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Southern Nevada Water Authority

Geology of White Pine and Lincoln Counties and Adjacent Areas, Nevada and Utah: The Geologic Framework of Regional Groundwater Flow Systems



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Geology of White Pine Counties and Adjacent Areas, Nevada and Utah: The Geologic Framework of Regional Groundwater Flow Systems

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CONTENTS

List of Figures v
List of Plates vii
List of Tables ix
Acknowledgements xi
List of Acronyms and Abbreviations xiii

1.0 Introduction 1-1
1.1 Project Background 1-1
1.2 Purpose and Scope of Geologic Investigation 1-1
1.3 Document Organization 1-3

2.0 Description of Geologic Study Area 2-1
2.1 Geologic Study Area 2-1
2.2 Physiographic Setting and Background 2-3

3.0 Methodology 3-1
3.1 Objectives 3-1
3.2 Technical Approach 3-2
3.3 Geologic Data Compilation 3-2
3.4 Preparation of Geologic Maps and Cross Sections 3-3

4.0 Conceptual Geologic Model 4-1
4.1 Geology and Stratigraphy 4-1
4.1.1 Overview 4-1
4.1.2 Proterozoic Rocks 4-8
4.1.3 Paleozoic Rocks 4-8
4.1.3.1 Cambrian Rocks 4-8
4.1.3.2 Ordovician to Devonian Rocks 4-9
4.1.3.3 Mississippian to Lower Permian Rocks 4-11
4.1.3.4 Park City Group 4-13
4.1.4 Mesozoic Rocks 4-13
4.1.5 Cenozoic Rocks 4-14
4.1.5.1 Upper Cretaceous(?) to Miocene Sedimentary Rocks 4-15
4.1.5.2 Tertiary Volcanic Rocks 4-15
4.1.5.3 Miocene to Holocene Sediments 4-18
4.2 Hydrogeologic Units 4-18
4.2.1 Precambrian Metamorphic Rocks 4-20
4.2.2 Cambrian to Precambrian Siliciclastic Rocks 4-20
4.2.3 Cambrian Carbonate Rocks 4-20
4.2.4 Mississippian to Ordovician Carbonate Rocks 4-21
4.2.5 Mississippian Siliciclastic Rocks 4-21
4.2.6 Permian and Pennsylvanian Carbonate Rocks 4-21
4.2.7 Cretaceous to Triassic Siliciclastic Rocks 4-22

CONTENTS (CONTINUED)

4.2.8 Tertiary to Jurassic Intrusive Rocks 4-22
4.2.9 Older Tertiary Sediments 4-22
4.2.10 Tertiary Volcanic Rocks 4-22
4.2.11 Quaternary and Tertiary Basalt 4-23
4.2.12 Quaternary and Tertiary Sediments 4-23
4.3 Structural Geology 4-23
4.3.1 Evolution of the Regional Structure 4-23
4.3.2 Effect of Structures on Groundwater Flow 4-27
4.3.2.1 The Antler Deformation 4-27
4.3.2.2 The Sevier Deformation 4-27
4.3.2.3 The Eocene-Miocene Episode of Calc-Alkaline Volcanism 4-29
4.3.2.4 The Miocene-Quaternary Basin-Range Episode of Extension 4-29
4.4 Descriptions of Basins and Ranges and Potential for Interbasin Groundwater Flow 4-31
4.4.1 Basins and Ranges along and within the White River Flow System 4-33
4.4.1.1 Ruby Mountains, Bald Mountain, and Buck Mountain . . . 4-33
4.4.1.2 Maverick Springs Range 4-33
4.4.1.3 Butte Mountains and White Pine Range 4-34
4.4.1.4 Horse, Grant, and Quinn Canyon Ranges 4-35
4.4.1.5 Worthington Mountains and Timpahute Range 4-36
4.4.1.6 Golden Gate Range, Mount Irish, Pahranagat Range, and Northern Sheep Range 4-37
4.4.1.7 Southern Sheep Range, Las Vegas Range, and Elbow Range 4-38
4.4.1.8 Cherry Creek Range 4-38
4.4.1.9 Northern Egan Range 4-39
4.4.1.10 Southern Egan Range 4-40
4.4.1.11 Seaman Range 4-40
4.4.1.12 North Pahroc, South Pahroc, and Hiko Ranges 4-41
4.4.1.13 Schell Creek Range 4-42
4.4.1.14 Fairview, Bristol, West, Ely Springs, Highland, Black Canyon, Burnt Spring, and Chief Ranges, and Pioche Hills 4-43
4.4.1.15 Delamar Mountains 4-44
4.4.1.16 Meadow Valley Mountains 4-45
4.4.1.17 Arrow Canyon Range 4-45
4.4.1.18 Fortification Range, Wilson Creek Range, and White Rock Mountains 4-46
4.4.1.19 Clover Mountains and Bull Valley Mountains 4-47
4.4.1.20 Mormon Mountains 4-47

