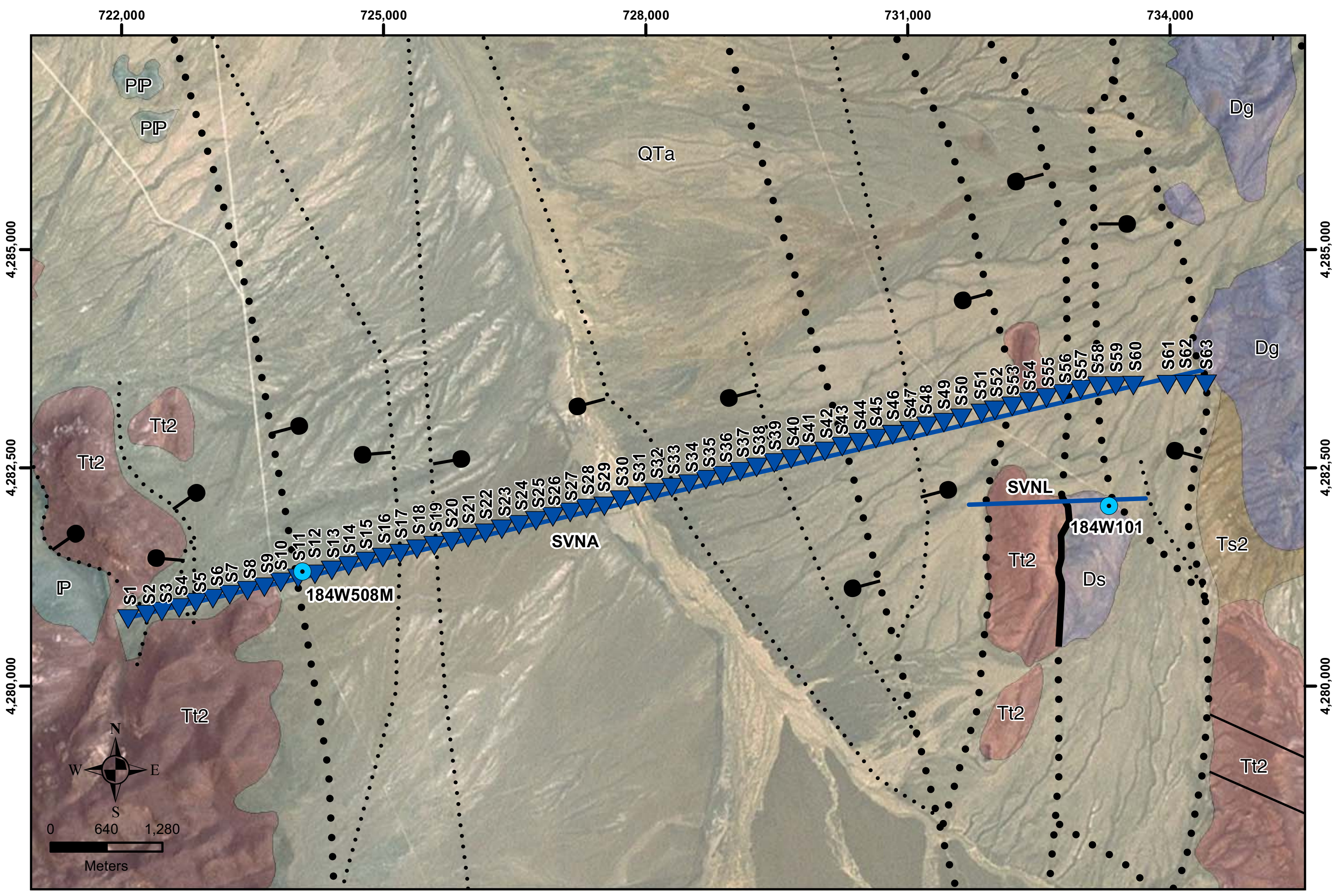
Source: Pari and Baird (2011)

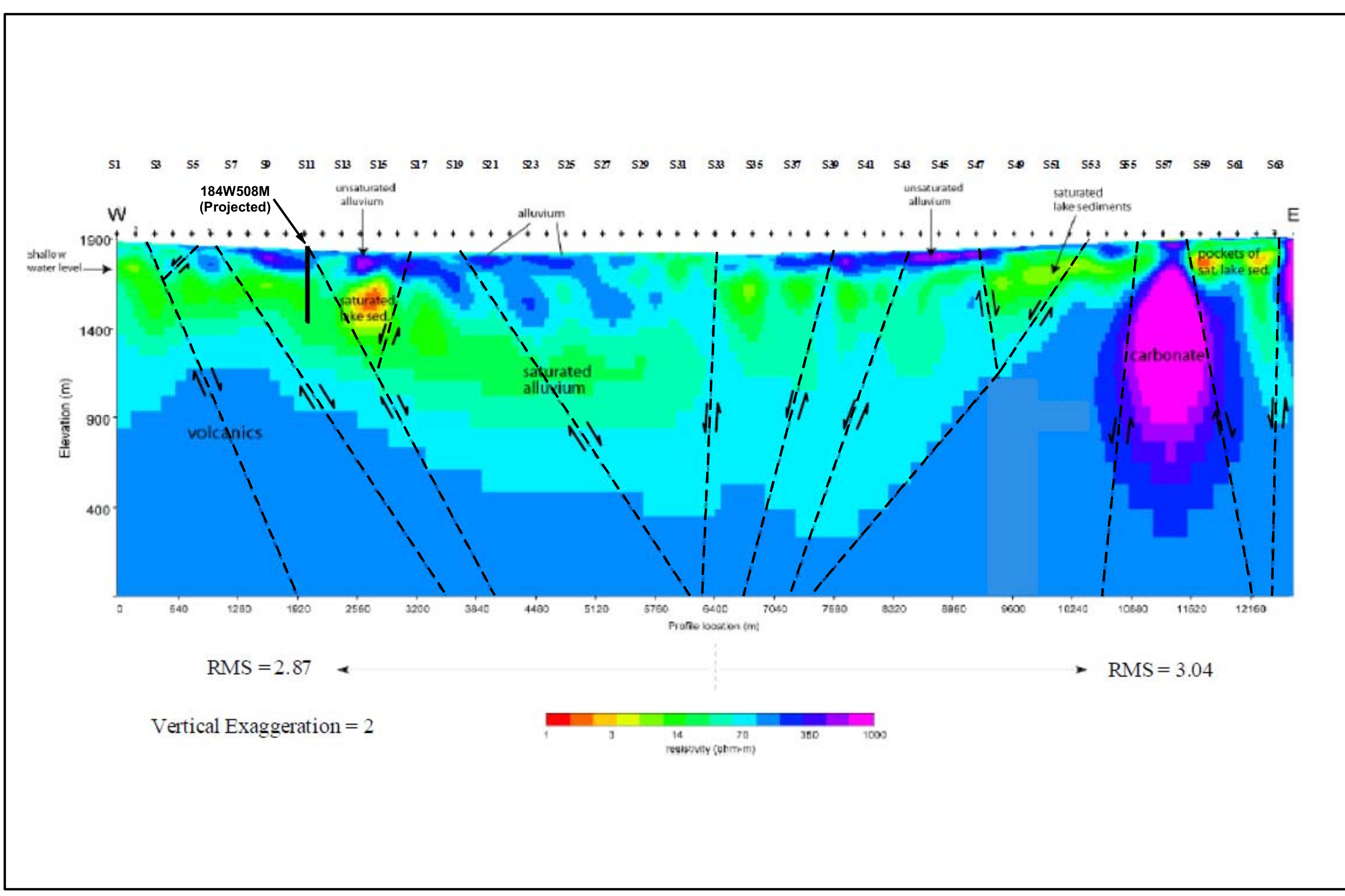
Figure 5-16
Map and 2D Model of SVN10 West



Source: Pari and Baird (2011)

Figure 5-17
Map and 2D Model of SVNB





Legend

- AMT station
- AMT profile SVNA
- SNWA well
- SNWA monitor well 184W508M

Regional Fault

Normal fault

Solid where known; dotted where concealed. Bar and ball on downthrown side of fault.

Subsidiary Fault

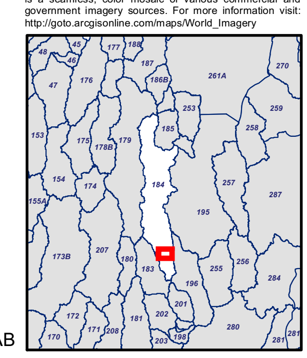
Normal fault

Solid where known; dotted where concealed. Bar and ball on downthrown side of fault.

Geologic Unit and Description

- QTa — Quaternary and Tertiary alluvium
- Ts2 — Tertiary, mostly tuffaceous sandstone and bedded airfall tuff
- Tt2 — Tertiary, poorly-densly welded ash-flow tuff and interbedded airfall tuff
- IP — Pennsylvanian Ely Limestone
- PIP — Permian and Pennsylvanian Riepe Spring Limestone and Ely Limestone
- Dg — Upper and Middle Devonian Guilmette Formation
- Ds — Middle and Lower Devonian Simonson and Sevy Dolomites

Grid based on Universal Transverse Mercator Projection, North American Datum 1983, Zone 11N meters. Imagery Source: ESRI 'World Imagery' service displaying i-cubed Nationwide Prime 1m or better resolution imagery for the contiguous United States. i-cubed Nationwide Prime is a seamless, color mosaic of various commercial and government imagery sources. For more information visit: http://goto.arcgisonline.com/maps/World_Imagery



Map ID 17526-3212 04/06/2011 JAB

Source: Pari and Baird (2011)

Figure 5-18
Map and 2D Model of SVNA

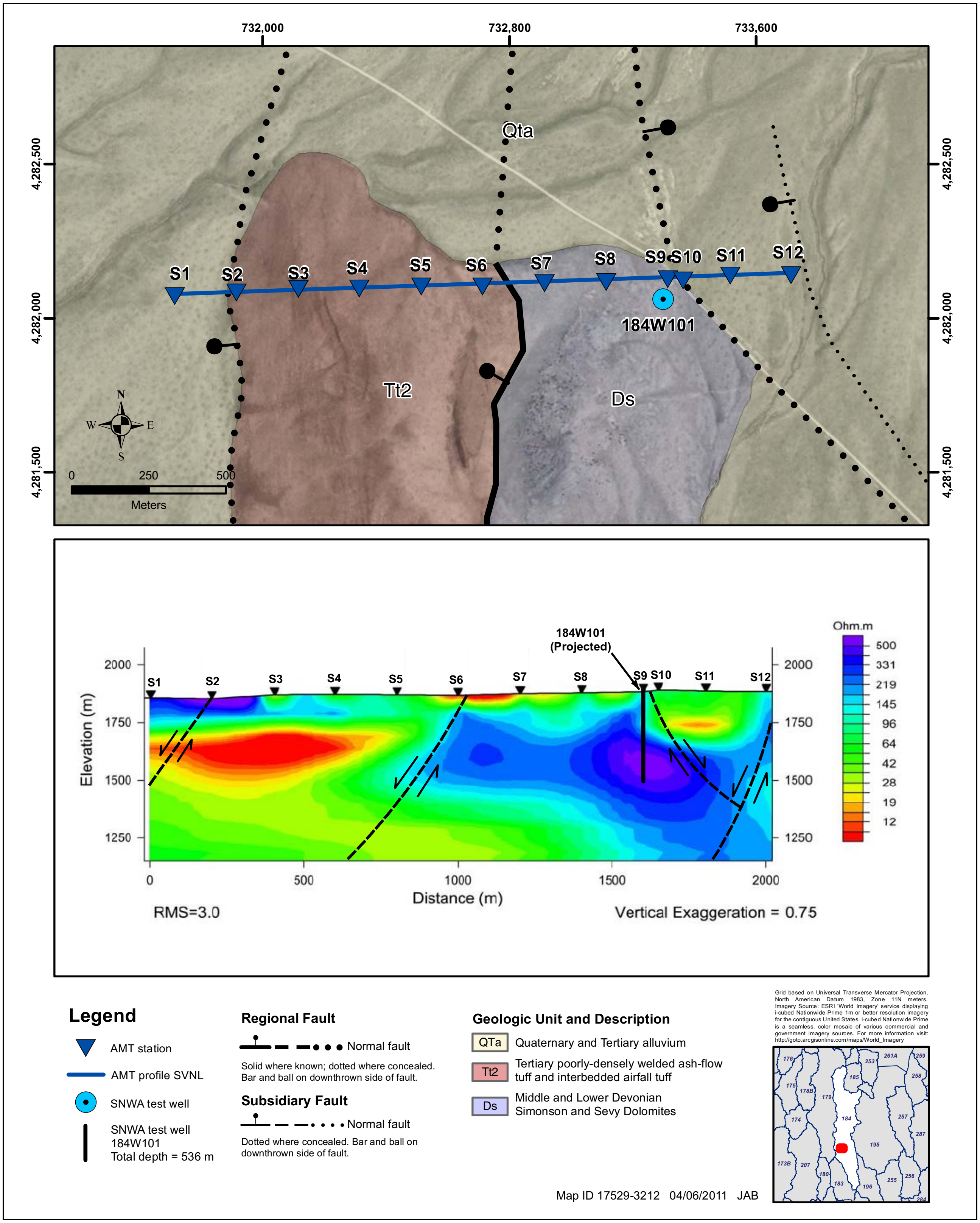
Well 184W508M is near AMT station S11 near the western end of the profile and SNWA Well 184W101 is south of station S56 near the eastern end of the profile. The western well was drilled to a depth of 360 m, encountering non-welded and moderately welded ash-flow tuffs throughout. The eastern well was drilled to a depth of 538 m, encountering carbonate rocks. The profile shows 10 interpreted faults as black lines. A clear transition between unsaturated (200 to 500 ohm-m) alluvium above and saturated alluvium/volcanic rocks (20 to 50 ohm-m) below is present at roughly 100 m depth in many parts of Profile A. Highly 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 interbasin faults that lack surface expression can be interpreted throughout the upper 1-km portion of the section image. The interpreted surface between the alluvium/basin-fill sediments and underlying volcanic rocks is shown on the cross section.

About 1 km south of the eastern end of Profile A (SVNA), AMT data were collected along Profile L (SVNL; see Figure 5-19) by McPhee et al. (2007), but the data were not interpreted. The profile, which is 2.0 km long, was compiled to add detail to fault interpretations in Profile A (SNVA), to test electrical responses in volcanic versus carbonate rocks, and to interpret the data in SNWA test well 184W101, west of the Limestone Hills. The geologic map and profile, interpreted by Pari and Baird (2011) are shown in Figure 5-19. The profile images four basin-range faults. Test Well 184W101, near station S9, had a total depth of 536 m, wholly in carbonate rocks.

About 4 km south of Profile A (SVNA), AMT data were measured by McPhee et al. (2008) for Profile Q (SVNQ) through a pass between the southern Snake Range and the northern Limestone Hills. This pass, at The Troughs, is one of the two most likely routes for any groundwater moving from Spring Valley to Hamlin Valley to the east. Profile P (SVNP) was published by McPhee et al. (2008), who did not interpret the geology. The geologic map and the profile, interpreted by Pari and Baird (2011), are shown on Figure 5-20. At its eastern edge, the profile images a prominent buried, down-to-the-west and west-dipping normal fault that forms the eastern side of an axial graben of Tertiary volcanic rocks. Farther west, between stations S10 and S11, a prominent east-dipping and down-to-the-east normal fault forms the western side of the graben. This fault continues north and south of the map area; south of the map area, this fault is the eastern range-front fault of the Limestone Hills. Farther west along the profile, between stations S9 and S10, a west-dipping and down-to-the-west normal fault is imaged. AMT data for two other profiles were collected in the area of The Troughs, one of which was attempted to look for east-trending faults in the pass, but the results were not conclusive (McPhee et al., 2007, 2008). Gravity data, discussed in Section 5.1.1, were more diagnostic in an attempt to image east-trending structures near The Troughs. A less detailed geologic map and cross section is provided as Figure 4-20 and discussed in Figure 4.4.25.

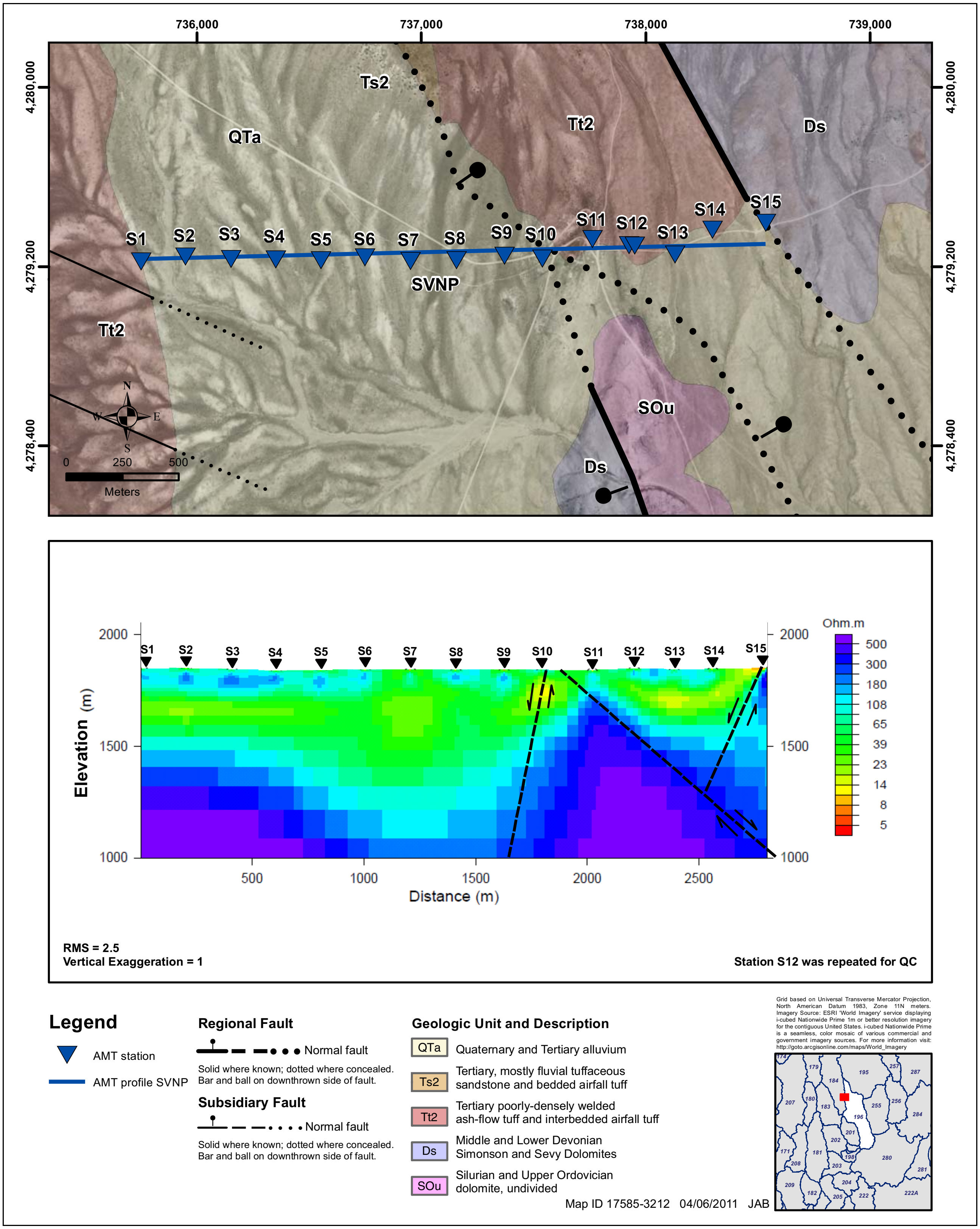
5.2.2 AMT Data for Snake Valley

Under contract from SNWA, the USGS completed four generally east-trending AMT profiles in Snake Valley. SNWA has collected AMT data for additional profiles that are being processed and interpreted. Of the four USGS profiles, preliminary profiles of three of them, whose imaged geology was not interpreted, were published by McPhee et al. (2007). Later, AMT data for the fourth profile (Figure 5-21) were collected, then all four profiles were interpreted and published by McPhee et al. (2009). The southern of these, Profile 4 (SNK4) in the Big Springs area along the southeastern flank of the Snake Range (Figure 5-14) is reproduced here as Figure 5-21. It was done to identify



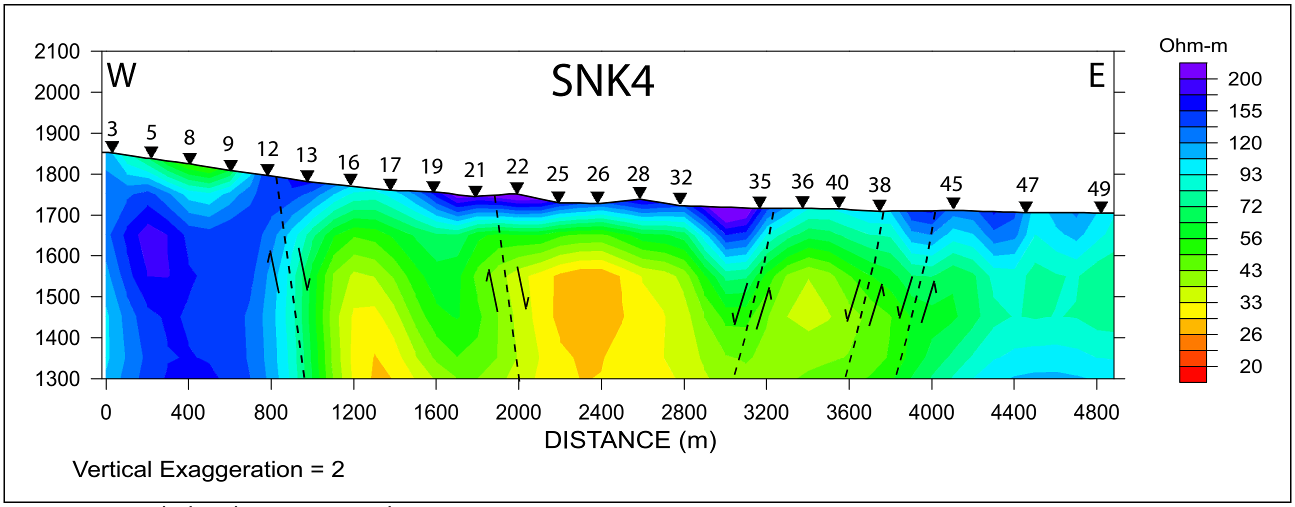
Source: Pari and Baird (2011)

Figure 5-19
Map and 2D Model of SVNL



Source: Pari and Baird (2011)

Figure 5-20
Map and 2D Model of SVNP



Note: Inverted triangles = AMT stations.