CONTENTS (CONTINUED)

4.4.1.21 North Muddy Mountains, Muddy Mountains, and Dry Lake Range 4-48
4.4.2 Basins and Ranges West and East of the White River Flow System 4-49
4.4.2.1 Antelope Range, White Pine County 4-49
4.4.2.2 Kern Mountains and Adjacent Small Ranges 4-50
4.4.2.3 Deep Creek Range, Utah 4-50
4.4.2.4 Snake Range and Limestone Hills 4-51
4.4.2.5 Confusion Range, Conger Range, Burbank Hills, and Tunnel Spring Mountains 4-52
4.4.2.6 Needle Range and Wah Wah Mountains 4-53
4.4.2.7 Fish Springs and House Ranges 4-54

5.0 Geophysics 5-1
5.1 Gravity 5-1
5.1.1 Gravity Data for Spring and Snake Valleys 5-2
5.1.2 Gravity Data for Cave, Dry Lake, and Delamar Valleys 5-2
5.1.3 Gravity Data for Coyote Spring Valley 5-9
5.2 Audiomagnetotellurics Studies 5-9
5.3 Seismic Studies 5-16

6.0 Summary 6-1
6.1 General Geology of the Study Area 6-1
6.2 General Hydrogeology of the Study Area 6-2

7.0 References 7-1

Appendix A - General Photos of the Study Area

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FIGURES

NUMBER	TITLE	PAGE
1-1	Location of Project Basins	1-2
2-1	Hydrographic Basins, Ranges, and Flow Systems within the Geologic Study Area	2-2
2-2	Map of Pliocene and Pleistocene Lakes and Streams in Lincoln County and Adjacent Areas, Nevada	2-4
3-1	Index Map of Previous Small-Scale Mapping Used in the Geologic Evaluations and to Create the Geologic and Hydrogeologic Maps of Plates 1, 2, 6, and 7	3-4
4-1	Geologic Time Scale, Including Rock Type and Tectonic Events	4-2
4-2	Geologic Units of Lincoln County, Nevada	4-4
4-3	Geologic Units of White Pine County, Nevada	4-5
4-4	Geologic Units of Western Utah	4-6
4-5	Geologic Units of Clark County, Nevada	4-7
4-6	Schematic Diagram of Sevier Thrust Sheets, Illustrating the Movement of Paleozoic Carbonates over Cratonic Sediments	4-25
4-7	Paleozoic Carbonates Thrust over Jurassic Aztec Sandstone in the Muddy Mountains near Muddy Peak	4-26
4-8	One Scenario for Development of the Snake Range Decollement during Late Cenozoic Extension	4-28
4-9	Diagrammatic Map Showing Enhancement or Impedance of Groundwater Flow along or across Faults, Transverse Zones, and Calderas	4-30
4-10	Potential for Interbasin Groundwater Flow within the Geological Study Area	4-32
5-1	Previously Available Gravity Stations (Green Dots) and Gravity Stations Established During the 2004/2005 Field Seasons (Red Dots) in Spring and Snake Valleys, Nevada and Utah	5-3
5-2	Index Map to the Spring Valley, Nevada, Study Area	5-4
5-3	Isostatic Residual Gravity Field	5-5
5-4	Depth to Pre-Cenozoic Basement in the Spring Valley Study Area	5-6

FIGURES (CONTINUED)

NUMBER	TITLE	PAGE
5-5	Index Map, Showing Gravity Stations, of Cave, Dry Lake, and Delamar Valleys within the Geologic Study Area	5-7
5-6	Cave, Dry Lake, and Delamar Valley Basin Gravity Anomalies Derived from Depth-to-Basement Algorithm	5-8
5-7	Index Map Showing Coyote Spring Valley Study Area and Vicinity	5-10
5-8	Isostatic Residual Gravity Contours for Coyote Spring Valley and Vicinity	5-11
5-9	Basin Thickness Map of the Study Area	5-12
5-10	Locations of AMT Profiles (Red) and ECN-01 Seismic Line (Blue) Performed in the Geologic Study Area	5-13
5-11	AMT Model along Profile A across Southern Spring Valley, Nevada	5-14
5-12	AMT Model along Profile B across Southern Spring Valley, Nevada	5-14
5-13	AMT Model along Profile E across Central Cave Valley, Nevada	5-15
5-14	(a) ECN-01 Seismic Reflection Section Displayed in Time (b) Results of Gravity Depth-to-Basement	5-17

PLATES

NUMBER	TITLE
1	Geology of White Pine and Northern Lincoln Counties, Nevada and Adjacent Areas, Nevada and Utah . . . . . Pocket
2	Geology of Southern Lincoln and Northern Clark Counties, Nevada, and Adjacent Areas, Arizona . . . . . Pocket
3	Explanation of the Geologic Units for the Maps and Cross Sections of Plates 1, 2, 4, and 5 . . . . . Pocket
4	Cross Sections Showing Geology of White Pine and Northern Lincoln Counties, Nevada and Adjacent Areas, Nevada and Utah . . . . . Pocket
5	Cross Sections Showing Geology of Southern Lincoln and Northern Clark Counties, Nevada . . . . . Pocket
6	Hydrogeology of White Pine and Northern Lincoln Counties, Nevada and Adjacent Areas, Nevada and Utah . . . . . Pocket
7	Hydrogeology of Southern Lincoln and Northern Clark Counties, Nevada and Adjacent Areas, Arizona . . . . . Pocket
8	Cross Sections Showing Hydrogeology of White Pine and Northern Lincoln Counties, Nevada and Adjacent Areas, Nevada and Utah . . . . . Pocket
9	Cross Sections Showing Hydrogeology of Southern Lincoln and Northern Clark Counties, Nevada . . . . . Pocket

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TABLES

NUMBER	TITLE	PAGE
4-1	Brief Summary of Hydrogeologic Units	4-19

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ACRONYMS

AMT	audiomagnetotelluric
BLM	U.S. Bureau of Land Management
DVFS	Death Valley Flow System
GSLDFS	Great Salt Lake Desert Flow System
GVFS	Goshute Valley Flow System
HGU	hydrogeologic unit
MVFS	Meadow Valley Flow System
SNWA	Southern Nevada Water Authority
USGS	U.S. Geological Survey
WRFS	White River Flow System

ABBREVIATIONS

afy	acre-feet per year
ft	foot
Ga	billion years
km	kilometer
m	meter
Ma	million years
mg	milligram
mGal	milliGal
mi	mile

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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 is a description of the geologic and hydrogeologic data compilation, map and cross section development, and hydrogeologic framework completed in support of the Southern Nevada Water Authority's (SNWA) Clark, Lincoln, and White Pine Counties Groundwater Development Project. This report and related work products were used in developing hydrogeologic conceptual models and a three-dimensional regional groundwater flow model for selected basins of eastern Nevada and western Utah.

1.1 PROJECT BACKGROUND

The Clark, Lincoln, and White Pine Counties Groundwater Development Project (hereafter referred to as the Project) proposes to develop unused groundwater resources within selected basins of eastern Nevada where SNWA holds groundwater rights and applications. These basins include Coyote Spring, Cave, Dry Lake, Delamar, Spring, and Snake valleys (hereafter referred to as the Project Basins), and are depicted in Figure 1-1.