Figure 5-21
2D Inverse Model Computed from the Transverse-Magnetic-Mode Data along Profile SNK4 in Western Snake Valley, Nevada (RMS = 3.0)

structures that control the springs. Most of these structures are Quaternary faults that were mapped cutting alluvial-fan deposits. The line, which extends for 5.0 km, is about 4 km south of the Big Springs complex and 1 to 3 km south of South and North Little Spring, respectively. The interpreted profile McPhee et al. (2009) provides a spectacular example of the usefulness of AMT geophysics, with at least 5 basin-range faults imaged. The main down-to-the-east, range-front fault zone is the western one in the profile, near station 12. The other faults, farther east, suggest why springs are abundant in the area.

5.2.3 AMT Data for Cave Valley

AMT data were collected along a single east-trending line, Profile E (CVE) against the eastern side of southern Cave Valley and west of Sidehill Pass. The location is shown on Figure 5-22. Profile E (CVE), collected and interpreted by McPhee et al. (2005, 2006a and b), has a length of 3.4 km. The geologic map and profile (Pari and Baird, 2011) are shown on Figure 5-23. Profile E clearly images the western range-front basin-range fault of the Schell Creek Range. Other buried interbasin faults, including one between stations S2 and S3, are less clear but probable.

Profile E (CVE) compares favorably with existing drill holes and with the adjacent industry seismic profile (Scheirer, 2005) discussed in Section 5.3. Existing SNWA well 180W504M, drilled south of the line of Profile E (CVE) and east of the main range-front fault, penetrated basin-fill sediments to a depth of 150 m, then passed into carbonate rocks to a total depth of 272 m. Sidehill Pass Federal No. 18-13 (see also Section 5.3), drilled north of the line of Profile E (just north of the map in Figure 5-23) and west of the main range-front fault, penetrated about 1,550 m of basin-fill sediments before passing into the Mississippian Joana Limestone, which continued to a total depth of about 2,000 m (Hess, 2004).

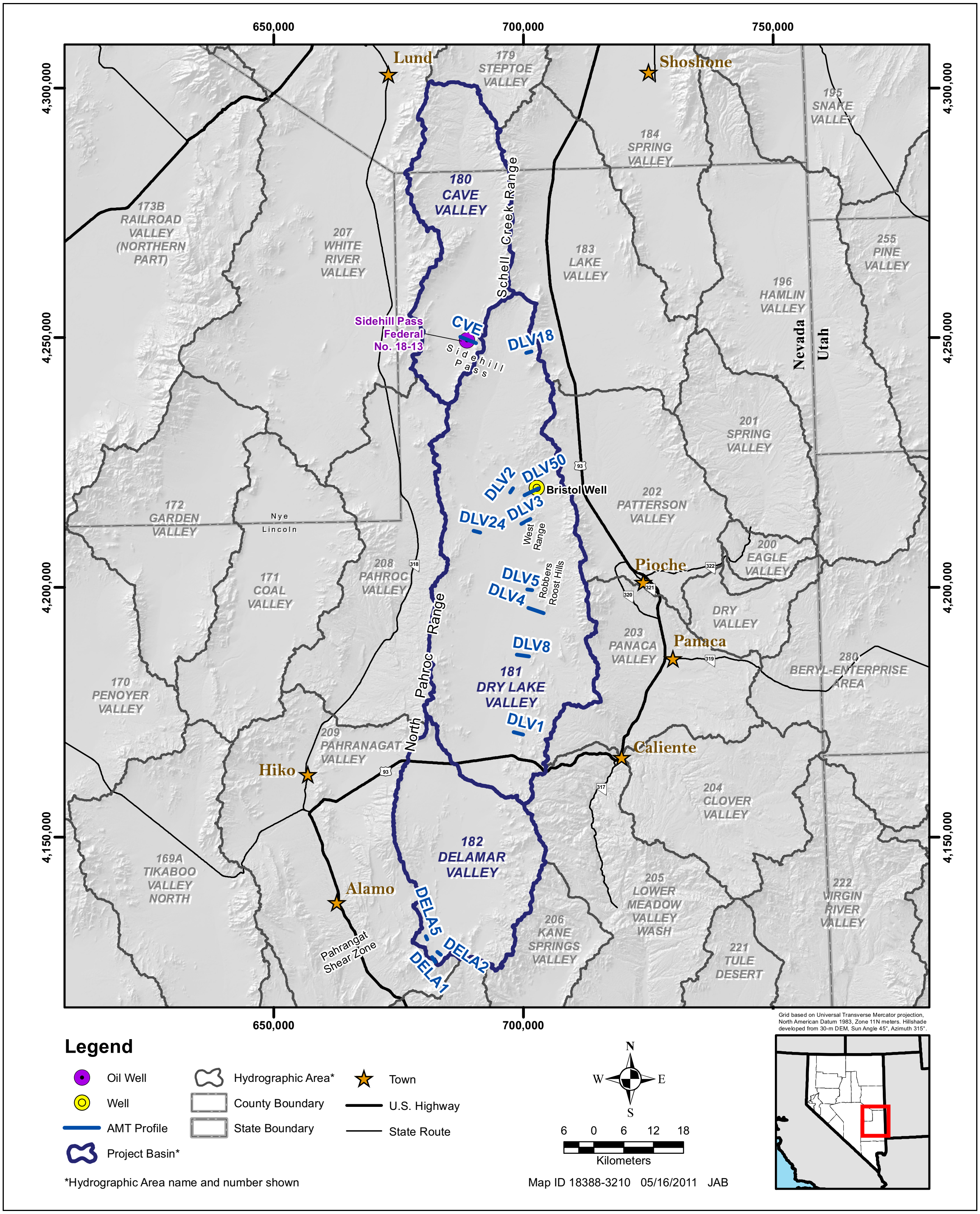
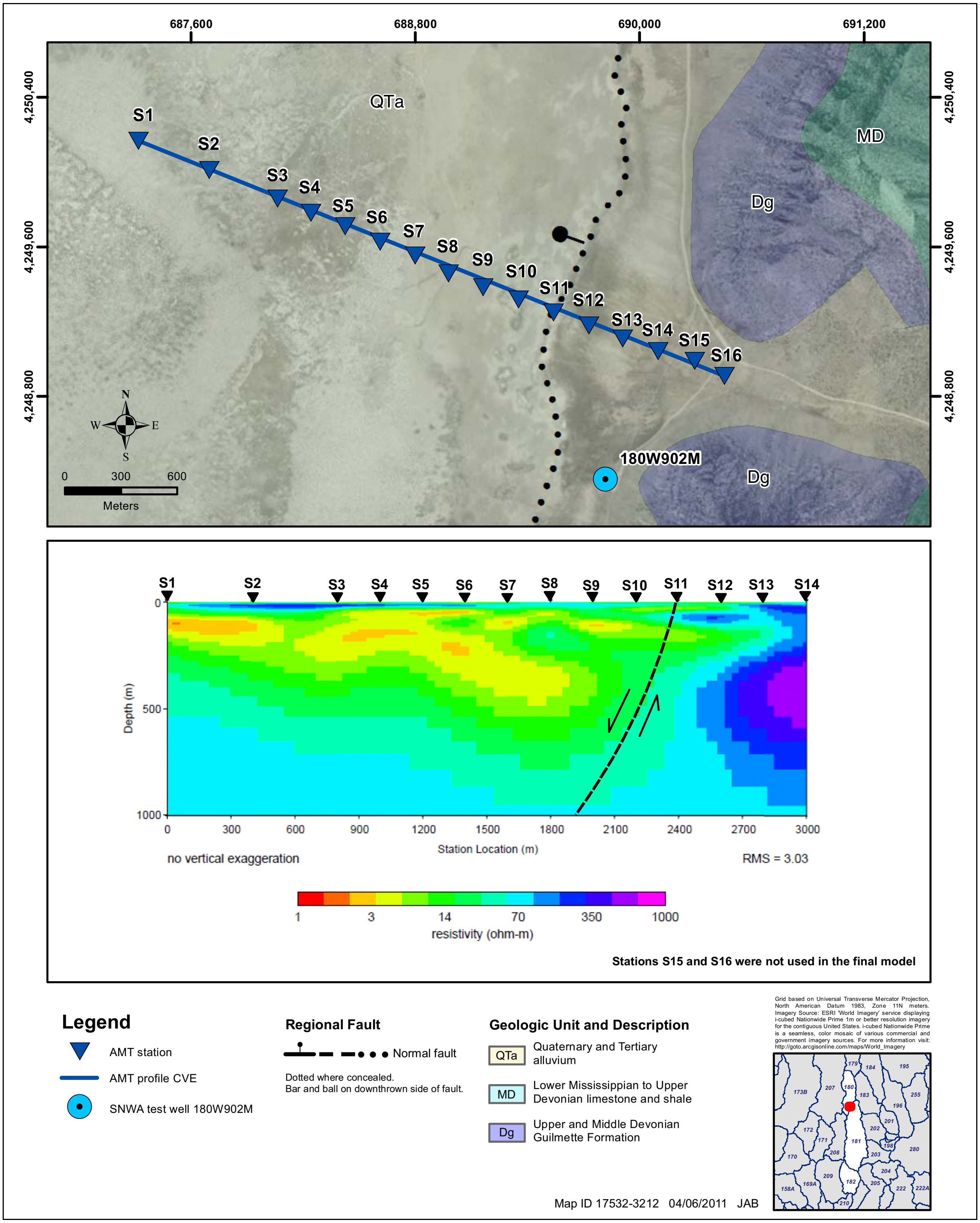


Figure 5-22
Map of Cave, Dry Lake, and Delamar Valleys, Nevada and Utah, Showing Location of AMT Profiles



Source: Pari and Baird (2011)

Figure 5-23
Map and 2D Model of CVE

5.2.4 AMT Data for Dry Lake Valley

A total of nine, generally east-trending, AMT profiles were completed in Dry Lake Valley, seven by the USGS (McPhee et al., 2008) and two by SNWA. All profiles were interpreted and discussed by Pari and Baird (2011). Only some of the profiles, however, are discussed here; the locations of these are shown on Figure 5-22.

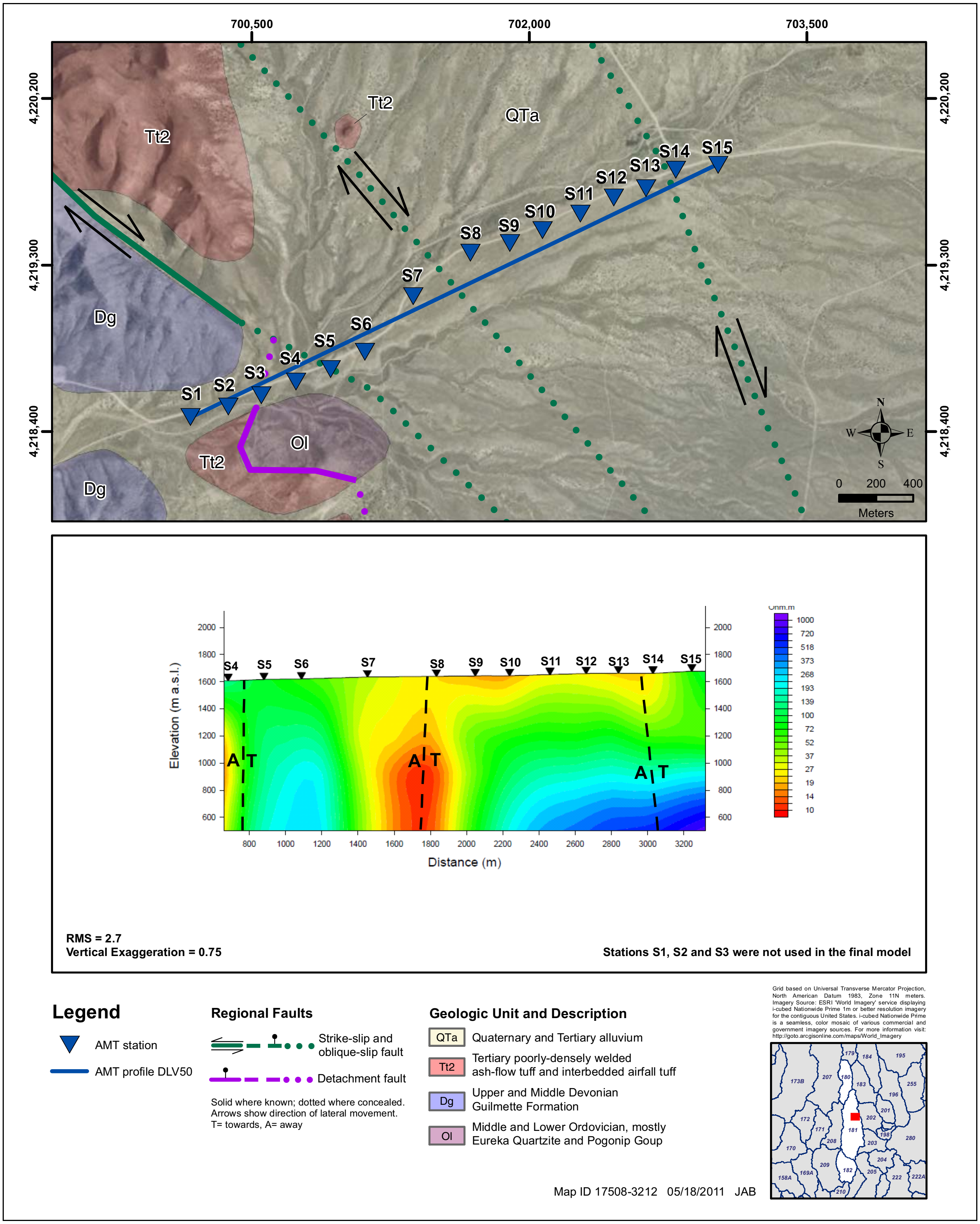
Just east of Dry Lake Valley, AMT data were collected by SNWA in a structurally complex area west of Bristol Wells and just east of the West Range to test the AMT technique where Tertiary ash-flow tuffs are faulted against Devonian and Ordovician carbonate rocks. The data in Profile 50 (DLV50), which has a length of 3.2 km, shows that the technique clearly displayed large buried structures whether they cut volcanic or carbonate rocks. However, stations S1 through S3 were omitted from the profile due to poor data quality. The profile was interpreted by Pari and Baird (2011), as shown in Figure 5-24. Both the western end of the profile (station S4) and the eastern part (between stations S13 and S14) of the profile show mapped buried right-lateral faults. In between these two faults, the profile clearly shows a still larger buried right-lateral fault between stations S7 and S8, characterized by its vertical nature. Although not mapped because of the scale (1:250,000) of the geologic map (Plate 1), this strike-slip fault was mapped at a scale of 1:24,000 by Page and Ekren (1995). It is clearly a major structure that contains highly conductive hydrothermal clay, fault gouge, and groundwater.

Farther south, AMT data were collected along a single line on the western side of Dry Lake Valley, at the northern end of the North Pahroc Range. The data in Profile 24 (DLV24), which has a length of 1.4 km, were collected, but not interpreted geologically, by McPhee et al. (2008). The geologic map and interpreted profile, by Pari and Baird (2011), are shown in Figure 5-25. Three faults are imaged by Profile 24 (DLV24), one a mapped but buried right-lateral fault between stations S1 and S2, and two buried normal faults that define a graben between stations S4 and S8.

About 32 km to the south, on the western side of the Robber Roost Hills, AMT data were obtained from a line 2.5 km long, but not geologically interpreted, by McPhee et al. (2008). The geologic map and Profile 8 (DLV8) were interpreted by Pari and Baird (2011), as shown in Figure 5-26. Two major splays of the range-front fault zone on the eastern side of Dry Lake Valley were imaged, a major fault that includes Quaternary displacement near station S5, and a buried major splay farther east, at station S11. Two smaller faults were identified to the west. The fault that includes Quaternary movement is clearly a major fault, for it contains highly conductive material, probably hydrothermal clay and fault gouge, and it probably contains significant groundwater. About 10 km north of the profile, historic open fissures formed by movement along the Quaternary fault were mapped by Swadley (1995).

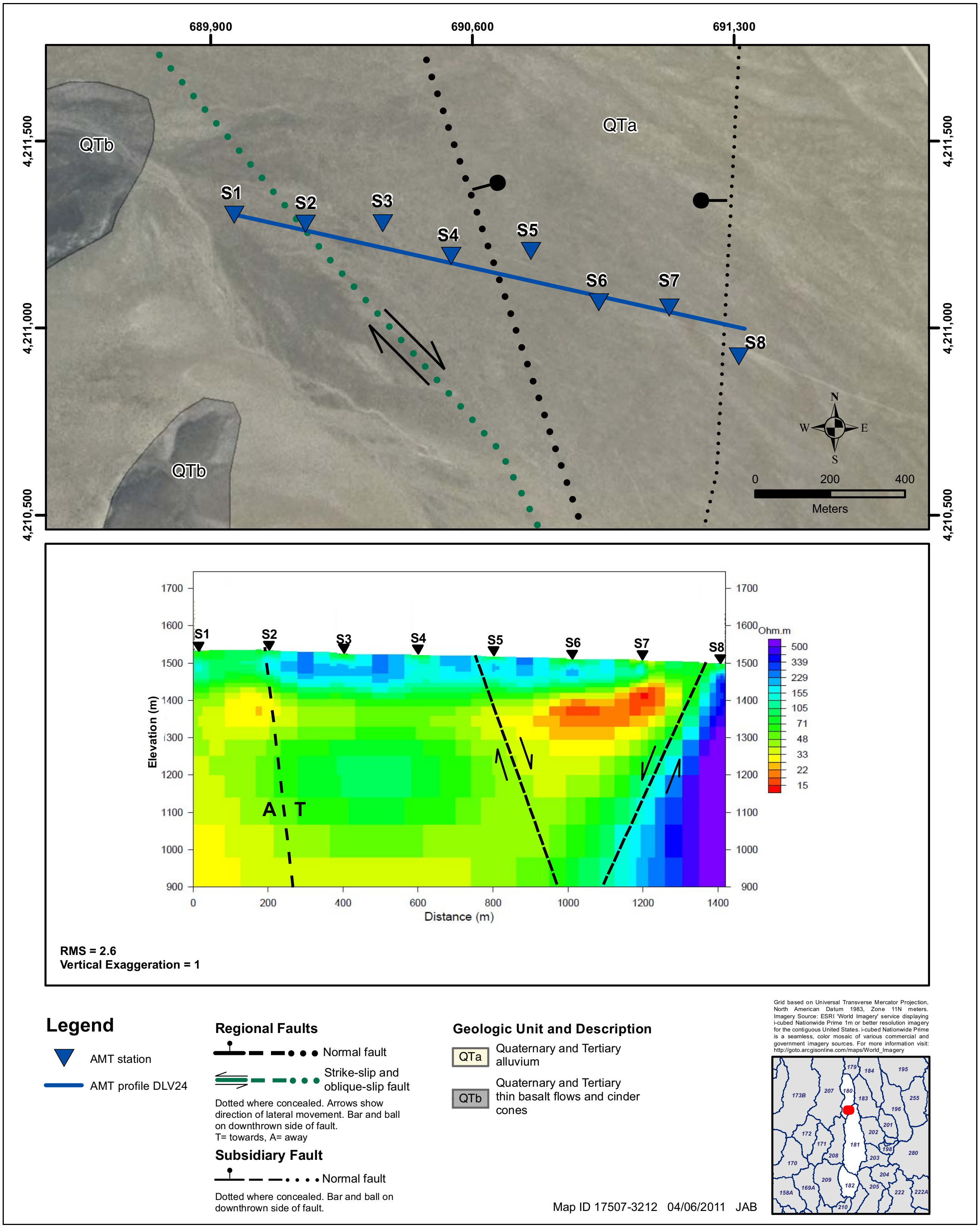
5.2.5 AMT Data for Delamar Valley

Three AMT profiles (Pari and Baird, 2011) were performed in the southwestern Delamar Valley to image northeast-trending, left-lateral strike-slip faults of the PSZ (Ekren et al., 1977; Scott et al., 1993), which mostly displaces Tertiary ash-flow tuffs. Two of the profiles, whose locations are shown on Figure 5-22, are given here. The faults of the PSZ pass into north-trending basin-range normal faults at both ends so the faults of the PSZ can be looked upon as accommodation zones during east-west basin-range extension. In other words, their slip where they trend northeast is