In 2004, SNWA applied to the Bureau of Land Management (BLM) for issuance of rights of way to construct Project facilities, most of which will be located on public lands administered by the BLM. These facilities include groundwater production wells, water conveyance facilities, water storage and regulating reservoirs, and power facilities. BLM issuance of these rights of way to construct, maintain, and operate these facilities requires a federal action for which the National Environmental Policy Act and Endangered Species Act must be considered. BLM has determined that preparation of an Environmental Impact Statement is required to assess the potential environmental effects that may result from permitting the rights of way, including the potential indirect effects of the proposed groundwater development. This report was prepared in support of that assessment.

1.2 PURPOSE AND SCOPE OF GEOLOGIC INVESTIGATION

The purposes of this report 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 potential continuity of groundwater flow.

The scope of this geologic investigation included significant data compilation and acquisition, and development of geologic and hbydrogeologic 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 conducted to improve the geologic understanding of selected areas. The scope of work was defined, in part, to differentiate between aquifers and aquitards, that is, hydrogeologic units (HGUs) with high and low hydraulic conductivity, respectively. The geologic investigation also focused on identifying areas where aquitards of sufficient thickness are present and inhibit groundwater flow.

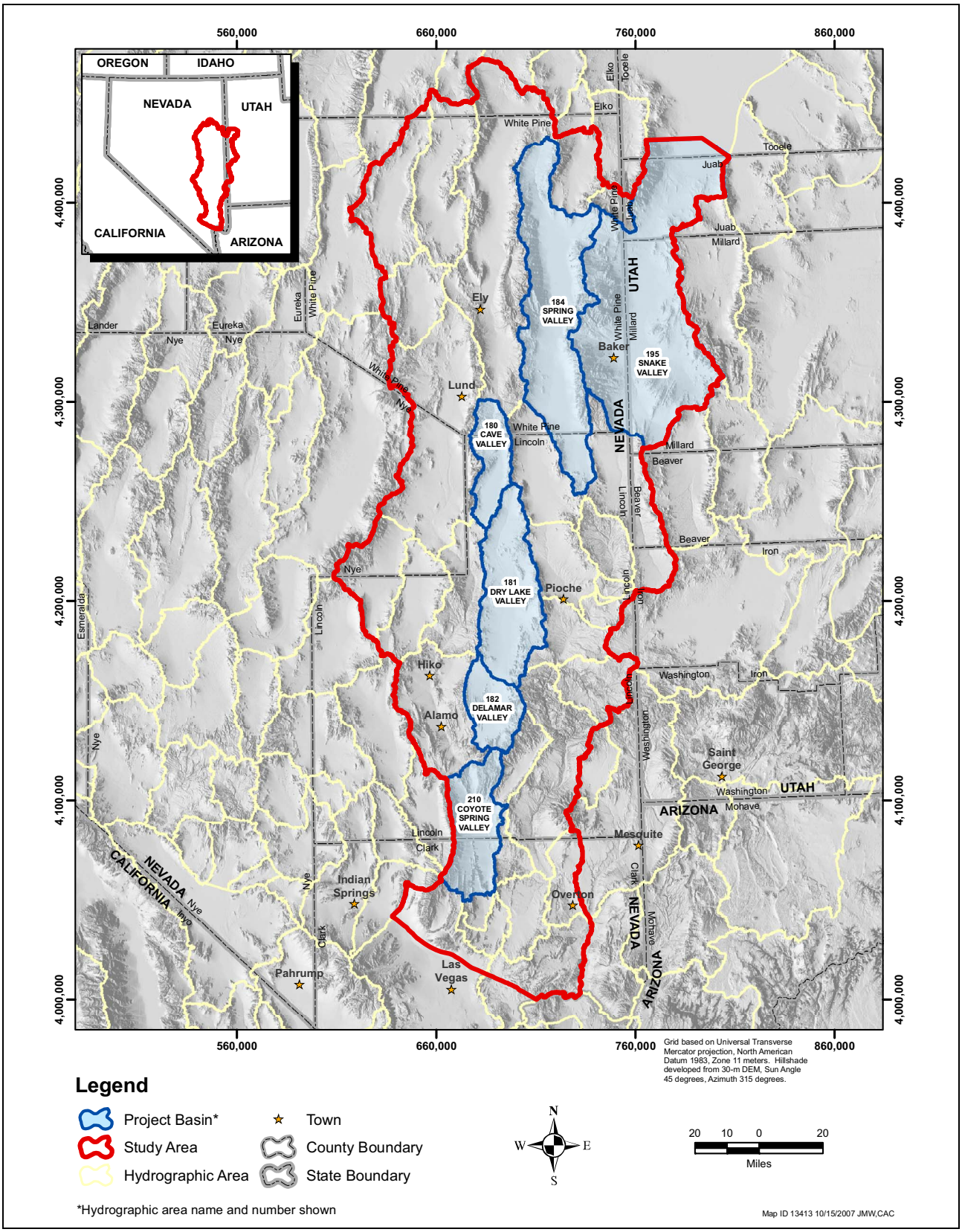


Figure 1-1
Location of Project Basins

1.3 DOCUMENT ORGANIZATION

This document consists of the following seven sections and Appendix A showing general photos of the study area.

- 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 describes the geologic study area and physiographic setting of the area, including a discussion on the regional geologic features and regional flow systems.

- 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. Section 4.0 is divided into subsections describing the various aspects of the geology and hydrogeology, as follows:

  - Section 4.1 discusses the geology and stratigraphy of the geologic study area of this report, including 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 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 is a summary of the general geology and general hydrogeology of the geologic study area.

- Section 7.0 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

DESCRIPTION OF GEOLOGIC STUDY AREA

The area of study for the geologic investigation encompasses the Project Basins and additional basins that comprise regional groundwater flow systems in which the Project Basins reside. The physiographic setting of the geologic study area is presented, followed by summary descriptions of the regional groundwater flow systems comprising the geologic study area.

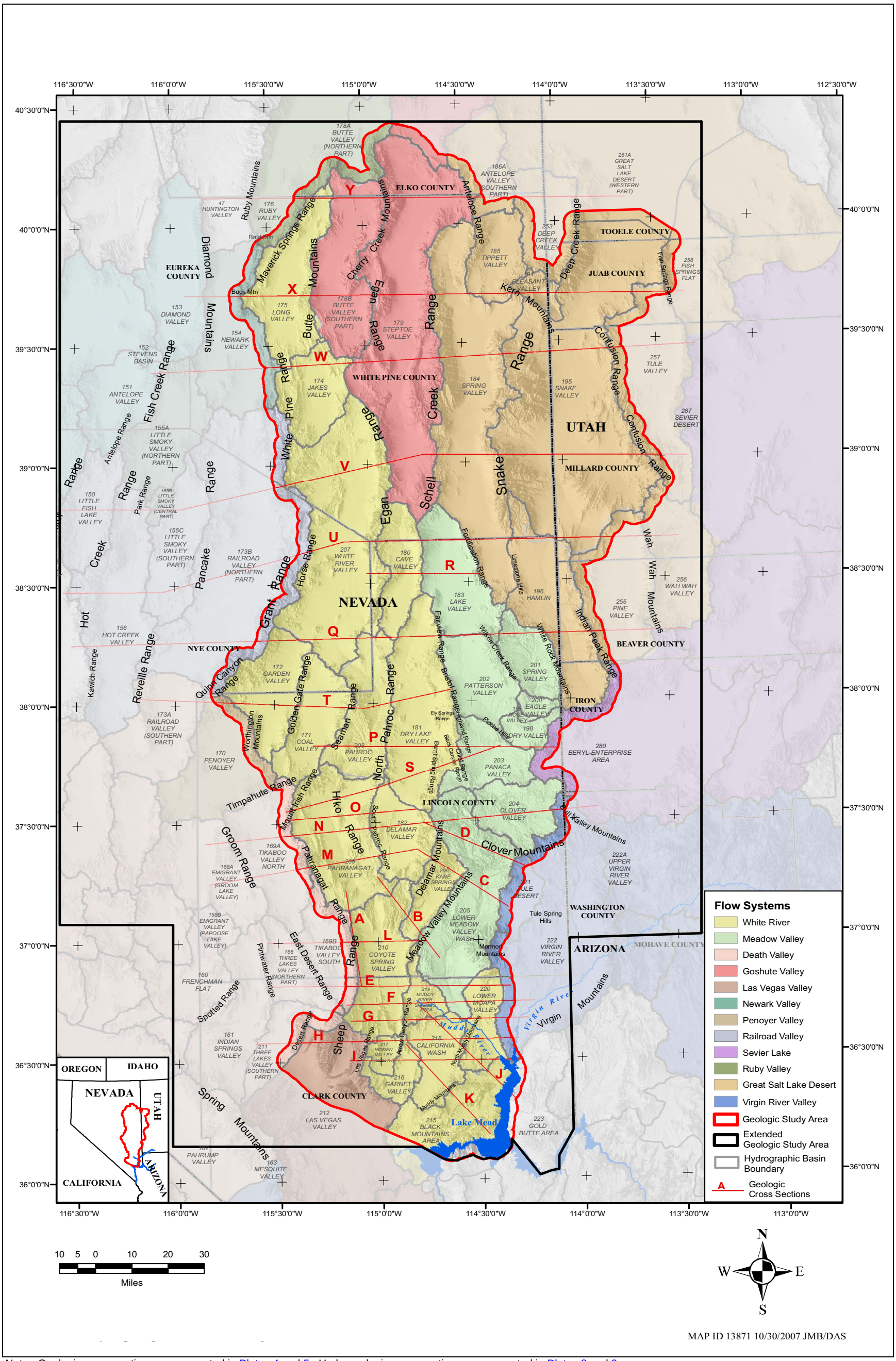
2.1 GEOLOGIC STUDY AREA

The area covered by this geologic investigation, hereafter referred to as the geologic study area, includes all hydrographic areas within the White River Flow System (WRFS). The geologic study area also includes adjacent basins that may be in hydraulic connection with basins within the WRFS. The geologic study area is delineated by a thick red line on Figure 2-1. The purpose of including such a large area is to allow investigation of the potential hydraulic continuity or discontinuity between these basins due to geologic influences. In addition, geology of the same scale was compiled, and cross sections extended, over an even larger area whose boundary is identified by a thick black line seen outside the boundary of the geologic study area (Figure 2-1). This was done to assess the broader geologic framework in order to determine the best model area and to provide additional data should the boundaries of the model area later change.

More specifically, the geologic study area includes all of the basins in Lincoln and White Pine counties, Nevada, except for certain basins in southwestern and southeastern Lincoln County and along the northern edge of White Pine County. Several basins in adjacent counties are included, such as basins overlapping into Elko County, basins in Eureka, northern Nye, and northern Clark counties, Nevada, and basins in the western areas of Juab, Millard, Beaver, and Iron counties, Utah. These basins are also delineated on Figure 2-1.