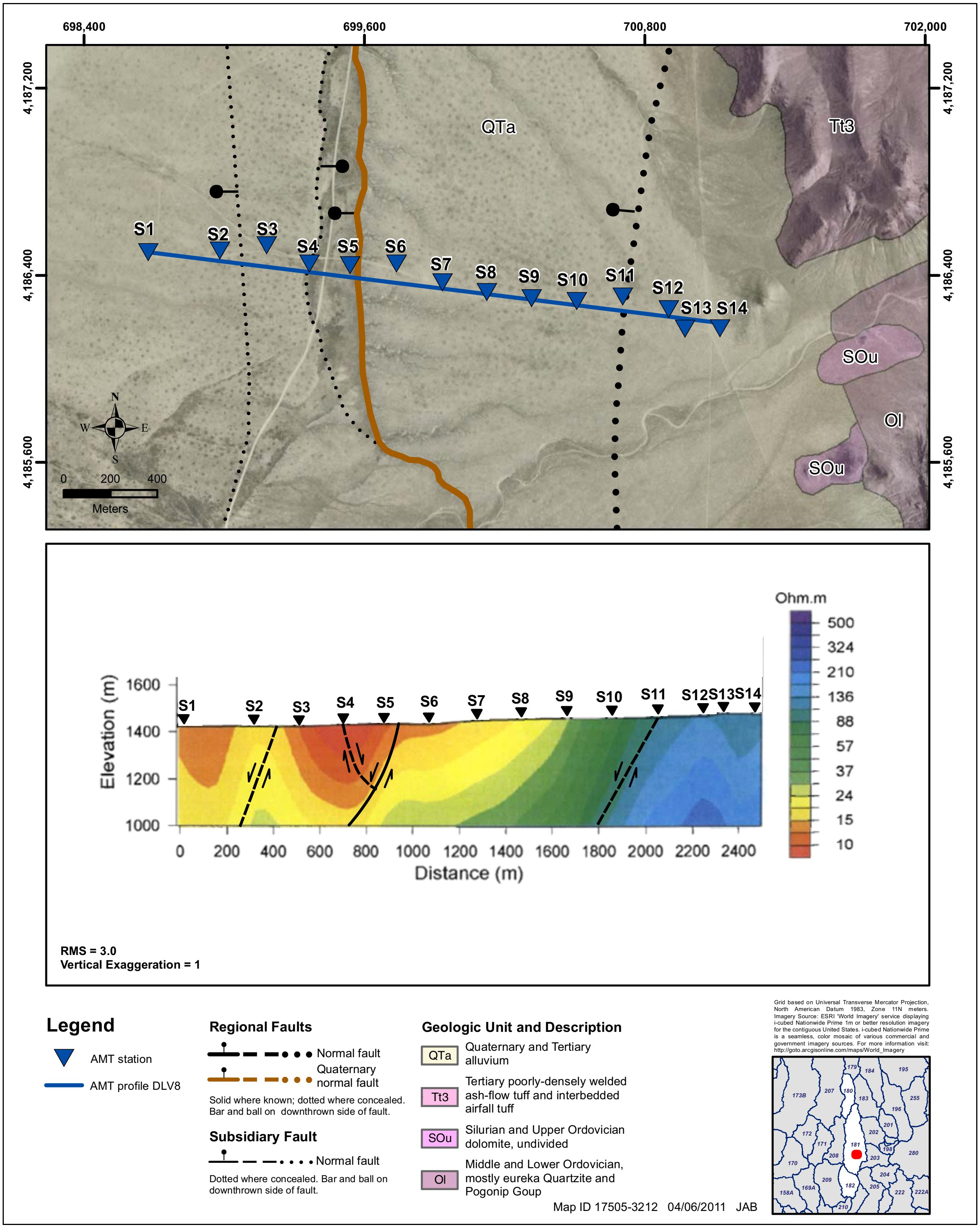
Source: Pari and Baird (2011)

Figure 5-24
Map and 2D Model of DLV50



Source: Pari and Baird (2011)

Figure 5-25
Map and 2D Model of DLV24



Source: Pari and Baird (2011)

Figure 5-26
Map and 2D Model of DLV8

largely strike slip and where they trend north their displacement is largely dip slip. The dip of purely strike-slip faults is generally vertical, whereas the dip of normal faults is on average 60 degrees.

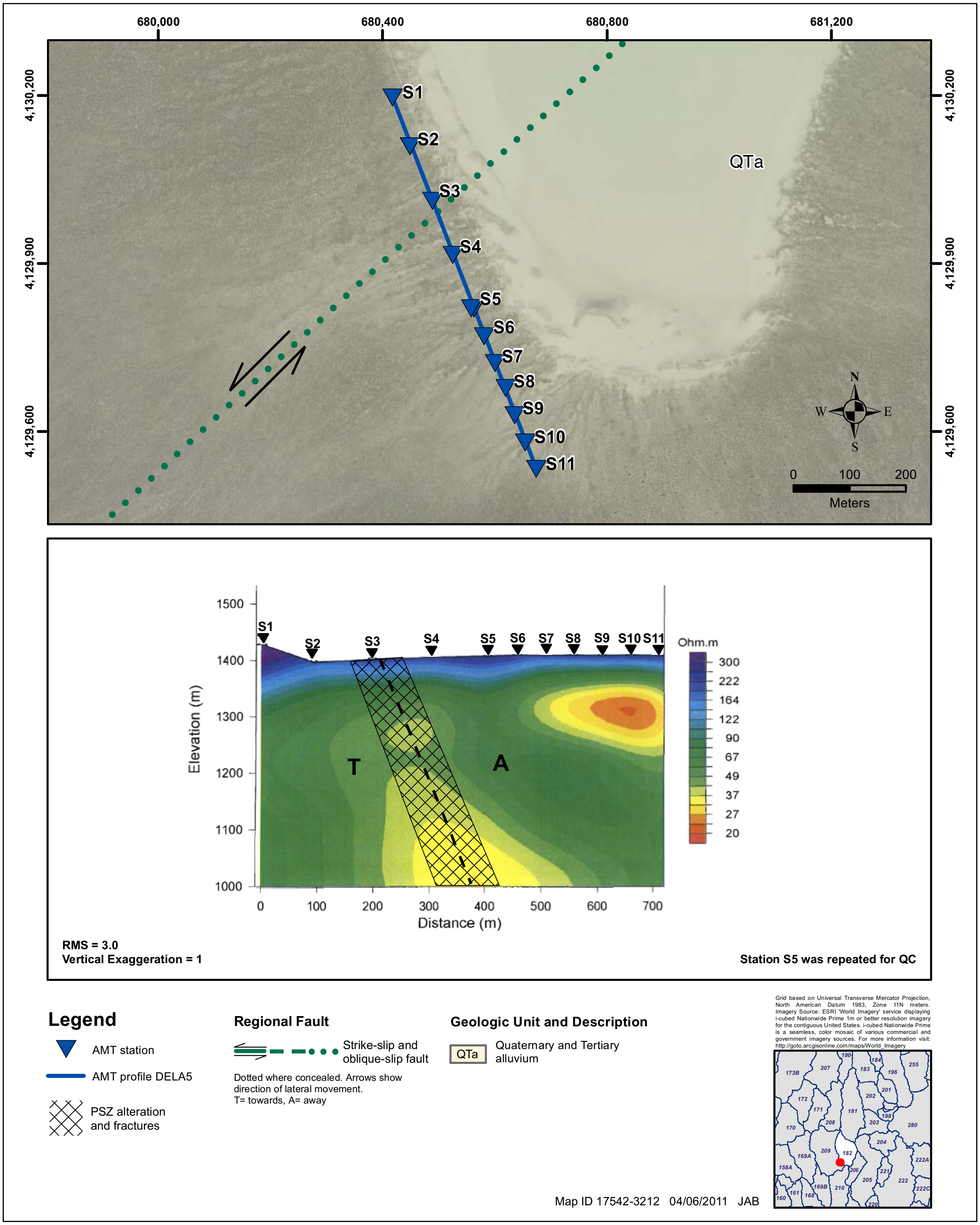
The northern of the three profiles, Profile 5 (DELA5) from south of Delamar Lake, crossed the buried projection of the Delamar Lake fault of the PSZ and has a length of 0.7 km, oriented perpendicular to the fault. The AMT data were compiled by McPhee et al. (2008) but the profile was not geologically interpreted. The geologic map and profile were interpreted by Pari and Baird (2011), as shown in Figure 5-27. The profile images a wide, steeply southeast-dipping fault zone between stations S3 and S4. The fault zone is marked by conductive material, probably representing hydrothermal clay, fault gouge, and groundwater in the fault zone.

About 5 km south of Profile 5, AMT data were measured by McPhee et al. (2008) along a line 1.2 km long, across the Maynard Lake fault, which is the main fault of the PSZ. The data in this profile, known as Profile 1 (DELA1), were not geologically interpreted by McPhee and her colleagues but were interpreted by Pari and Baird (2011). Figure 5-28 reproduces the geologic map and profile. Profile 1 (DELA1) images a broad subvertical strike-slip fault beneath stations S5 and S6. The lesser conductivity in the central core of the fault may be due to fault gouge (see Section 2.2.1.2).

5.3 Seismic Studies

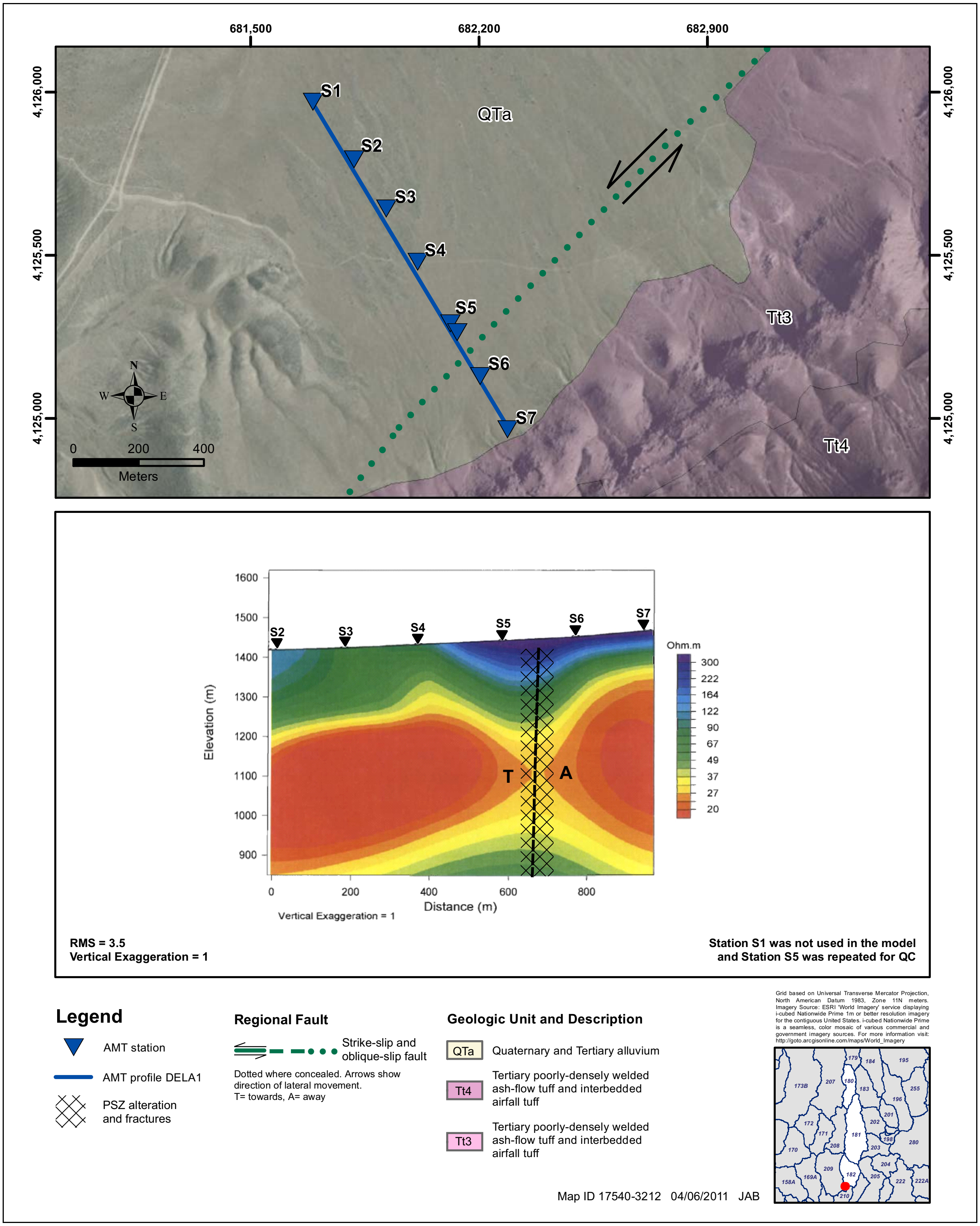
An additional view into the subsurface structure of southern Cave Valley and northern Dry Lake (Muleshoe) Valley is provided by a portion of the industry-shot ECN-01 seismic reflection line (Scheirer, 2005) (Figure 5-29). The seismic line crosses near the maximum depth position of Cave Valley. The seismic 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 basin structure inferred from gravity analysis (Figure 5-29) shares a number of similarities with the seismic image: Cave Valley is asymmetric and reminiscent of a half-graben (Scheirer, 2005). The overall shapes of Cave versus Muleshoe, in deeper portions, appear similar in the seismic and gravity models. Location and depth of American Petroleum Institute (API) well 27-017-05221 are superimposed schematically on Figure 5-29 to illustrate its general agreement with the gravity depth-to-basement estimate and to show its position with respect to the seismic structures.



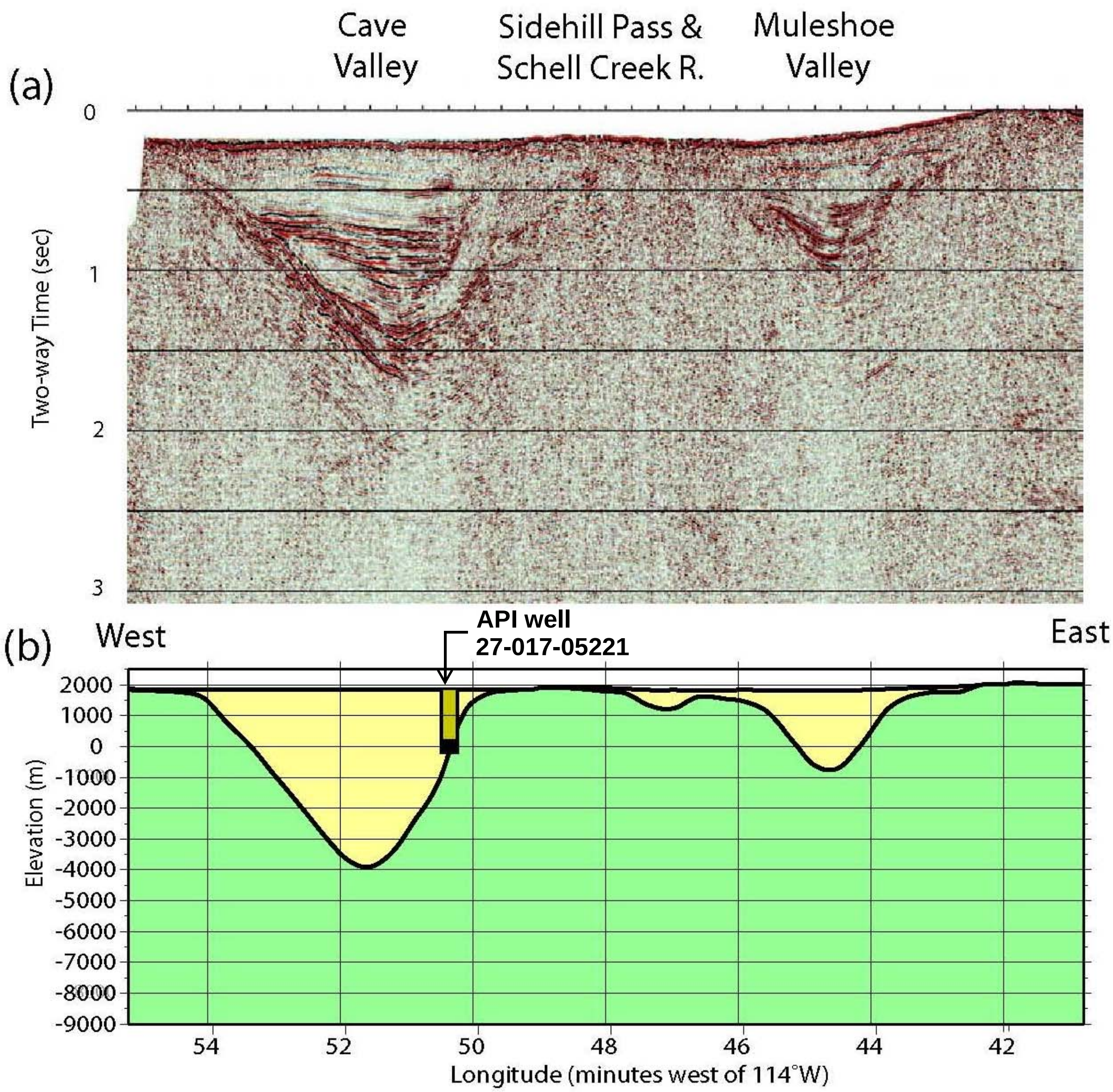
Source: Pari and Baird (2011)

Figure 5-27
Map and 2D Model of DELA5



Source: Pari and Baird (2011)

Figure 5-28
Map and 2D Model of DELA1



(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. API well 27-017-05221 is displayed on the section, and its alluvial interval is shown in dark yellow. Vertical exaggeration = 1.5.

Source: after Scheirer (2005)

Figure 5-29
(a) ECN-01 Seismic Reflection Section Displayed in Time
(b) Results of Gravity Depth-to-Basement

6.0 Professional Opinions on Previous Studies in the Project Area

Several previous studies on the hydrogeology in the project area have resulted in conclusions that, in part, differ from those of this SNWA report. In addition, some testimony, cross-examinations, and arguments by protesting parties during past hearings have questioned conclusions made in hydrogeological reports or testimony by SNWA. We anticipate that protestants in the upcoming proceedings by the Nevada State Engineer (NSE) will raise a number of these same issues relating to the geology of Spring, Delamar, Dry Lake, and Cave valleys. Therefore this section identifies several of those issues and discusses whether the anticipated positions of protestants, based upon previous studies, are supported by the geology of the region. First we summarize the pertinent, previously published and unpublished reports on studies containing positions we disagree with. Then we cover the issues raised by these studies or previous testimony, basin by basin, from north to south and west to east, starting with the project basins of Spring, Delamar, Dry Lake, and Cave valleys.

6.1 Previous Studies

6.1.1 The BARCASS Report

In 2004, the U.S. Congress funded the BARCASS to investigate the hydrogeology, recharge and discharge, groundwater flow, geochemistry of the aquifer system, and groundwater budgets for White Pine County, Nevada, and adjacent areas in Nevada and Utah. The work was done by the USGS, with minor collaboration from the Desert Research Institute and the Utah Department of Natural Resources. A main report (Welch et al., 2007) and six accompanying reports resulted. Some subsections and maps in the main report were separately authored. The most important hydrogeologically of these were the 1:500,000-scale geologic map (Sweetkind et al., 2007a), hydrogeologic conclusions (Sweetkind et al., 2007b), and classification of basin boundaries into three categories of likely flow, possible flow (comparable to our use of permissible flow in Figure 4-9), and no flow likely (Knochenmus et al., 2007).

Welch et al. (2007) proposed interbasin groundwater flow routes and volumes as part of the BARCASS effort to balance basin water budgets. As a result, recharge and evapotranspiration estimates drive the BARCASS interbasin-flow estimates regardless of the geology of the hydrographic-area boundaries. Other SNWA reports will discuss the accuracy of the BARCASS water budget based on its recharge and evapotranspiration estimates.

In their classification of flow boundaries, Knochenmus et al. (2007) relied heavily on their geologic map (Sweetkind et al., 2007a) but its compilation at that large a scale required simplistic portrayal of the geology that removed almost all faults and some confining units. A major confining unit in the map area, the Chainman Shale (their “upper siliciclastic rock unit”), has a maximum thickness of about 2,000 ft, so that when dipping steeply or dissected by faults, it cannot be shown at their map scale, leading them to erroneous conclusions about flow paths. Furthermore, the geology that Sweetkind et al. (2007a) compiled was obsolete, for it came from State geologic maps (Stewart and Carlson, 1978; Hintze, 1980a). Even though more up-to-date geologic maps had long been published, virtually none of these post-1980 references (for example, those in our map bibliography of Section 8.0) were used or cited. In addition, the report of Dixon et al., 2007a had been released and was available to BARCASS authors, but it also was ignored. The Sweetkind map contains two cross sections taken from the literature but neither matches the map. Therefore reliance on the Sweetkind map, coupled with the use of water budgets rather than measured data, led Knochenmus et al. (2007) and Welch et al. (2007) to erroneous conclusions about the likelihood, as well as specific paths and volumes, of interbasin flow. In addition, Welch et al. (2007, p. 37-38) assumed that the carbonate aquifer is in most places hydraulically connected within ranges and beneath basins because the geologic map of Sweetkind et al. (2007a) showed only a few faults. In fact, geologic evidence shows that most ranges are hydraulically separated from adjacent basins by high-angle faults of thousands of feet of dip-slip and strike-slip displacement, and basins and ranges are internally broken by faults of large and small magnitude that not only may create barriers in their own right but juxtapose aquifers against confining units. In other words, most basins, ranges, and even small pieces of both may be compartmentalized with respect to their neighbors in terms of groundwater flow. With respect to the project basins that the BARCASS addressed, their hydrogeologic map, hydrogeology conclusions, and flow routes across basin boundaries are largely in error.