The groundwater flow systems incorporated in this evaluation are delineated on Figure 2-1. These systems include all of the WRFS, which covers much of eastern Nevada from just beyond the Elko/White Pine county line to Lake Mead. The WRFS (Eakin, 1966), as used here, was called the Colorado Flow System by Harrill and Prudic (1998; see also Belcher, 2004). The Meadow Valley Flow System (MVFS) subset of the Colorado Flow System is included. This flow system originates north of Pioche at the Lincoln/White Pine county border, in Nevada, and extends to Moapa in northern Clark County, Nevada, where it joins the WRFS. A portion of the Great Salt Lake Desert Flow System (GSLDFS) is covered in this investigation. This flow system originates in the Snake Range of eastern Nevada and surrounding basins, extending eastward into Utah and then northward to the Great Salt Lake Desert.

Other flow systems in the geologic study area are the southern Goshute Valley Flow System (GVFS) of White Pine and Elko counties, Nevada; the eastern edges of the Ruby Valley, Newark Valley, and Railroad Valley flow systems of western White Pine, Eureka, and northern Nye counties, Nevada; the eastern edge of the Penoyer Valley area of Lincoln and Nye counties, Nevada; the northeastern portion of the Death Valley Flow System (DVFS) in Lincoln and Nye counties, Nevada; the northeastern part of the Las Vegas Valley of the Colorado Flow System; the western edge of the Virgin River Flow System of the Mesquite, Nevada, area; and the western edge of the Sevier Lake



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 FLOW SYSTEMS WITHIN THE GEOLOGIC STUDY AREA

Flow System of western Utah. These flow systems are defined by Eakin (1966), Harrill et al. (1988), and Harrill and Prudic (1998).

2.2 PHYSIOGRAPHIC SETTING AND BACKGROUND

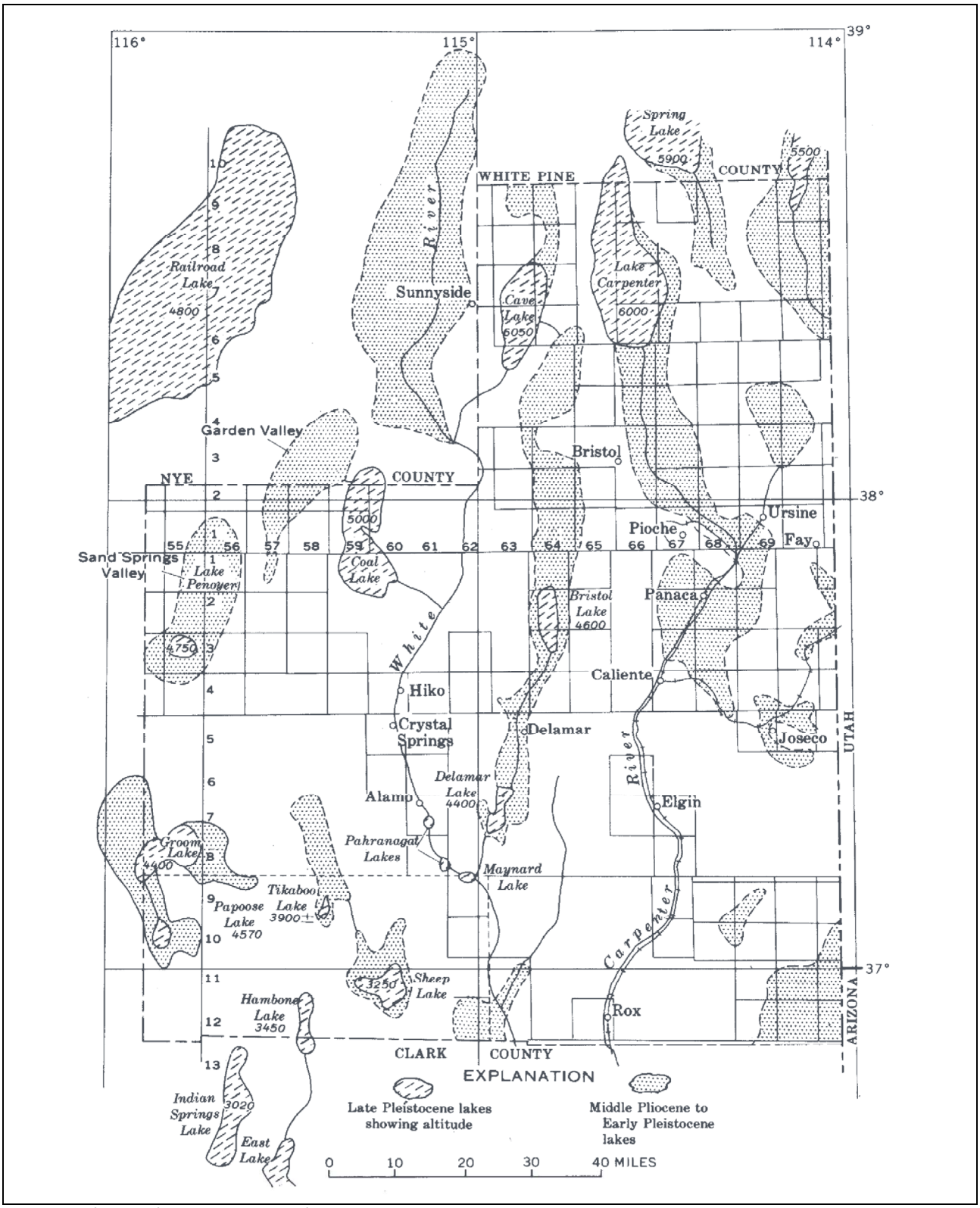
The geologic study area (Figure 2-1) is within the Great Basin physiographic province, characterized by north-trending basins and ranges that are formed by generally north-striking basin-range normal faults. The area has been subjected to several periods of deformation since Precambrian time. The most recent episode of deformation, which produced the present topography, is the basin-range episode of normal faulting. This 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 within that region. Exceptions occur only along the Great Basin boundary along the Colorado River, 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 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 descendant drainages of the White River are intermittent.