6.1.2 Reports by Elliott and Other USGS Authors

In 2006, Elliott et al. published the results of a USGS study of the surface-water resources of GBNP, under contract from the NPS. The study covered two years (October 2002 to October 2004) of stream-flow measurements, short as surface-water studies go. The release of the report took place four months before the start of hearings on Spring Valley for the NSE in September 2006, and most conclusions addressed groundwater issues rather than surface-water issues. Specifically, the report suggested repeatedly that any SNWA pumping in the basin-fill aquifer or underlying carbonate aquifer of Spring or Snake valleys “might” dry up perennial streams in the Park. In fact, the report contained few data that addressed groundwater, such as water levels, drill data, pump tests, groundwater flow volumes or directions or groundwater chemistry or isotopes. Hypothetical statements such as “might” are generally used when an author has little or no supporting evidence, inasmuch as a conclusion that anything “might” happen is a conclusion without any meaning and fails to add to existing knowledge.

Elliott et al. (2006) based their conclusions, in part, on obsolete geologic mapping that did not recognize high-angle basin-range faults in Spring Valley, the Snake Range, and Snake Valley. Therefore their groundwater speculations that SNWA pumping “might” affect GBNP streams were erroneous. A view of a basin without faults is simplistic, leading to a model in which the sedimentary basin fill in Spring and Snake Valleys is generally isotropic and homogeneous, therefore porous-media flow concepts only apply. A later report by Prudic (2006) defended the conclusions of Elliott et al. (2006), continued the use of the hypothetical “might” with respect to the effects on GBNP streams from SNWA pumping, and suggested “evidence” that consisted of analogies with supposedly close surface water/groundwater interactions in areas outside Nevada. The simplistic and obsolete USGS geologic framework of Elliott et al. (2006) was maintained by the 2007 USGS BARCASS study (Section 6.1.1).

In a grant proposal to NPS for additional study of GBNP, the USGS (2008) claimed that the Elliott report had "identified" that some of the streams and springs in GBNP were "susceptible to ground-water withdrawals" by anticipated SNWA groundwater pumping. The objectives of the 2008 USGS proposal included attempts to (1) find evidence for the conclusions already made by Elliott et al (2006) that SNWA pumping would lead to depletion of GBNP streams, and (2) improve the geologic framework. Funding was approved by the NPS. Some USGS studies have been completed, and others are continuing. To address objective (1), USGS studies included additional work on the hydrology and alluvial thicknesses of GBNP streams. Two masters students, Jackson (2010) and Dotson (2010), whose studies built upon previous students in GBNP (Acheampong, 1992; Glonek, 2001), were supported by the USGS. Jackson (2010) and Dotson (2010) found that loss rates along several GBNP perennial streams at issue were low because the stream gravels were sealed by calcium carbonate, and therefore that there was no connection between GBNP streams and the groundwater beneath Snake Valley. A study of springs was made by Prudic (2007) and Prudic and Glancy (2009), but no connection was found between these springs and Snake Valley groundwater. Allander and Berger (2010) used seismic refraction methods to determine alluvial thicknesses along three profiles adjacent to Baker Creek but found that the creek is disconnected from the groundwater.

For objective (2), Asch and Sweetkind (2010 and 2011) collected AMT data along two profiles along Lehman Creek and south of Kious Spring, in Snake Valley southeast of the GBNP headquarters west of Baker. In their literature review, they noted that earlier reports (dePolo, 2008; dePolo et al., 2009) had discovered Quaternary faults in this area. The two profiles identified one of these, a mostly buried high-angle Quaternary fault that they had not previously recognized or factored into their groundwater interpretations. They interpreted the fault to be of minor displacement and too young to have much of a bearing on the uplift and development of the Snake Range. This fault zone, however, had been previously identified and mapped (Dixon et al., 2007a, Plate 1; Rowley et al., 2009, Plate 1). Its location was constrained by gravity data (Mankinen et al., 2006; Mankinen and McKee, 2009) and previous AMT profiles (McPhee et al., 2009). It was interpreted (Dixon et al., 2007a; Mankinen and McKee, 2009; McPhee et al., 2009, Figure 1; Rowley et al., 2009) to be the main eastern range-front basin-range fault of the Snake Range. Asch and Sweetkind (2010 and 2011) neither acknowledged or cited these previous reports. Nonetheless, their improved understanding of the geologic framework makes it unlikely that they will argue for any drawdown of GBNP streams by SNWA pumping because high-angle faults tend to compartmentalize basins into separate hydraulically-connected parts. Whether for object (1) or (2), the introductions of nearly all these USGS reports continued to state that SNWA pumping "might" dewater GBNP streams, but the conclusions of all reports admitted that they found no evidence of this effect. Even Prudic (2006, p. 3) admitted that "most of the Park's surface-water resources likely would not be affected by pumping because of either low-permeability rocks or because groundwater is sufficiently deep as to not be directly in contact with the streambeds."

6.1.3 Myers' Unpublished Reports

Dr. Tom Myers, Hydrologic Consultant from Reno, Nevada, wrote a number of reports as a consultant for protestants in the Hearings of the NSE. There are four hearings reports, two (Myers, 2006a and b) for the Spring Valley hearings and two (Myers, 2007b and c) for the Delamar Valley/Dry Lake Valley/Cave Valley hearings. In addition, Myers (2007a) wrote a review of SNWA reports for the Bureau of Land Management Environmental Impact Statement (EIS) Project. Two of the hearings reports (Myers, 2006a, 2007b) developed conceptual groundwater-flow models. Speaking only to the hydrogeology in the five reports, we are of the opinion that the hydrogeology is simplistic and that Myers largely ignored geology input for his own reports and misunderstood the geology that SNWA submitted. In addition, the geologic map that Myers cited is obsolete, taken from the 1:500,000-scale State geologic map (Stewart and Carlson, 1978). In Myers (2006a), all faults from Stewart and Carlson (1978) were removed, the units generalized, and the resulting map shown at page-size 1:1,000,000 scale, thus largely illegible and unintelligible. In Myers (2007b), three page-size figures of the three valleys were reproduced at nearly 1:1,000,000 scale. Only about a single page of text in both reports (Myers, 2006a and 2007b) covered topographic setting and hydrogeology, and most citations to the geology are from several hydrologic publications that contain minimal coverage of geology. His apparent lack of understanding of the importance of the geologic framework of the subject basins led Myers to erroneous conclusions regarding routing and amounts of interbasin flow and potential effects of pumping.

In his rebuttal report for SNWA's positions on Spring Valley, Myers (2006b) had no criticisms of SNWA's concepts on geology or interbasin flow. But Myers (2007c) rebuttal for the hearings on Dry Lake, Delamar, and Cave valleys disputed SNWA's positions on interbasin flow between (1) northern and southern Cave Valley, (2) southern Cave to Pahroc valleys, (3) Delamar to Coyote Spring valleys, (4) Delamar to Pahranagat valleys, and (5) Coyote Spring Valley to Lake Mead. Myers' rebuttal contains no supporting evidence. His arguments stem largely from his misunderstanding of fracture flow and the geology of basin boundaries. They will be discussed in the sections below, except for #5, which is discussed in Sections 4.4.17 and 4.4.21.

The review of SNWA's EIS documents by Myers (2007a) dealt only in part with geology, and his only substantive comments disputed the concept of fracture flow, which he referred to as an "opinion." Myers (2007c, p. 14) disputed the fundamental principle of fracture flow that faults can be both conduits and barriers in his particularly revealing comment that "SNWA cannot have it [barrier and conduit flow] both ways." Section 2.2 of this report stated the scientific principals of fracture flow to show that this theory is generally accepted by geologists and hydrogeologists and is not the mere opinion of the authors.

6.2 Issues in Basins within the Project Area

6.2.1 Issues in Spring Valley

6.2.1.1 Flow to or from Tippett Valley

Knochenmus et al. (2007) showed the entire Antelope Range as well as the basin boundary between Tippett and Spring valleys as a boundary of likely flow, and Welch et al. (2007, Figure 41) showed northeastward flow of 2,000 afy from Spring Valley to Tippett Valley.

Geologic evidence (Plates 1 and 6, Section 4.4.22) shows that the high Antelope Range is a complexly faulted horst of Paleozoic rocks, including the Chainman Shale confining unit, and of Tertiary volcanic rocks. The range is bounded on both sides by large range-front faults. These faults and most faults internal to the range are oriented northerly, therefore tend to create barriers to flow east to west. The southern end of Tippett Valley is bounded by the complexly faulted Red Hills (Plates 4 and 8, Cross Section X—X'), of similar rocks and structures to the Antelope Range. Most groundwater is in the low main aquifer, that of the basin-fill sediments of Spring and Tippett valleys. Gravity data (Section 5.1.1) show thick basin fill and clear buried faults oriented mostly perpendicular to possible flow in passes between Tippett and Spring valleys.

Our opinion is that interbasin flow is confined to a narrow path between two passes at the southern end of Tippett Valley, on either side of the Red Hills. Considering the lack of water-level data, flow direction is inconclusive and the boundary may just be a groundwater divide.

6.2.1.2 Flow to Snake Valley between the Kern Mountains and Snake Range

Knochenmus et al. (2007) showed a steep eastward gradient in carbonate rocks across the northern Spring Valley basin boundary, then beneath the shallow basin fill in basin(s) between the southern Kern Mountains and northern Snake Range, to Snake Valley. Yet they gave no data points and stated that the flow route is only "possible". Welch et al. (2007, Figure 41) showed a flow of 16,000 afy along this path.

Gravity data (Section 5.1.1) indicate that barriers to flow are presented by prominent faults and buried bedrock ridges north and south of the Red Hills. In addition, the barriers caused by the Red Hills (Plates 4 and 8, Cross Section X—X') make it more likely that no groundwater passes eastward from northern Spring Valley. Furthermore, geologic and geophysical evidence (Sections 4.4.25 and 5.1.1) suggests that Spring Valley consists of geophysical sub-basins that are separated by buried bedrock ridges that may restrict flow from one sub-basin to another. The best explanation is that the water in the basin(s) between the Kern Mountains and Snake Range more likely is from local recharge from the high Kern Mountains and the high northern end of the Snake Range rather than from basins to the west.

Our opinion is that Welch et al. (2007) are premature in their suggestion for a large volume of flow shown in Figure 41. Some flow is permissible from northeastern Spring or Tippett valleys to the basin(s) between the Kern Mountains and the Snake Range, but such flow would hardly be in the volumes suggested by Welch et al. (2007).

6.2.1.3 Flow from Steptoe Valley to Southern Spring Valley

Welch et al. (2007) proposed four flow routes from Steptoe Valley, two to the east and two to the west, through the high ranges that bound the basin on either side.

All previous workers (e.g., Harrill et al., 1988) have considered all groundwater flow within Steptoe Valley to be northward. The two paths to the east, from the southern end of the valley through the Schell Creek Range, are discussed north to south in this and the next (6.2.1.4) sections.

Both paths to the east proposed by Welch et al. (2007) are through parts of the range where Knochenmus et al. (2007) considered flow to be possible. The northern of these, calculated to have flow of 4,000 afy along a path to southern Spring Valley, is about 10 mi south of Connors Summit, the pass where US 6/US 50 crosses the Schell Creek Range.

The geologic map (Plates 1 and 6) shows that the Schell Creek Range at the suggested northern path is high (at least 1,600 ft of relief between any possible passes and Steptoe Valley) and broad (more than 10 mi). The range here is bounded on both sides by large range-front faults oriented perpendicular to the flow suggested by Welch et al. (2007) and internally complexly deformed by faults that contain fault blocks and slivers of Chainman Shale, a major confining unit (Plates 4 and 8, Cross Section V—V'; Section 4.4.13). Gravity data show the Schell Creek Range to be massive and of relatively high density, with no breaks or faults that might be interpreted to be flow paths (Section 5.1.3). The geologic map of Sweetkind et al. (2007a), however, showed only lower and upper Paleozoic carbonate rocks, with no Chainman Shale or range-front or internal faults, because their map scale did not allow these complexities to be given. The result is that their map gives the false impression that there are no barriers to groundwater flow.

In our opinion, groundwater flow through the entire Schell Creek Range is unlikely. There is no geological or gravity-data support for any groundwater flow along the northern of the two paths from southern Steptoe Valley to southern Spring Valley.

6.2.1.4 Flow from Steptoe Valley to Lake, Spring, and Hamlin Valleys

The southern of the two paths (see Section 6.2.1.3 for the northern one) proposed by Welch et al. (2007) for flow to the east from southern Steptoe Valley is 16 mi south of Connors Summit. Here the volume of flow was proposed to be 20,000 afy (Welch et al., 2007, Figure 41) to northern Lake Valley.

The geologic map (Plates 1 and 6) shows that the Schell Creek Range is made up of lower Paleozoic carbonate rocks that have been complexly faulted, with few faults oriented parallel to the BARCASS flow path that could act as conduits. No passes through the range here are lower than 7,900 ft elevation, a relief of more than 300 ft from Steptoe Valley. It is unreasonable to expect groundwater to pass beneath broad, high ranges such as the Schell Creek Range, in part, because the lithostatic pressure from the weight of rocks above any flow path hydraulically connected to groundwater in adjacent basins would tend to close prospective flow paths. The geologic map of Sweetkind et al. (2007a) shows only carbonates, with no faults, because their map scale did not allow such details to be given. Gravity data (Section 5.1.3) show a relatively high-gravity, homogeneously dense range with no discernible density breaks or faults that may be interpreted to be flow paths.

It is our opinion not only that the flow path proposed by Welch et al. (2007) does not exist, nor is there any groundwater flow anywhere out of southern Steptoe Valley.

As a consequence of their flow path containing 20,000 afy from Steptoe Valley to Lake Valley, Welch et al. (2007) proposed another flow path, from Lake Valley through the central Fortification Range—at the county line between White Pine and Lincoln Counties—to southern Spring Valley. They considered this flow to be 29,000 afy. Knochenmus et al. (2007) classified flow anywhere across the Fortification Range to be possible, even south of the county line.

The geologic map (Plates 1 and 6) shows the basin boundary of the central Fortification Range to be high and abrupt, and at the flow path (Plates 4 and 8, Cross Section U—U') suggested by Welch et al. (2007) to consist of mostly upper Paleozoic carbonates but with Chainman Shale likely at shallow depth and below the water table in repeated fault blocks (Section 4.4.18). Several miles south of the county line, the range is underlain by a caldera of the Indian Peak caldera complex (Plates 4 and 8, Cross Section Q—Q' and R—R'). The range is bounded on both sides by range-front faults and is cut internally by additional north-trending faults. Sweetkind et al. (2007a), in contrast to our more detailed geologic map, showed only upper Paleozoic carbonates cut by a single fault on the western side.

In our opinion, the flow path proposed by Welch et al. (2007) through the Fortification Range does not exist. There is no evidence for any flow through the high Fortification Range, which we classify as unlikely with respect to flow through it. The existence of the Chainman Shale and the Indian Peak caldera complex underlying the range creates impermeable barriers that would prevent the passage of any groundwater along that path.

The next downgradient flow path that Welch et al. (2007) hypothesized is a path from southern Spring Valley eastward through the basin boundary of the Limestone Hills and into Hamlin Valley. They considered this path to support 33,000 afy of groundwater.

The geologic map (Plates 1 and 6; Figure 4-20) shows that the rocks in the Limestone Hills consist of lower Paleozoic limestone and Tertiary ash-flow tuffs bounded on both sides by north-trending, range-front normal faults and internally broken by small faults of the same trend (Plates 4 and 8, Cross Section U—U'; Section 4.4.25). Gravity and AMT studies (Sections 5.1.1 and 5.2.1) supports these structural interpretations. Sweetkind et al. (2007a), however, showed the rocks to consist of lower Paleozoic carbonates bounded on the west side by a single fault, as befits the lack of detail that his map scale allows.

It is our opinion that flow through the Limestone Hills is permissible and, locally at lower passes in the north and south, likely. However, the volume (33,000 afy) proposed by Welch et al. (2007) is unreasonably high. The geologic framework can support some flow through cross faults in carbonate rocks, but the north-trending faults that define the range present partial barriers. Furthermore, the groundwater from Spring Valley is from only the southern geophysical sub-basin (see discussions in Sections 4.4.25 and 5.1.1). As noted in the previous paragraphs, we find no support for any contribution to this geophysical sub-basin from Lake Valley.

6.2.2 Issues in Cave Valley

6.2.2.1 Shingle Pass Fault

Knochenmus et al. (2007) showed the entire southern Egan Range as a hydrographic boundary for possible flow through it and Welch et al. (2007, Figure 41) ascribed a volume of 9,000 afy passing westward along a flow path 6 mi north of Shingle Pass through the Egan Range. Myers (2007c, p. 11) however, suggested that all groundwater in northern Cave Valley is blocked from passing southward into southern Cave Valley by the footwall block (southern side) of the Shingle Pass fault because the *fault block contains Chainman Shale and extends northeastward across Cave Valley. Therefore Myers (2007b, p. 3) reasoned that all groundwater in northern Cave Valley passes through Shingle Pass, where it supplies Moon River and Hot Creek springs in the middle of White River Valley. He concluded that any SNWA pumping in Cave Valley will decrease discharge in these springs.*

Geologic evidence (Plates 1 and 6, Plates 4 and 8, Cross Section R—R'; Section 4.4.10) indicates that the Egan Range north of Shingle Pass consists of nearly the entire stratigraphic succession in this part of Nevada, including the Chainman Shale and other confining units, all dipping eastward. As a result, we show the entire southern Egan Range as an unlikely flow boundary (Figure 4-9), except for a permissible path at Shingle Pass.

Groundwater in Cave Valley flows from north to south. The Shingle Pass fault is a large, northeast-trending, oblique-slip (left-lateral and normal) accommodation fault that breaks the Egan Range at Shingle Pass, then continues northward as the eastern, down-to-the-east, primarily normal, range-front fault of the Egan Range. We interpret that a second large fault, but a down-to-the-west normal fault, continues northeast from Shingle Pass, crossing northern Cave Valley and joining the western down-to-the-west, range-front normal fault of the Schell Creek Range. The second fault serves to separate the northern Cave Valley sub-basin from the southern Cave Valley sub-basin because the footwall (southern) side of the fault reaches almost entirely across Cave Valley. The Shingle Pass fault provides a permissible outlet for some groundwater to pass from northern Cave Valley southwestward into White River Valley. But all the groundwater in northern Cave Valley will not pass through Shingle Pass (with an elevation of somewhat less than 7,000 ft) because an easier and lower-elevation conduit exists in the large north-trending, range-front fault (Plates 4 and 8, Cross Section R—R') that bounds the base of the entire western side of the Schell Creek Range at an elevation of less than 6,500 ft elevation (Section 4.4.10 and Figure 4-12). This large range-front fault, clearly imaged multiple times by geophysics (Sections 5.1.4, 5.2.3, and 5.3), downthrows the footwall block of the second fault. This fault effectively removes the footwall block of the second fault from blocking southward groundwater flow because the north-trending fault along the western Schell Creek Range creates a broad avenue of north-trending fractures, between the downthrown hanging wall and the Schell Creek range front.

Moon River and Hot Creek springs are hot regional springs in the middle of White River Valley controlled by north-trending faults that get their groundwater from more northern parts of the valley (Burns and Drici, 2011; Thomas and Mihevc, 2011). In a comprehensive summary of springs throughout and near the geologic study area, Volume 3 of SNWA (2008) summarized the hydrology, geology, geologic cross sections, and results of monitoring many springs in White River Valley, including Hot Creek Spring. Moon River Spring, which is 2.6 mi southwest of Hot Creek Spring, is probably controlled by the same down-to-the-west, basin-range fault that controls Hot Creek Spring. There is no geologic evidence that these springs get any water from Cave Valley.

It is our opinion that Knochenmus et al. (2007) are incorrect in showing the entire southern Egan Range as a boundary that allows possible flow. It is also our opinion that Welch et al. (2007, Figure 41) was not correct in ascribing a volume of 9,000 afy passing westward through the Egan Range along a flow path 6 mi north of Shingle Pass. Furthermore, it is our opinion that Myers (2007c) erred in suggesting that all groundwater from northern Cave Valley is blocked from passing into southern Cave Valley by the footwall block of the second fault. Finally, Myers (2007b) was incorrect in suggesting that all groundwater in northern Cave Valley passes through Shingle Pass. He also is wrong in suggesting that any groundwater from Cave Valley will supply Moon River and Hot Creek springs. While the Shingle Pass fault may allow minor amounts of groundwater to flow to White River Valley (Section 4.4.10; Figure 4-13), there is no evidence that supports a large flow. It is our opinion that the western range-front fault of the Schell Creek Range provides the primary conduit for groundwater flow in Cave Valley.

6.2.2.2 Flow through Southern Cave Valley

Myers (2007c, p. 11) maintained not only that no groundwater flowed from northern to southern Cave Valley (Section 6.2.2.1) but that, because recharge to southern Cave Valley is small, little groundwater would go south from southern Cave Valley. Myers stated that most of that flow would end up in Pahranagat Valley.

In our opinion and consistent with our conclusions in Section 6.2.2.1, most groundwater in northern Cave Valley finds its way to southern Cave Valley along the western range-front fault of the Schell Creek Range. From there, groundwater passes southward through several north-trending normal- and oblique-slip faults, and fractured carbonate and volcanic rocks along and between the faults, from southern Cave Valley, then into Pahroc Valley to the west and Dry Lake Valley to the east (see Section 4.4.10; Plates 4 and 8, Cross Section Q—Q'; Figure 4-13).

6.2.3 Issues in Dry Lake and Delamar Valleys

6.2.3.1 The Timpahute Transverse Zone

Some protestants have questioned the possible hydrologic effect of the east-trending Timpahute transverse zone, which crosses the project area (Plates 1 and 6), including the low, virtually imperceptible divide between Dry Lake Valley and Delamar Valley, where the zone is roughly coaxial with US 93.

Transverse zones are defined and described in Section 4.3.1, and several of them are mapped on Plates 1 and 6, including the Timpahute transverse zone. Transverse zones are poorly known and controversial. Because they separate areas north and south of them that have undergone different amounts, rates, and types of east-west basin-range extension, much like east-striking transform faults in the ocean basins, they are discontinuous along strike. Perhaps this is because they are not always expressed as faults and, because they are primarily boundaries, they may be expressed as discrete narrow east-west zones in some places, jump north or south in other places, and be miles wide in still other places. Furthermore, transverse zones are in general deep-seated structures, so in many places they are not likely to be expressed as obvious features at the surface.

Detailed geologic mapping (Section 4.4.12) and gravity surveys (Section 5.1.4) have identified parts of the east-trending Timpahute transverse zone in the bedrock on both (western and eastern) sides of the valley where Dry Lake Valley passes into Delamar Valley. East-trending faults may be traced to the west as far west as Pahroc Summit Pass, between the North and South Pahroc ranges where US 93 crosses into Sixmile Flat and north of which a SNWA monitoring well was sited. The Timpahute transverse zone, however, has not been identified in the Sixmile Flat area (Plates 4 and 8, Cross Section S—S'). Furthermore, water levels at the monitoring well along the transverse zone do not indicate any flow west across Pahroc Summit Pass. More importantly, chemistry and isotopes for water from wells in Delamar and Dry Lake valleys are different from those for groundwater in Pahranagat Valley (Burns and Drici, 2011). Perhaps most telling is the cross section (basin-boundary profile) and geologic map of Plates 1 and 6 and Figure 4-15, which show a series of large, north-trending normal faults that define the range fronts on either sides of Dry Lake and Delamar valleys and bifurcate the valley itself. These faults, oriented parallel to the potentiometric gradient, are conduits to southward groundwater flow and barriers to westward flow.

In our opinion, no groundwater passes along the Timpahute transverse zone into Pahranagat Valley.

6.2.3.2 Flow from Delamar Valley to Pahranagat Valley

Myers (2007b, p. 1) hypothesized that "the entire amount [of discharge from Dry Lake and Delamar valleys] discharges as interbasin flow to Pahranagat Valley." He furthermore seemed to suggest flow paths at various places through the basin boundary, in addition to the Pahranagat shear zone (Myers, 2007b, p. 1-2, 44; Myers, 2007c, p. 13-15).

Although the South Pahroc and Hiko ranges, which separate Delamar Valley from Pahranagat Valley, are relatively low and largely made up of volcanic and underlying carbonate rocks, these two north-trending ranges are defined by innumerable north-trending basin-range faults that would present barriers to flow across them (Plates 1 and 6; Plates 4 and 8 Cross Sections M—M', N—N', and O—O',). Flow would more likely continue south in conduits provided by north-trending faults within and on either side of Delamar Valley rather than swing west into Pahranagat Valley. In Pahranagat Valley north of Alamo, Nevada, Crystal Springs (Dixon and Van Liew, 2007), Hiko Springs, and Ash Springs are regional springs (Section 4.4.6, Volume 3 of SNWA, 2008) controlled by north-trending basin-range faults (Plates 4 and 8 Cross Sections O—O'). Chemistry and isotopes from water at these and other springs in Pahranagat Valley north of Alamo are consistent with a source from White River Valley but are different from water in Dry Lake and Delamar valleys (Thomas et al., 2001; Burns and Drici, 2011; Thomas and Mihevc, 2011). Although the PSZ clearly brings some groundwater (see section below) from southern Delamar Valley to southern Pahranagat Valley, the hydraulic gradient in Pahranagat Valley is southward and the PSZ enters only southern Pahranagat Valley south of Alamo (Figure 4-11), from where this groundwater continues to flow southward into Coyote Spring Valley.

It is our opinion that Myers (2007b) is wrong in stating that the entire amount of discharge from Dry Lake and Delamar valleys discharges as interbasin flow to northern and central Pahranagat Valley. Our opinion is based on the presence of barriers created by many north-trending basin-range faults, between Delamar and Pahranagat valleys, the isotopic evidence, and the entry of the PSZ into only southern Pahranagat Valley. The only possible flow path from Delamar Valley to Pahranagat Valley is that described in Section 6.2.3.3, below.

6.2.3.3 Flow along the Pahranagat Shear Zone

Myers (2007c, p. 13) claimed that SNWA's proposed route for groundwater flow from southern Delamar Valley southwestward to Coyote Spring valleys "does not make sense." Although he seemed to accept flow along the PSZ to southern Pahranagat Valley, he questioned how flow could cross the shear zone and continue southward into Coyote Spring Valley (Myers, 2007c, p. 13-15). He gave no evidence that groundwater from southern Pahranagat moves northward against the hydraulic gradient to supply more northern parts of Pahranagat Valley. Nor did he offer alternatives as to where the groundwater in Coyote Spring Valley comes from.

We discussed the geologic evidence for groundwater movement from southern Delamar Valley to southern Pahranagat and northern Coyote Spring valleys in Section 4.4.6. The area is underlain mostly by brittle volcanic rocks at the surface and continuing below the water table, and these rocks are fractured not only by the northeast-striking left-lateral faults of the PSZ (Plates 5 and 9, Cross Sections B—B') but by north-striking normal faults that feed into the shear zone both north and south of it. All these faults are connected because the PSZ is an accommodation fault zone that developed during basin-range extension so it is connected with, and formed during, the same deformational episode as basin-range faults (Sections 4.3.1 and 4.4.6). As an accommodation zone, the northeast-trending faults of the PSZ connect with north-trending normal faults on both sides, so groundwater moves through the whole system.

It is our opinion that the PSZ provides a likely flow path that would allow groundwater to travel from southern Delamar Valley to southern Pahranagat Valley. Presently available scientific information is not available to pinpoint the exact routes for water from Delamar and southern Pahranagat valleys to northern Coyote Spring Valley, but there are doubtless many paths.

6.2.4 Issues in Steptoe Valley

6.2.4.1 Flow from Steptoe Valley to Jakes Valley

Of the four groundwater flow paths proposed by Welch et al. (2007, Figure 41) west and east (see Sections 6.2.1.3 and 6.2.1.4) out of southern Steptoe Valley, two were considered to pass westward through high parts of the Egan Range west of Ely, Nevada. The Egan Range at both these flow paths was judged by Knochenmus (2007) to be a hydrographic boundary of likely flow. Presumably this conclusion was guided by the compilation of Sweetkind et al. (2007a) that showed nearly all rocks in the range here to be upper Paleozoic carbonates, with no faults shown bounding or within the range. The northern of these two paths is the subject of this section; the southern path is described in Section 6.2.4.2. The northern path was shown in Figure 41 to cross the western of three prongs of the range about 10 mi northwest of Ely, allowing 14,000 afy of groundwater into Jakes Valley. Apparently the proposed path from Steptoe Valley follows or is north of US 50, which goes through the main business district of Ely, then northwest across a pass into Copper Flat before bearing west across the western prong of the Egan Range.

It is our opinion that the Egan Range beneath both westward flow paths is a boundary of unlikely flow. Regarding the northern of these two proposed paths, geologic evidence shows that the prong of the Egan Range is an overturned strike ridge of upper Paleozoic carbonate rocks, with 500 to 1,500 ft of relief, that is bounded on both sides by range-front normal faults oriented perpendicular to the BARCASS-hypothesized flow path (Plates 1 and 6; Section 4.4.3). These faults would likely block any westerly groundwater flow. Southeastern Copper Flat and the pass to Ely, along the possible flow path, are underlain by the northern part of the huge, active Ruth copper mining district, an area of complex geology where confining zones of many types can be found. The district includes Cretaceous and Tertiary plutons that probably pass into batholiths at depth, as well as faulted pieces of the Chainman Shale that act as barriers to flow. Metamorphosed rocks and hydrothermally altered rocks formed by the plutons are dense and rich in clay minerals, resulting in additional confining units. It is our opinion that no westward flow paths exist in the Ruth copper mining district area.

6.2.4.2 Flow from Steptoe Valley to White River Valley

Welch et al. (2007, Figure 41) proposed another west-flowing path for groundwater from Steptoe Valley to the White River Valley, located 11 mi south of the one described in Section 6.2.4.1. The path is similarly depicted through a part of the Egan Range considered by Knochenmus et al. (2007) to be a basin boundary where flow is likely through it. The path that Welch et al. (2007) showed follows US 6 through the southern part of Ely, Nevada, then southwest to cross the range at Murry Summit, 700 ft above Ely. Welch et al. (2007) suggested that 8,000 afy moves by this path into White River Valley.

Geologic evidence shows that the flow path proposed by BARCASS goes through mostly west-dipping upper Paleozoic carbonates underlain on their eastern side by buried Chainman Shale (Plates 1 and 6; Section 4.4.4). But the flow path passes along the southern part of the Ruth mining district, likely underlain by buried plutons and metamorphosed and mineralized rocks, all of which are likely confining zones. The range here is bounded on both sides by large range-front faults oriented perpendicular to the supposed flow path, and these faults would act as barriers to any westward groundwater flow. In addition, the range is internally broken by many small- to moderate-displacement faults also oriented mostly perpendicular to flow.

It is our opinion that no flow path exists from Steptoe Valley to the White River Valley through this part of the Egan Range.

6.2.5 Issues in Snake Valley

6.2.5.1 Impact of Pumping in Great Basin National Park

Elliott et al. (2006) and subsequent USGS workers in GBNP hypothesized that SNWA pumping in Spring or Snake valleys “might” lead to a drawdown of surface water in GBNP.

Except for some lower Paleozoic carbonates in fault blocks, most rocks that underlie GBNP are Cambrian and Precambrian confining units (Plates 1 and 6; Plates 4 and 8, Cross Sections V—V'; Section 4.4.25). The carbonates themselves are hydraulically compartmentalized by being displaced against the more abundant confining units by low-angle normal faults recognized by the USGS hydrologists and by more common high-angle normal faults mapped on Plates 1 and 6.

Pumping by SNWA in Spring or Snake valleys would be from groundwater in basin-fill sedimentary rocks. This groundwater is not physically hydraulically connected to the surface water in GBNP, (Kistinger et al., 2009, p. 311) except perhaps rarely where streams debouch from bedrock canyons into Spring and Snake valleys. In fact, in most places where perennial streams derived from the Park drain into the valleys, the water table in the basin fill is well below the surface water. The streams in these locations here become losing streams and soon lose their flow into the basin-fill deposits by natural processes instead of by pumping. In the rare short reaches where the water table is at the level of stream flow, stream gravels have been cemented by calcium carbonate, effectively sealing them and preventing any surface water/groundwater connection (Dotson, 2010; Jackson, 2010).

Basing conclusions on previous, mostly obsolete geologic maps, the USGS (Elliott et al., 2006) did not recognize that the Snake Range is a basin-range horst uplifted along huge, high-angle range-front normal faults on the eastern and western sides of the range. Nor did they study the surficial and basin-fill deposits in Snake and Spring valleys, so they did not notice abundant young (Pleistocene to Holocene) faults that cut the deposits. Therefore, the USGS geologic framework in which groundwater moves was incomplete and largely incorrect. Asch and Sweetkind (2010 and 2011), however, used AMT geophysics to find one large buried fault cutting basin-fill deposits, the same one previously recognized and mapped by Dixon et al. (2007a, Plate 1), McPhee et al. (2009, Figure 1), and Rowley et al. (2009, Plate 1). These studies were not cited by Asch and Sweetkind. This fault, however, is just one of hundreds of large- to medium-displacement, high-angle normal faults that cut the basin fill east and west of GBNP and contributed to the uplift of the Snake Range (Dixon et al., 2007a; Mankinen and McKee, 2009; McPhee et al., 2009; Rowley et al., 2009; Sections 5.1.1 and 5.2.2; Plates 4 and 8, Cross Section V—V'). Therefore, even if the basin-fill deposits had shallow water tables and GBNP streams were hydraulically connected to the groundwater, the many faults have compartmentalized the basin fill, so that any groundwater pumping would have many barriers to any hydraulically connected streams.

In our opinion, the hypothesis by Elliott et al. (2006) and subsequent USGS workers that pumping by SNWA anywhere in Spring or Snake valleys would affect surface water flows in GBNP perennial streams is wrong.

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7.0 SUMMARY

7.1 Summary of Approach

In developing the geologic framework that is described in this report, we compiled and interpreted significant amounts of data while building the geologic and hydrogeologic maps and cross sections presented here. This has allowed us to produce a digital hydrogeological framework that has provided the foundation for developing conceptual and numerical models of groundwater flow of portions of the area covered by this geologic analysis.

We developed the 1:250,000-scale digital geologic maps (Plates 1 and 2) using data that included the distribution, geometry, thickness, composition, and physical properties of geologic units used to define aquifers, HGUs, and potential confining units. When combined with the geographic breadth of our map coverage, the 1:250,000 scale provides a more detailed and comprehensive picture of the region's geology than any other map in existence. As noted in this report, many earlier maps produced by others use a 1:500,000 scale or larger (e.g., Sweetkind et al., 2007a, which the USGS used in support of its BARCASS study), but such a scale does not typically capture many of the geologic features identified here. Of course, a 1:250,000 scale may not capture all details in geologic features that affect groundwater flow either, but this report incorporates all available map scales of even greater scale in our mapping and analysis, as well as focusing new field observations on all problem areas we can identify.

We evaluated the maps presented here in conjunction with information provided by geologic data, gravity surveys, AMT investigations, and other sources to identify likely pathways for groundwater flow. More specifically, we identified faults that might serve as conduits or barriers (or both) to groundwater flow, and we evaluated the potential for specific faults to serve as conduits or barriers. The region's predominantly north-south faults are excellent conduits to groundwater flow in those directions, but those same faults typically act as barriers to east-west flow. An understanding of faults is critical to evaluating whether groundwater could possibly flow from one basin to another, and also in determining where groundwater might be located within certain basins.

7.2 Summary of Opinions on Key Issues

As described in more detail in Section 6.0, we have evaluated the likelihood of a number of possible flow paths identified by others in previous reports. For each suggested flow path across boundaries of hydrographic areas, we have reviewed our geologic framework, maps, cross sections, and data to determine whether groundwater flow would be likely, permissible, or unlikely along the path, and whether any possible flows would be volumetrically limited by the geology of the area. In the case of nearly every flow path suggested in the other reports described (e.g., BARCASS and Myer's multiple reports), we found that the geologic framework of the area supports either no possible groundwater flow or flow in amounts far less than the amounts suggested by others.

7.2.1 Spring Valley

In Spring Valley, we found that flow between Tippett Valley and Spring Valley is permissible but far from likely and, if it exists at all, is confined to a small permissible southward flow path on the northeast side of the Red Hills.

We also found that some flow is possible from northeastern Spring Valley or Tippett Valley to the basin(s) between the Kern Mountains and the Snake Range, but that such flow would be far less than the 16,000 afy suggested by Welch et al. (2007) (Section 6.2.1.2). The geology of the area, which includes prominent faults and buried bedrock ridges north and south of the Red Hills, makes it more likely that no groundwater moves eastward from northern Spring Valley.

We also found no geologic support for the proposition that groundwater flows from Steptoe Valley to Spring Valley through the Schell Creek Range, as that high range is generally bounded by various confining zones, including large north-south range-front faults that are perpendicular to the suggested flow path (Sections 6.2.1.3 and 6.2.1.4). Similarly, we see no geologic evidence that would support the existence of a flow path from Steptoe Valley to Lake Valley, then Spring Valley, as the suggested flow path in those areas crosses at right angles to many large- to medium-displacement faults and strike ridges of the impermeable Chainman Shale and a caldera of the Indian Peak caldera complex (Section 6.2.1.4).

Some flow is permissible and even likely from Spring Valley to Hamlin Valley through the Limestone Hills, but the volume of 33,000 afy proposed by Welch et al. (2007) is unreasonable and is unsupported by the geology of the area. We believe that the existence of faults in the Limestone Hills are at least partial barriers to flow, and the source of groundwater may be relatively small (the southern geophysical sub-basin of Spring Valley), and therefore that the estimate of others that for flow through this path is more reasonable (Rush and Kazmi, 1965; Nichols, 2000; Burns and Drici, 2011) (Section 6.2.1.4).

7.2.2 Cave Valley

We found that although Shingle Pass may allow minor amounts of groundwater to pass to the White River Valley, no evidence has demonstrated such flow (Section 6.2.2.1). Additionally, we found that a large, north-trending, range-front fault on the eastern side of Cave Valley along the Schell Creek Range acts as a significant southward conduit of groundwater from northern to southern Cave Valley (Section 6.2.2.2). That fault likely serves as the primary conduit of water in Cave Valley, despite the existence of Chainman Shale in the hanging wall (west) of the fault that extends across most of Cave Valley. That hanging-wall block does not impede the primary conduit (i.e., the north-south fault) that likely transports most groundwater southward.

7.2.3 Dry Lake and Delamar Valleys

We found that the geologic framework does not support significant groundwater flow from Dry Lake and Delamar valleys into northern and central Pahranagat Valley (Section 6.2.3.1). North-trending faults in the area of the Timpahute transverse zone appear to be conduits to southward groundwater flow and barriers to westward flow. It is far more likely, based on the geologic framework, that the majority of groundwater in Pahranagat Valley comes from basins to the north and west (i.e., Garden, Coal, and Pahroc valleys).

We also found that the only likely flow path from Delamar Valley to Pahranagat Valley is through the PSZ to southern Pahranagat Valley south of Alamo (Section 6.2.3.2). Furthermore, the clear southward hydraulic gradient in Pahranagat Valley argues that any groundwater entering southern Pahranagat Valley along the PSZ must go southward and westward from southern Pahranagat Valley.

7.2.4 Steptoe Valley

We found that the geology does not support a flow path from Steptoe Valley to Jakes Valley, as range-front faults on both sides of the Egan Range, in concert with smaller faults within the range and many confining units in and adjacent to the Ruth mining district, act as barriers to possible flow (Section 6.2.4.1). Furthermore, we found that no flow path exists from Steptoe Valley to White River Valley for the same reasons (Section 6.2.4.2).

7.2.5 Snake Valley and Great Basin National Park

The hypothetical suggestion by Elliott et al. (2006) and subsequent USGS reports that SNWA pumping in Spring or Snake valleys “might” lead to decreased surface water flows in GBNP is not supported by the geologic framework of the region (Section 6.2.5.1). The groundwater of those valleys is not geologically or hydraulically connected in any significant way to the streams in GBNP, particularly as hundreds of large- to medium-displacement, high-angle normal faults provide barriers between valley groundwater and GBNP streams. Elliott et al. and subsequent USGS investigators have failed to consider their hypothetical statements through the lens of a complete and accurate geologic framework.

7.3 Conclusions

The geologic framework developed through the data interpretation and map construction described in this report is the most accurate, comprehensive, and up-to-date representation yet done of the Project Basins and surrounding area. No other reports or studies have addressed the region in this comprehensive manner or identified the region’s geologic features with the same level of detail as in this report. We believe that our approach provides ample support for our evaluation of possible flow paths discussed above, groundwater occurrence and movement, and the development of conceptual and numerical models of groundwater flow.

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8.0 REFERENCES

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Appendix A

General Photos of the Study Area

View northwest of Jackman Narrows, where the Muddy River cuts into folded and faulted Permian carbonate rocks of the northern part of the North Muddy Mountains. Towns of Glendale and Moapa in the background.

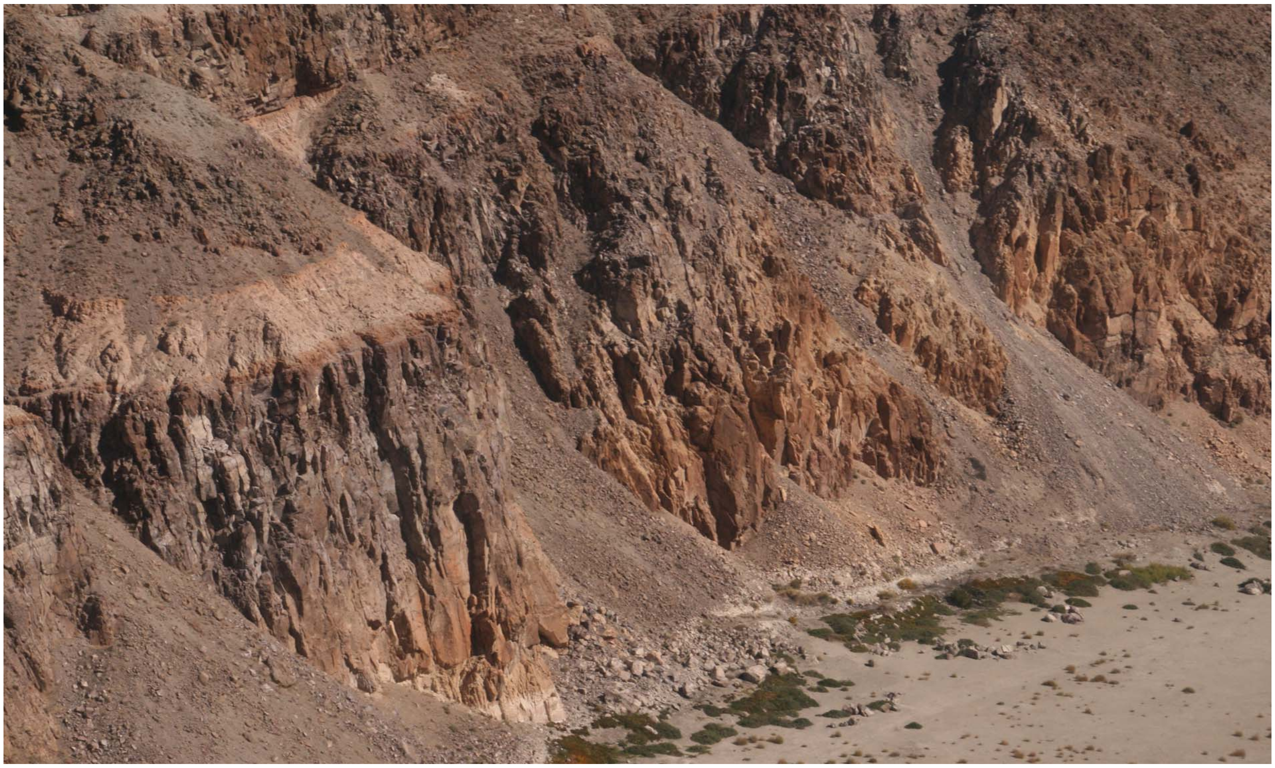
View north in Jackman Narrows showing highly fractured and contorted Permian limestone.

View overlooking Muddy River Springs, the source of the Muddy River northwest of Moapa.

View north of east dipping volcanic rocks underlain by Paleozoic rocks in northern Coyote Springs Valley. US 93 in center of photograph.

View north into southern Delamar Valley. Delamar Lake is light-colored playa in left center of photograph. Maynard Lake strand of the Pahranagat shear zone forms the scarp that is in shadows in the foreground, whereas the Delamar Lake strand passes beneath Delamar Lake and north of the hills on the left side of the photograph. Delamar Mountains in the right background.

View west from the Meadow Valley Mountains across the oblique-slip fault scarp of the Kane Springs fault zone (foreground), then across Kane Springs Valley, toward the Kane Springs Wash caldera complex in the Delamar Mountains.



View north along the northeast-southwest trace of the Maynard Lake Fault zone. Volcanic rocks highly fractured and faulted along fault zone. Maynard Lake (dry) in bottom of photograph.

View north of Rainbow Canyon, where perennial Meadow Valley Wash here cuts through the Caliente caldera complex south of Caliente, Nevada.

View north of Maynard Lake left-lateral fault segment of the Pahranagat Shear Zone. Note slickensides along the central core zone in center of photograph and brecciated volcanic rocks adjacent to this fault.

Brecciated fault debris along the Maynard Lake fault segment.

View west-northwest of Delamar mining district and northern Delamar Valley. Although Nevada's largest gold district from 1895 to 1910, now only a few walls of buildings remain along the main street.

View north of the Dry Lake Quaternary fault scarp (center foreground) on eastern side of Dry Lake Valley.


View east at drill hole 180W902M in Cave Valley near Sidehill Pass. Devonian and Silurian sedimentary rocks in background.


View to the southwest along the trace of the Shingle Pass fault zone in the southern Egan Range. The fault goes from the lower left of the view along the right base of the mountain in the center background.

View to the south looking at springs (to the right of the Nevada Highway 318 in left foreground and right middleground) in southern White River Valley. Seaman Range is in the background.

Plates

Explanation

Geologic Units

QTa	Quaternary and Tertiary basin-fill deposits
QTb	Quaternary and Tertiary thin basalt flows and cinder cones
Ts4	Tertiary fluvial and lacustrine sediments
Tt4	Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Ta4	Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Tr4	Tertiary high-silica rhyolite lava flows and volcanic domes
Tr3	Tertiary low-silica rhyolite lava flows and volcanic domes
Ta3	Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Ts3	Tertiary mostly fluvial tuffaceous sandstone and bedded airfall tuff
Tt3	Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Ts2	Tertiary mostly fluvial tuffaceous sandstone and bedded airfall tuff
Ta2	Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Tr2	Tertiary low-silica rhyolite lava flows and volcanic domes
Tt2	Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Tt1	Tertiary poorly-densely welded ash-flow tuff and interbedded airfall tuff
Tr1	Tertiary low-silica rhyolite lava flows and volcanic domes
Ta1	Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Ts1	Tertiary fluvial and lacustrine sediments
Tmb	Tertiary intracaldera megabreccia
Ti	Tertiary intrusive rocks
TKi	Tertiary-Cretaceous intrusive rocks
Ki	Cretaceous intrusive rocks
Ks	Upper and Lower Cretaceous sedimentary rocks, undivided
Ji	Jurassic intrusive rocks
₮s	Triassic sedimentary rocks, undivided
Pp	Upper and Lower Permian Park City Group, undivided
Par	Permian Arcturus Formation and Rib Hill Sandstone
Pa	Permian Arcturus Formation
Pr	Lower Permian Rib Hill Sandstone
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
D€	Devonian to Upper Cambrian sedimentary rocks, undivided
DS	Devonian and Silurian sedimentary rocks, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Dd	Upper and Middle Devonian Devils Gate Formation
Dg	Upper and Middle Devonian Guilmette Formation
Dn	Middle and Lower Devonian Nevada Formation
Ds	Middle and Lower Devonian Simonson and Sevy Dolomites
SOu	Silurian and Upper Ordovician dolomite, undivided
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and 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
	Open Water

Regional Faults

Normal Fault
Solid where known; Dashed where inferred; dotted where concealed. Bar and ball on downthrown side.

Strike-slip Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Thrust Fault
Solid where known; Dashed where inferred; dotted where concealed. Sawteeth on upper plate.

Detachment Fault
Solid where known; Dashed where inferred; dotted where concealed. Sawteeth on upper plate.

Quaternary Fault
Solid where known; Dashed where inferred; dotted where concealed. Bar and ball on downthrown side.

Subsidiary Faults

Normal Fault
Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain. Bar and ball on downthrown side.

Strike-slip Fault
Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain Arrows show direction of movement.

Thrust Fault
Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain. Sawteeth on upper plate.

Detachment Fault
Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain. Hollow sawteeth on upper plate.

Quaternary Normal Fault
Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain. Bar and ball on downthrown side.

Caldera Boundary
Solid where known; dashed where inferred; dotted where concealed

Cross Sections (Plates 4 and 5)

Major Road

Transverse Zone
(Zone of possible disruption)

National Park Service

Oil Well Data Used in Cross Sections
Nevada: Nevada Bureau of Mines and Geology
Utah: Utah Division of Oil, Gas and Mining

Wells

Town

Strike and Dip of Beds

Overturned Beds

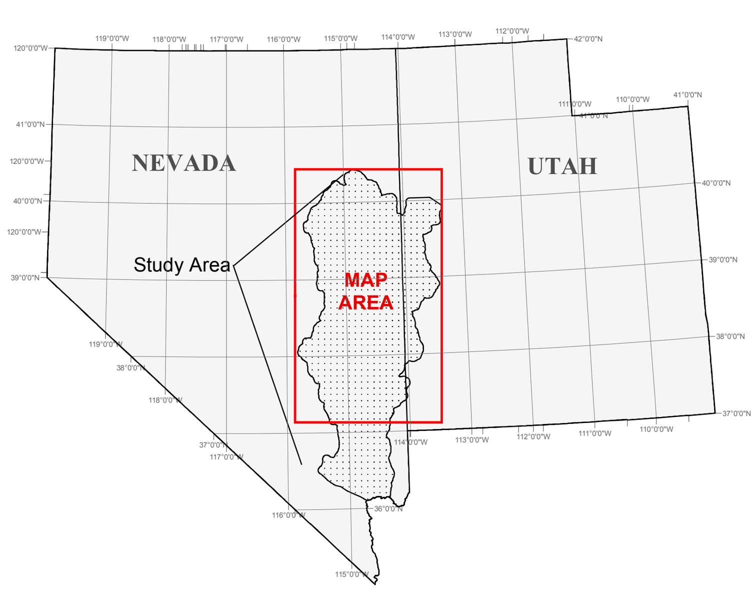
SCALE 1:250,000

Projection: UTM Zone 11 NAD83

0 25,000 50,000 75,000 Feet

0 5,000 10,000 15,000 20,000 25,000 Meters

0 5 10 15 20 Miles



SOUTHERN NEVADA WATER AUTHORITY

MAP ID 18286-3211 05/17/2011 JAB/BP

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

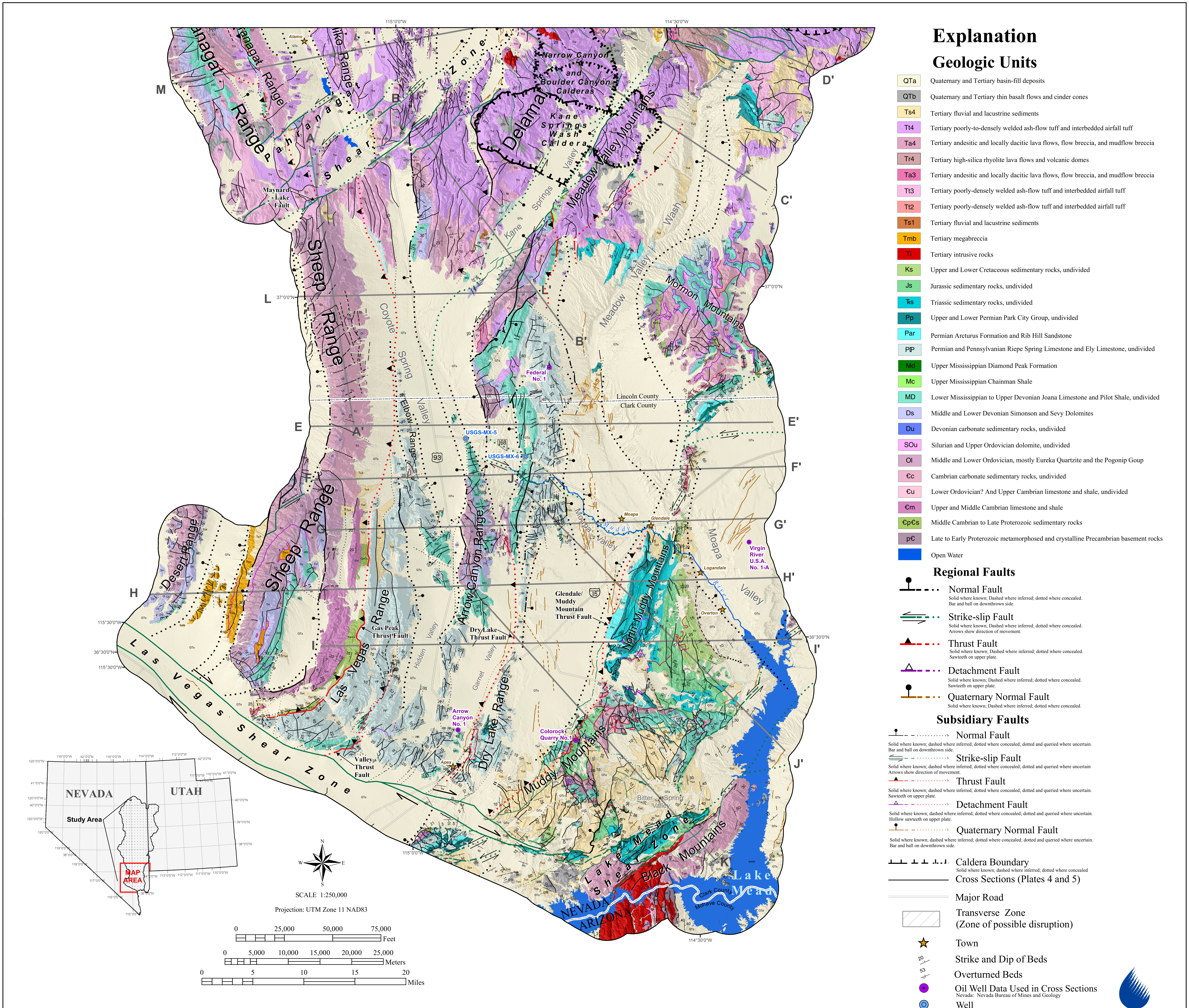
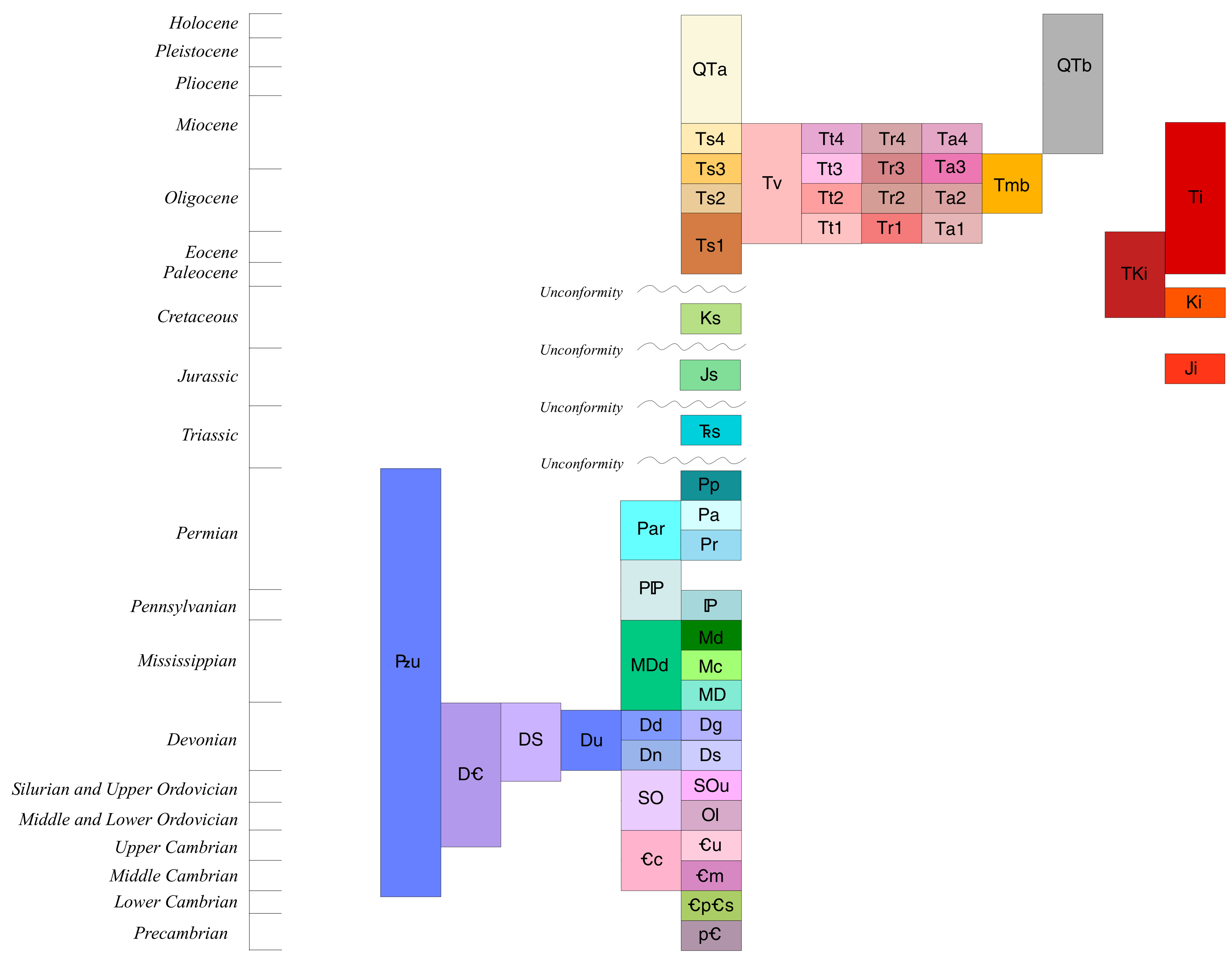


PLATE 2. GEOLOGY OF SOUTHERN LINCOLN AND NORTHERN CLARK COUNTIES, NEVADA , AND ADJACENT AREAS, ARIZONA

MAP ID 18287-3211 05/17/2011 BP



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 0-5000 feet thick and forms the upper valley-fill aquifer. Some basin-fill deposits bear local names, including the Muddy Creek Formation (southern part of Plate 2), Panaca Formation (southern part of Plate 1), Horse Camp Formation (northwestern part of Plate 1), and Salt Lake Formation (northeastern part of Plate 1).

QTb — Basalt lava flows (Holocene to lower 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.

Ts4 — Sedimentary rocks, unit 4 (Miocene)—Moderately to well consolidated, mostly fluvial sandstone, conglomerate, and minor lacustrine limestone. Primarily the Horse Spring Formation (11 to 20 Ma), a basal basin-fill sedimentary unit that is locally thick (3000+ feet) in the southern part of Plate 2.

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 northwestern part of Plate 1.

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 in the central part of Plate 1, 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 Plate 1. Unit in most places underlies all volcanic rocks.

Tv — Volcanic rocks (Miocene to Eocene)—Unit shown only in Plates 4, 5, 6, 7, 8, and 9, 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 Plates 1 and 2, unit is separated into several rock types based on age, following the mapping strategy of Ekren et al, (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 tuff of Honeycomb Rock (12.0 Ma), Ox Valley Tuff (14.0 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, Nevada; and the tuff of Saulsbury Wash (21.6 Ma), the Pahranagat Formation (22.6 Ma), the 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 (Oligocene and Eocene)—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 Plate 1. 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. In Utah, includes the Tunnel Spring Tuff (35.4 Ma).

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 and Eocene)—Low-silica rhyolite lava flows and volcanic domes, exposed in the northern part of Plate 1.

Ta4 — Intermediate-composition lava flows, unit 4 (Miocene)—Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia. Includes andesite of the Hamblin-Cleopatra volcano (11.5 to 14.2 Ma) in the Lake Mead area.

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 southeastern part of Plate 2, 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 and Eocene)—Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia. Exposed in the northern part of Plate 1. In the northeastern part of Plate 1 includes thin ash-flow tuffs, notably the Kalamazoo tuff. In Utah, includes the Horn Silver Andesite.

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 to Paleocene)—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 Plate 2, and the Iron Springs Formation (Upper Cretaceous), Cedar Mountain Formation (Upper Cretaceous), and Dakota Sandstone (Upper Cretaceous) in the southeastern part of Plate 2; and the Newark Canyon Formation (Paleocene? to Lower Cretaceous?) in the northern part of Plate 1.

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

Js — Sedimentary rocks, undivided (Jurassic)—Includes, in the southeastern part of Plate 2, the mostly marine Carmel and underlying Temple Cap formations (Middle Jurassic). Also in the southeastern part of Plate 2, includes the eolian Navajo Sandstone and mostly fluvial Kayenta and Moenave formations, all Lower Jurassic. Mostly clastic units. In the southern part of Plate 2, the Aztec Sandstone is the equivalent of the Navajo. Includes the Dunlop Formation (Lower Jurassic) in the northwestern part of Plate 1.

TRs — Sedimentary rocks, undivided (Triassic)—Includes, in the southeastern part of Plate 2, 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 Plate 1. In the northeastern part of Plate 1, includes the Thaynes Formation (Lower Triassic). The majority of these rocks are clastic.

PZu — Paleozoic sedimentary rocks, undivided—Shown on Plates 4, 5, 8, and 9, where rocks in the hanging wall of the Snake Range decollement are buried by younger rocks.

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 Plate 2, and the Queantoweap Sandstone in the southeastern part of Plate 2.

Pa — Arcturus Formation (Lower Permian)—Predominantly carbonate rocks in the northern part of Plate 1, thickening eastward.

Pr — Rib Hill Sandstone (Lower Permian)—Only in the northwestern part of Plate 1.

PIP — Riepe Spring Limestone and Ely Limestone, undivided (Lower Permian and Pennsylvanian)— Mapped only in the northern part of Plate 1. The Riepe Spring Limestone (Lower Permian) is exposed in the northwestern part of Plate 1. Includes the Brock Canyon Formation (Permian and/or Pennsylvanian) in the northwestern part of Plate 1; the Oquirrh Group (Lower Permian and Pennsylvanian) in the northeastern part of Plate 1; and the Bird Spring Formation (Lower Permian to Upper Mississippian) in Clark County, Nevada and the Pakoon Formation (Lower Permian) in Utah.

IP — Ely Limestone (Pennsylvanian)—May include Missippian rocks at its base. Mapped mostly in the central and northern part of Plate 1, thickening eastward. Includes the Wildcat Peak Formation in the northwestern part of Plate 1 and the Callville Limestone in the southern and eastern part of Plate 2.

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 Plate 1. 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 Plate 2.

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 Plate 1. Thus for this part of the map area, it separates the upper from the lower carbonate aquifer; in the area of Plate 2, 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 Plate 1. 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 Plate 2; the Eleana Formation (Mississippian and Upper Devonian) in the western part of Plate 2; the Webb Formation (Lower Mississippian) in Elko County ; the Ochre Mountain Limestone and underlying Woodman Formation (Lower Mississippian) in the eastern part of Plate 1; and the West Range Limestone (Upper Devonian) in northern Lincoln County. May include, at the top, thin deposits of the Chainman Shale.

DЄ — Devonian to Upper Cambrian carbonate and clastic rocks, undivided.

DS — Devonian and Silurian sedimentary rocks, undivided—Only shown on some cross sections (Plates 4, 5, 8, and 9).

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 Plate 2.

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 Plate 1. Includes the Sultan Limestone in Clark County.

Dn — Nevada Formation (Middle and Lower Devonian)—The western equivalent of the Simonson and Sevy Dolomites. Includes the Cockalorum Wash Formation, also in the western part of Plate 1.

Ds — Simonson Dolomite (Middle and Lower Devonian) and Sevy Dolomite, undivided (Lower Devonian)—Mapped in all but the western part of Plate 1.

SO — Silurian and Ordovician sedimentary rocks, undivided—Shown on some cross sections (Plates 4, 5, 8, and 9).

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 Plate 1.

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 Plate 1. Includes the Ely Springs Dolomite where it is thin in Clark County. In Utah, includes the Crystal Peak, Watson Ranch, and Fillmore formations and the House Limestone.

Єc — Cambrian carbonate sedimentary rocks, undivided—Shown only on some cross sections (Plates 4, 5, 8, and 9).

Єu — 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 Plate 2, includes the Emigrant Formation (Upper and Middle Cambrian).

Єm — Middle part (Upper and Middle Cambrian)—Mostly the Highland Peak Formation and its southwestern equivalent, the Bonanza King Formation. In Nevada, 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. Includes the Muav Limestone in eastern Clark County. In Utah, includes the Wah Wah Summit, Trippe, Pierson Cove, Eye of Needle, Swasey, Whirlwind, Dome, Chisholm, and Howell formations. This unit is a thick limestone sequence that marks the base of the lower carbonate aquifer.

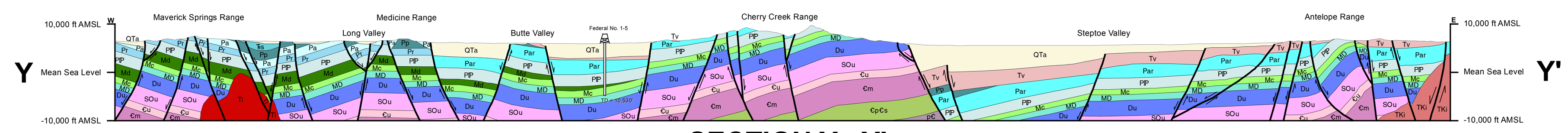
ЄpЄs — Lower part (Middle Cambrian to Late Proterozoic)—Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), Pioche Shale (Middle and Lower Cambrian), Carrara Formation (Middle and Lower Cambrian), Stella Lake Quartzite (Lower Cambrian), Prospect Mountain Quartzite (Lower Cambrian and 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?) in the southwestern part of Plate 2.

pЄ — Metamorphosed and crystalline Precambrian basement rocks (Late to Early Proterozoic)—Throughout most of Plates 1 and 2, 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 Plate 2, includes crystalline basement rocks.

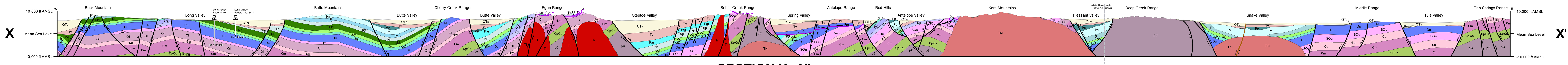
Open Water

PLATE 3. EXPLANATION OF GEOLOGIC UNITS FOR THE MAPS AND CROSS SECTIONS OF PLATES 1, 2, 4, AND 5.

MAP ID 18288-3211 04/20/2011 BP



SECTION Y - Y'



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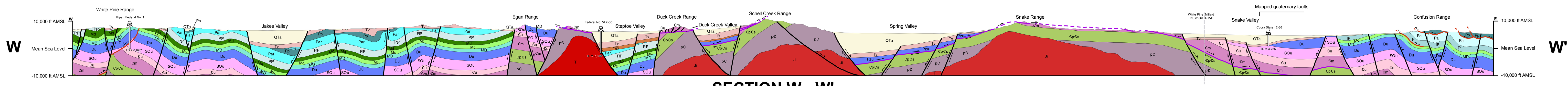

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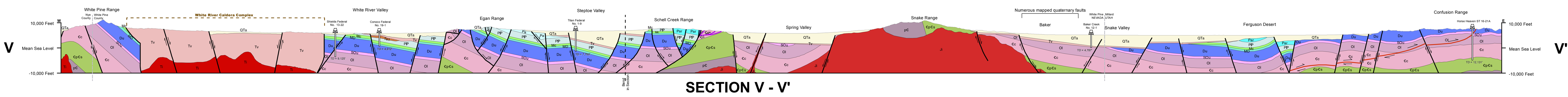

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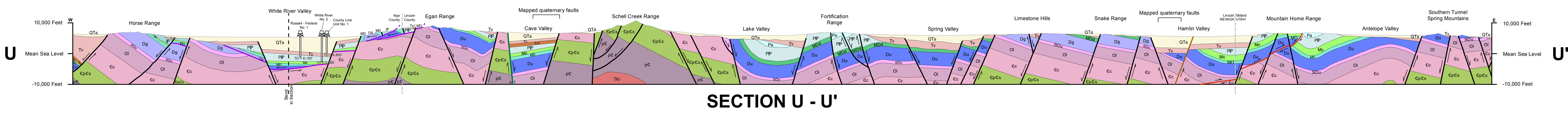

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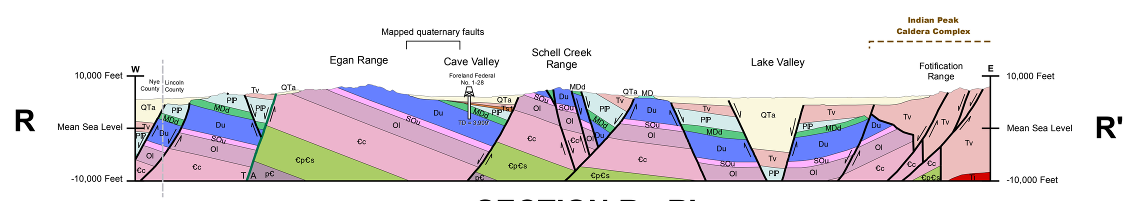

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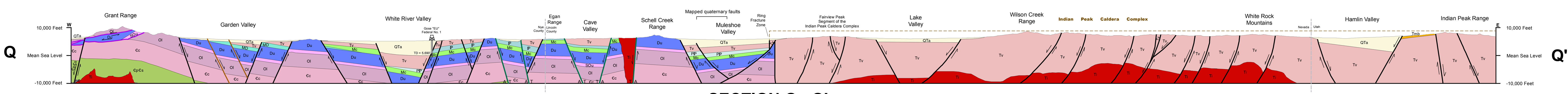

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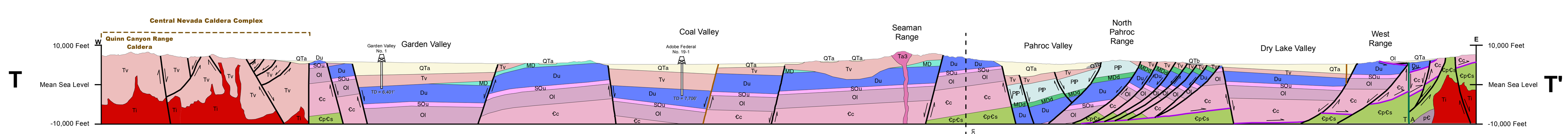
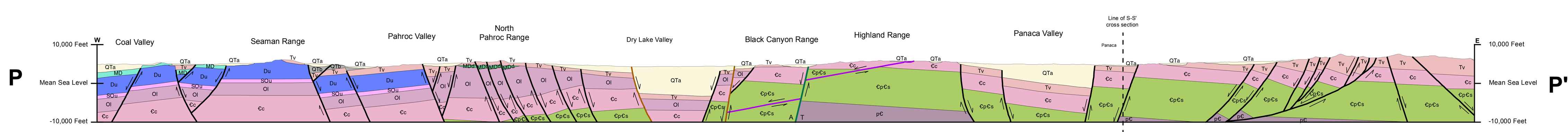
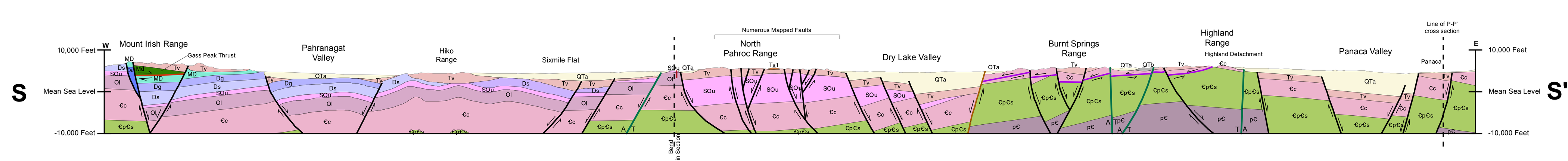


SECTION T - T'



SECTION P - P'



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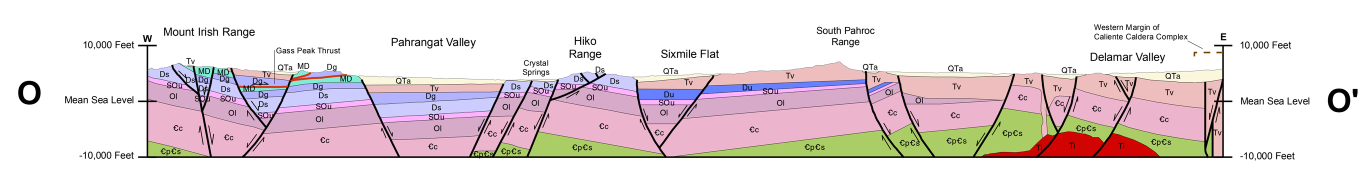

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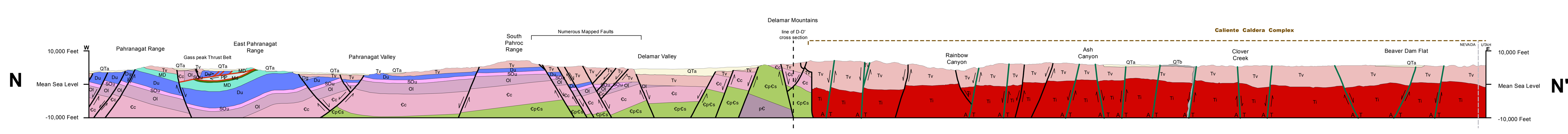

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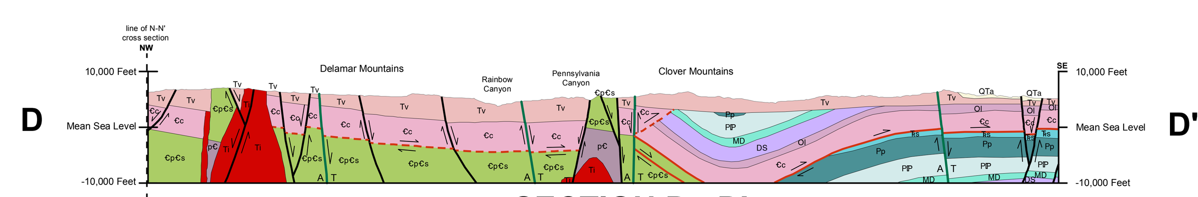

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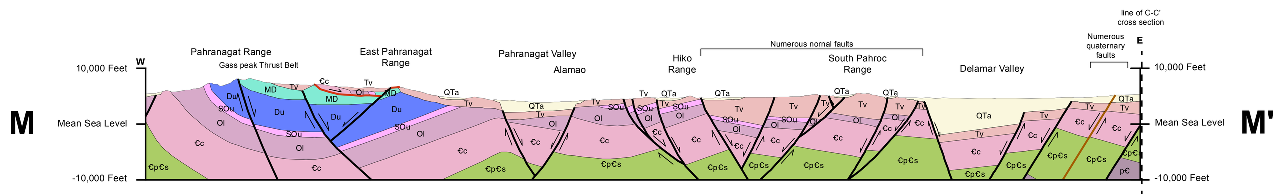

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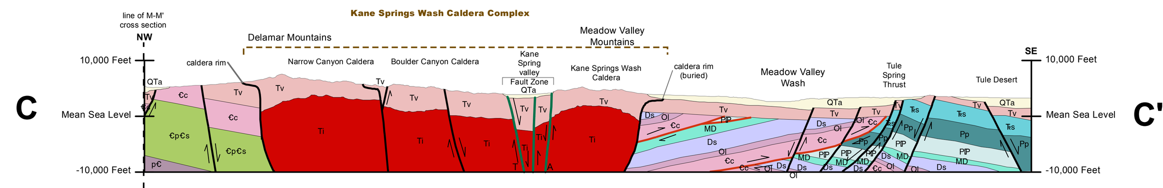


SECTION C - C'

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
Ta3	Tertiary andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia
Ts1	Tertiary fluvial and lacustrine sediments
Tmb	Tertiary intracaldera megabreccia
Ti	Tertiary intrusive rocks
TKi	Tertiary-Cretaceous intrusive rocks
Ki	Cretaceous intrusive rocks
Ks	Upper and Lower Cretaceous sedimentary rocks, undivided
Ji	Jurassic intrusive rocks
Js	Jurassic sedimentary rocks, undivided
Ts	Triassic sedimentary rocks, undivided
Pzu	Paleozoic Rocks, Undifferentiated
Pp	Upper and Lower Permian Park City Group, undivided
Par	Permian Arcturus Formation and Rib Hill Sandstone
Pa	Permian Arcturus Formation
Pr	Lower Permian Rib Hill Sandstone
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
DS	Devonian and Silurian sedimentary rocks, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Dd	Upper and Middle Devonian Devils Gate Formation
Dg	Upper and Middle Devonian Guilmette Formation
Dn	Middle and Lower Devonian Nevada Formation
Ds	Middle and Lower Devonian Simonson and Sevy Dolomites
SOu	Silurian and Upper Ordovician dolomite, undivided
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
Cc	Cambrian carbonate sedimentary rocks, undivided
Cu	Lower Ordovician? And Upper Cambrian limestone and shale, undivided
Cm	Upper and Middle Cambrian limestone and shale
CpCs	Middle Cambrian to Late Proterozoic sedimentary rocks
pC	Late to Early Proterozoic metamorphosed and crystalline Precambrian basement rocks

Geologic Structure

Normal Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Strike-slip Fault
T
A
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement. T= Towards, A = Away.

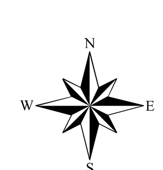
Thrust Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Detachment Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Quaternary Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Well Name
TD=1,234'

Oil Well Data Used in Cross Sections
TD = Total Depth (Feet)



SCALE 1:250,000

Projection: UTM Zone 11 NAD83

0 25,000 50,000 75,000 100,000 Feet

0 7,000 14,000 21,000 28,000 35,000 Meters

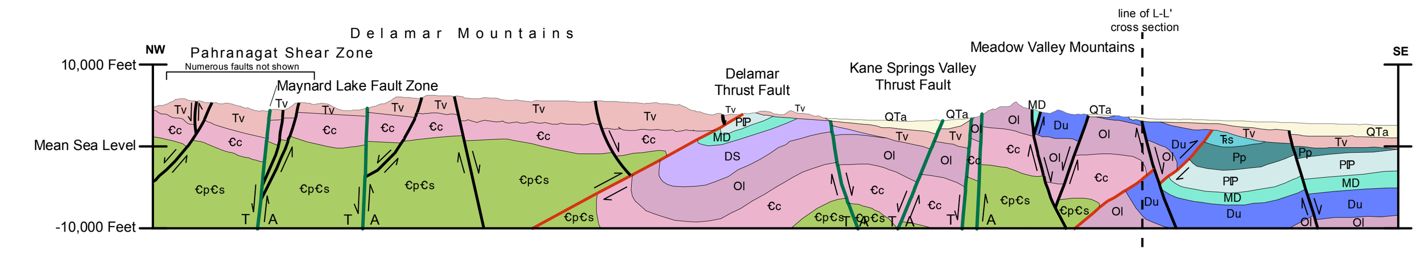
0 5 10 15 20 25 Miles

PLATE 4. CROSS SECTIONS SHOWING GEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

SOUTHERN NEVADA WATER AUTHORITY
MAP ID 18433-3211 05/25/2011 JAB/BP

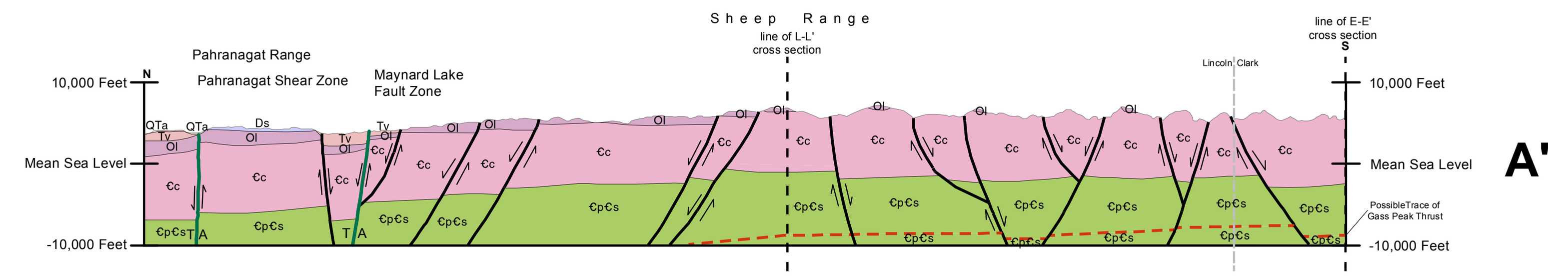
Explanation of Geologic Units
Shown on Cross Section

QTa	Quaternary and Tertiary basin-fill deposits
Tv	Tertiary volcanic ash-flows, flows and ash-fall tuffs
Ts4	Tertiary fluvial and lacustrine sediments
Tmb	Tertiary megabreccia
Ti	Tertiary intrusive rocks
Ks	Upper and Lower Cretaceous sedimentary rocks, undivided
Js	Jurassic sedimentary rocks, undivided
T̶s	Triassic sedimentary rocks, undivided
Pp	Upper and Lower Permian Park City Group, undivided
PP̶	Permian and Pennsylvanian Riepe Spring Limestone and Ely Limestone, undivided
MD	Lower Mississippian to Upper Devonian Joana Limestone and Pilot Shale, undivided
D€	Devonian to Upper Cambrian sedimentary rocks, undivided
DS	Devonian and Silurian sedimentary rocks, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Ds	Middle and Lower Devonian Simonson and Sevy Dolomites
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
€c	Cambrian carbonate sedimentary rocks, undivided
€p€s	Middle Cambrian to Late Proterozoic sedimentary rocks
p€	Late to Early Proterozoic metamorphosed and crystalline Precambrian basement rocks



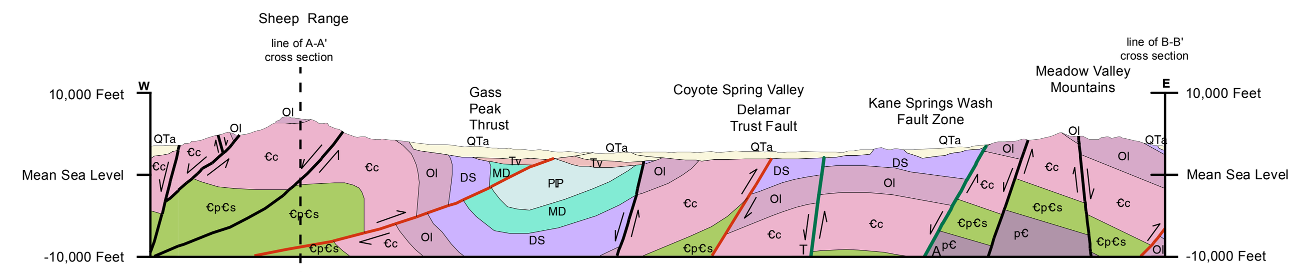
B B'

SECTION B - B'



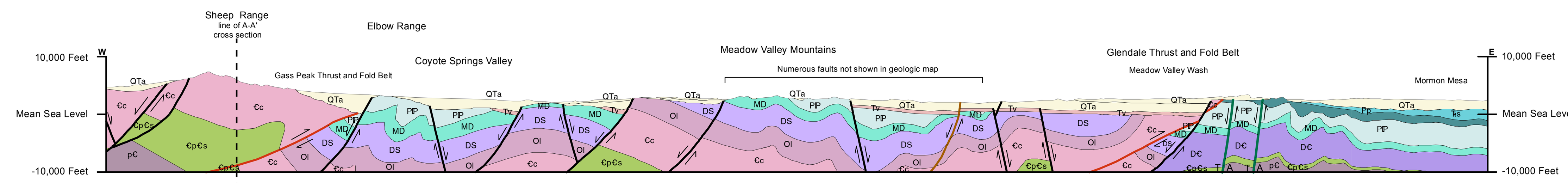
A A'

SECTION A - A'



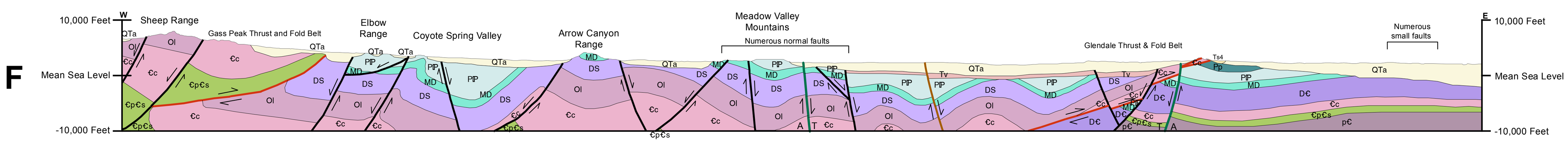
L L'

SECTION L - L'



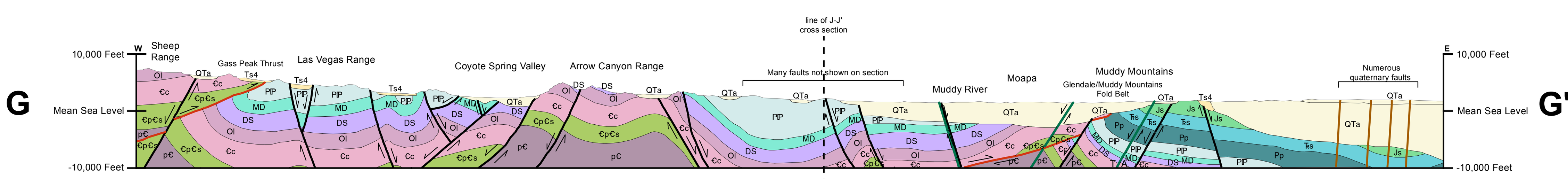
E E'

SECTION E - E'



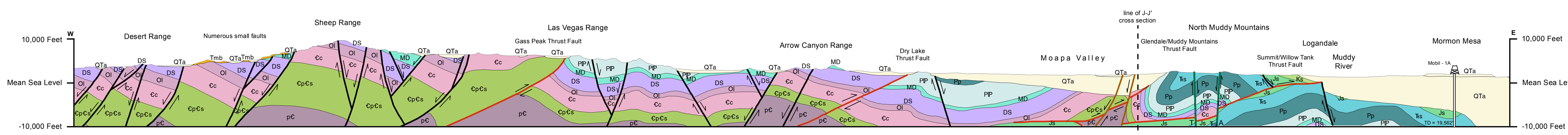
F F'

SECTION F - F'



G G'

SECTION G - G'



H H'

SECTION H - H'

Geologic Structure

Normal Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement.

Strike-slip Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement. T= Towards, A = Away.

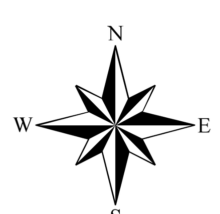
Thrust Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement.

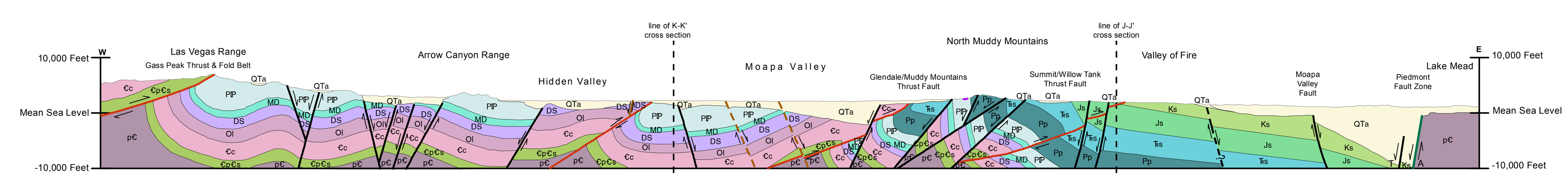
Detachment Fault
Solid where known; Dashed where inferred; dotted where concealed.

Quaternary Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement.

Well Name
TD=1,234'

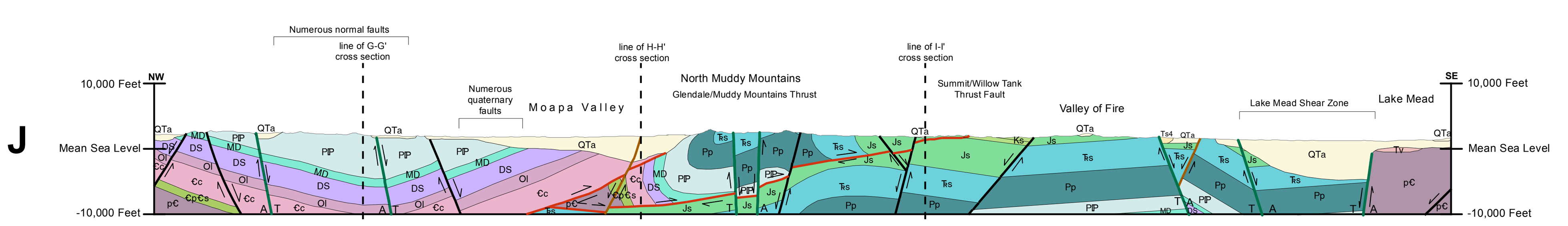
Oil Well Data Used in Cross Sections
TD = Total Depth (Feet)





I I'

SECTION I - I'



J J'

SECTION J - J'

SCALE 1:250,000

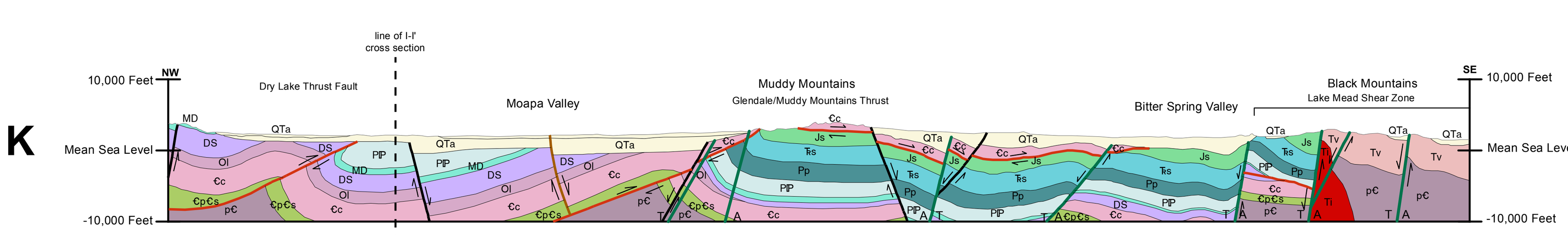
Projection: UTM Zone 11 NAD83

NO VERTICAL EXAGGERATION

0 25,000 50,000 75,000 Feet

0 5,000 10,000 15,000 20,000 25,000 Meters

0 5 10 15 20 Miles



K K'

SECTION K - K'

SOUTHERN NEVADA WATER AUTHORITY

PLATE 5. CROSS SECTIONS SHOWING GEOLOGY OF SOUTHERN LINCOLN AND NORTHERN CLARK COUNTIES, NEVADA

MAP ID 18434-3211 05/17/2011 BP

PLATE 6. HYDROGEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

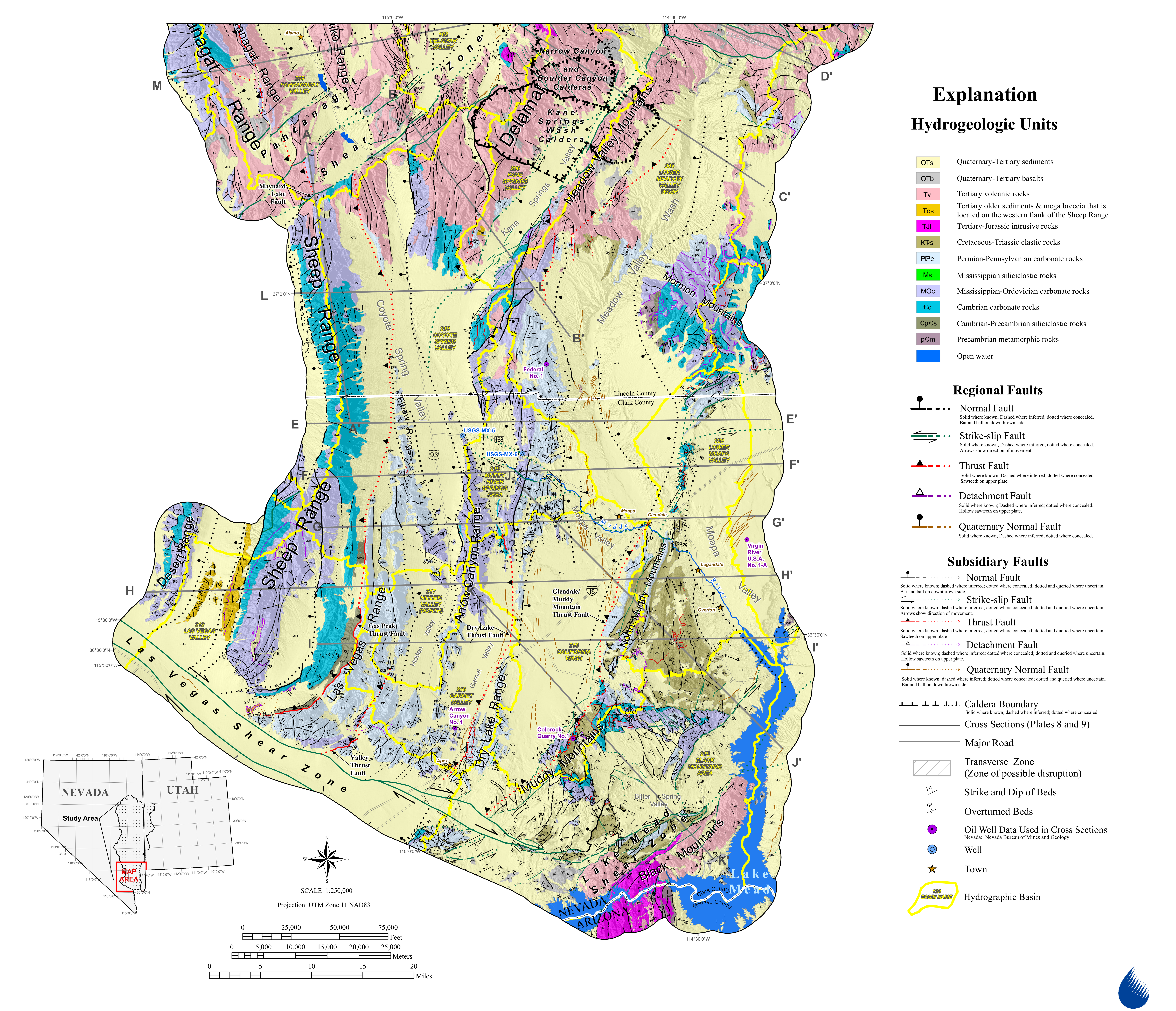
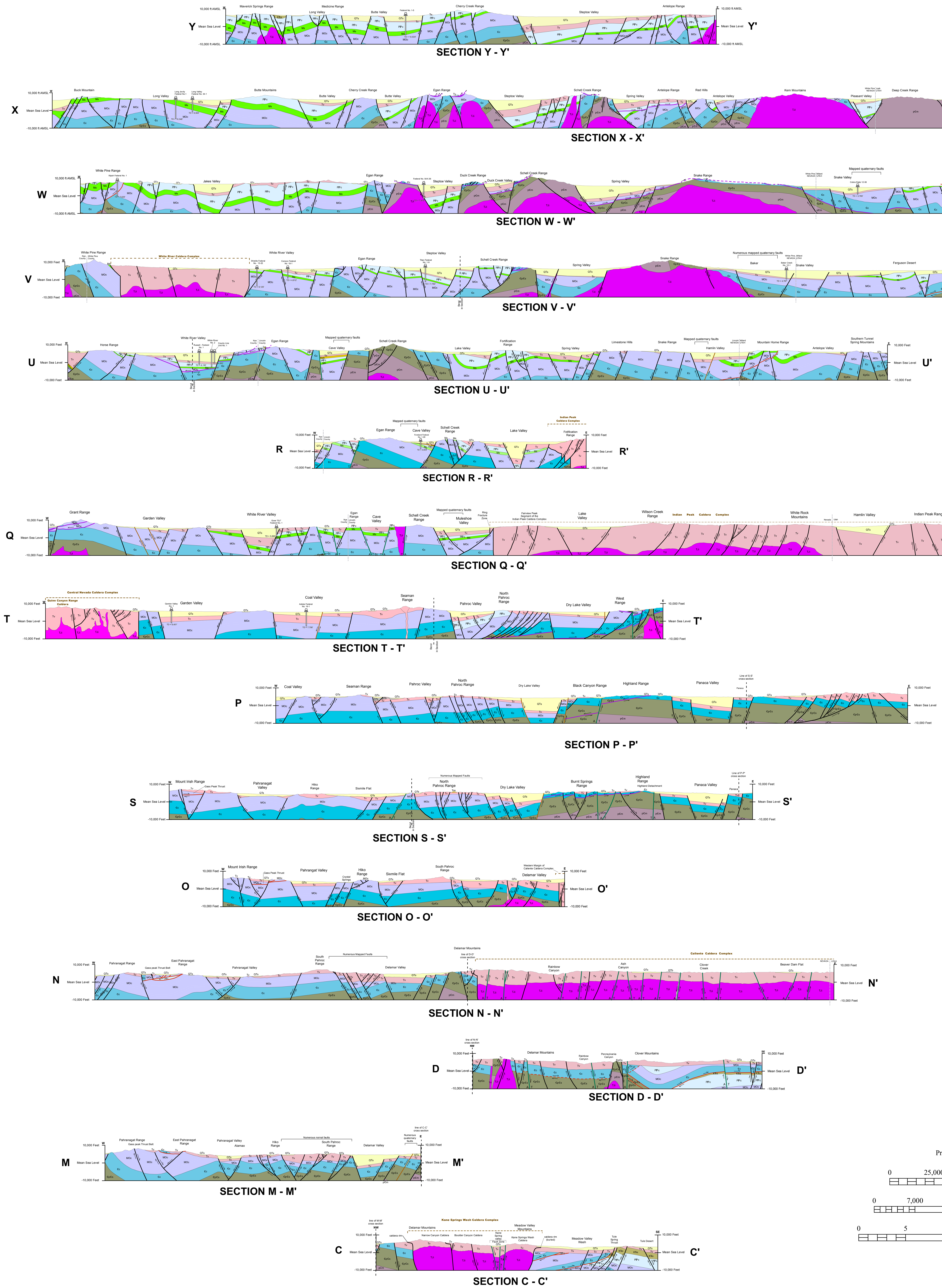


PLATE 7. HYDROGEOLOGY OF SOUTHERN LINCOLN AND NORTHERN CLARK COUNTIES, NEVADA, AND ADJACENT AREAS, ARIZONA

MAP ID 18292-3211 05/17/2011 BP



Explanation of Hydrogeologic Units

Shown on Cross Section

QTs	Quaternary-Tertiary sediments
QTb	Quaternary-Tertiary basalts
Tv	Tertiary volcanic rocks
Tos	Tertiary older sediments
TJi	Tertiary-Jurassic intrusive rocks
KTls	Cretaceous-Triassic clastic rocks
PlPc	Permian-Pennsylvanian carbonate rocks
Ms	Mississippian siliciclastic rocks
MOc	Mississippian-Ordovician carbonate rocks
Cc	Cambrian carbonate rocks
CpCs	Cambrian-Precambrian siliciclastic rocks
pCm	Precambrian metamorphic rocks

Geologic Structure

Normal Fault
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Strike-slip Fault
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Thrust Fault
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Detachment Fault
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Quaternary Fault
Solid where known; Dashed where inferred; dotted where concealed. Arrows show direction of movement.

Well Name
TD=1,234'

Oil Well Data Used in Cross Sections
TD = Total Depth (Feet)

SCALE 1:250,000

Projection: UTM Zone 11 NAD83

0 25,000 50,000 75,000 100,000 Feet

0 7,000 14,000 21,000 28,000 35,000 Meters

0 5 10 15 20 25 Miles

SOUTHERN NEVADA WATER AUTHORITY

PLATE 8. CROSS SECTIONS SHOWING HYDROGEOLOGY OF WHITE PINE AND NORTHERN LINCOLN COUNTIES, NEVADA, AND ADJACENT AREAS, NEVADA AND UTAH

MAP ID 18435-3211 05/17/2011 BP

Explanation of Hydrogeologic Units
Shown on Cross Section

QTs	Quaternary-Tertiary sediments
Tv	Tertiary volcanic rocks
TJi	Tertiary-Jurassic intrusive rocks
KTRs	Cretaceous-Triassic clastic rocks
PIPc	Permian-Pennsylvanian carbonate rocks
MOc	Mississippian-Ordovician carbonate rocks
Ꞓc	Cambrian carbonate rocks
ꞒpꞒs	Cambrian-Precambrian siliciclastic rocks
pꞒm	Precambrian metamorphic rocks

Geologic Structure

Normal Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement.

Strike-slip Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement. T= Towards, A = Away.

Thrust Fault
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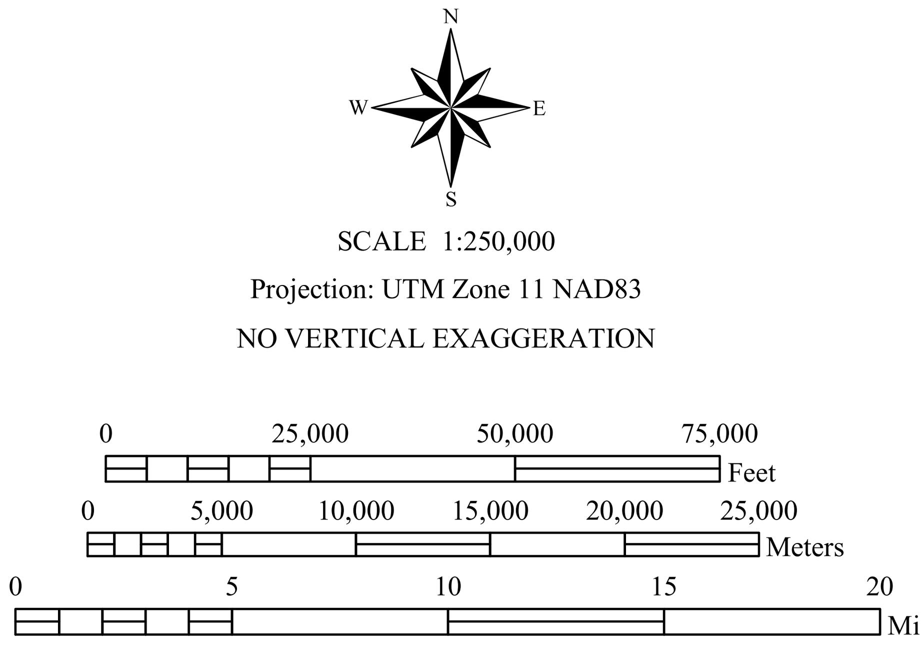
Arrows show direction of movement.

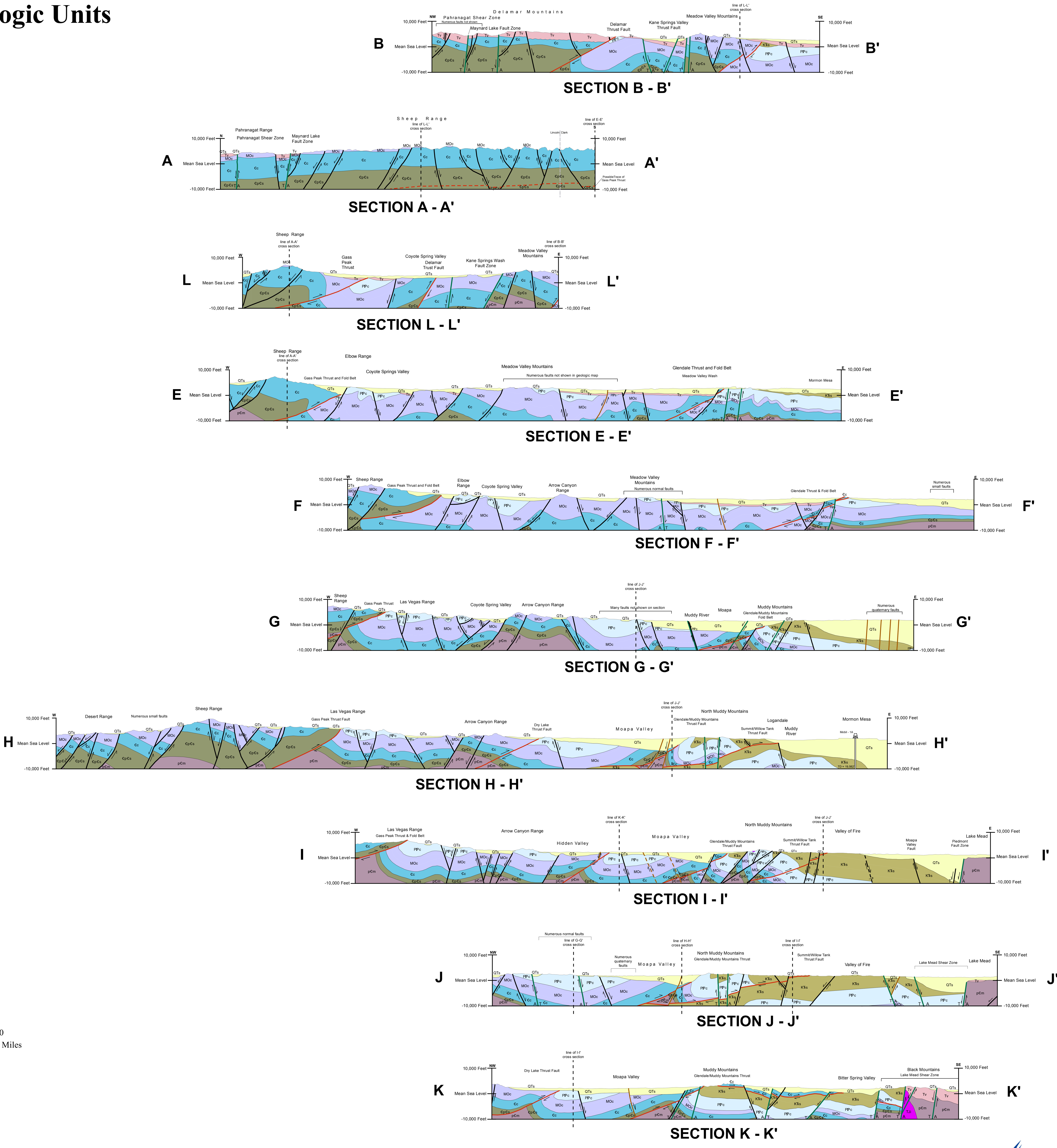
Detachment Fault
Solid where known; Dashed where inferred; dotted where concealed.

Quaternary Fault
Solid where known; Dashed where inferred; dotted where concealed.
Arrows show direction of movement.

Well Name
TD=1,234'
Oil Well Data Used in Cross Sections
TD = Total Depth (Feet)



SCALE 1:250,000
Projection: UTM Zone 11 NAD83
NO VERTICAL EXAGGERATION



SOUTHERN NEVADA WATER AUTHORITY

PLATE 9. CROSS SECTIONS SHOWING HYDROGEOLOGY OF SOUTHERN LINCOLN AND NORTHERN CLARK COUNTIES, NEVADA

MAP ID 18436-3211 05/17/2011 BP