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 in the defined regional groundwater flow systems (Figure 2-1). These systems may include a dozen or more closed or integrated topographic basins that are interconnected in the subsurface. These regional flow systems are defined by evidence that their groundwater flow paths pass beneath topographic divides and continue beneath adjacent basins and ranges (Eakin, 1966; Winograd and Thordarson, 1975; Harrill et al., 1988; Harrill and Prudic, 1998).

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 aquitards 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.

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



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

3.0

METHODOLOGY

The objectives of the geologic analysis and the methods applied in developing the work 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). Hydrogeologic units (HGUs) were derived by combining geologic stratigraphic units based on their hydraulic properties and spatial distribution, then the digital geologic maps were 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 is to develop a digital geologic and hydrogeologic framework in support of a groundwater model of a portion of the area covered by this geologic analysis. The geologic information compiled provides data on reasonable model boundaries, reasonable internal boundaries, extents of HGUs, and potential groundwater flow paths and flow barriers. Hydrologic interpretations that depend on these geologic data are given in accompanying hydrologic reports. The geologic framework also provides aquifer and aquitard thickness for the modeled area. Geologic evaluations outside of the model area (black line, Figure 2-1) provide a basis for interpreting groundwater interactions across model boundaries, including potential groundwater interactions between groundwater flow systems internal to the model and groundwater flow systems outside of the modeled area. This geologic analysis was manifested through the creation of geologic and hydrogeologic maps and cross sections of the geologic study area.

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

An important aspect of the geologic maps is the portrayal of the distribution and attitude of faults, especially those formed during the youngest (basin-range) episode of deformation. Faults may serve as barriers and/or conduits to groundwater flow. In the geologic study area, most faults trend northerly, parallel to the general southward topographic gradient of the WRFS. Thus for the WRFS, basin-range faults serve as significant conduits to groundwater flow in this direction. In other flow systems in the geologic study area, basin-range faults may either direct groundwater flow through a system of barriers and fault conduits and/or impede groundwater flow toward otherwise down-gradient groundwater basins. Part of the objective of this report is to evaluate the potential for these faults to influence groundwater flow, especially how they may act as either barriers or conduits to groundwater flow. Another objective of this report is to evaluate which faults are most likely to

provide conduits and/or barriers to groundwater flow so that they can be properly incorporated into a groundwater model of the region.

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 authors familiar with the geology of the region. 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 monitor holes drilled by SNWA for the Project. Other sources of information were geophysical studies of the region published by USGS and other entities, particularly data from gravity surveys performed by USGS in 2003 to 2005 (Mankinen et al., 2006; McPhee et al., 2005, 2007; Scheirer, 2005). These latter studies have given insight as to the 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 over the area by the authors of this report.

Based on the evaluation of the compiled data and the expertise of the geologists involved in this investigation, geologic maps were constructed for the area of the groundwater model (Plates 1 and 2). Geologic cross sections were constructed (Plates 4 and 5) and tied into 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, 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, aquitards, 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, aquitards, 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 for the groundwater model. The hydrogeologic maps and cross sections were also interpreted to evaluate probable groundwater flow paths and flow barriers.

3.3 GEOLOGIC DATA COMPILATION

The compilation of geologic data was derived from a number of sources, including literature review, review of State Engineer's records, oil and gas test well and other borehole data, evaluation of drilling data and information from SNWA monitor wells, evaluation of studies performed by USGS, and consultation with geologic experts in the area. This literature was reviewed and compared with other literature and other sources of geologic information prior to incorporation into the geologic maps and cross sections.

Geologic data from wells were compiled from reports to the State Engineer, when available, and data on oil and gas test wells drilled within the geologic study area, and from monitor wells drilled by

SNWA in 2003 and 2005 in upper Moapa, Coyote Spring, Cave, Dry Lake, and Delamar 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.

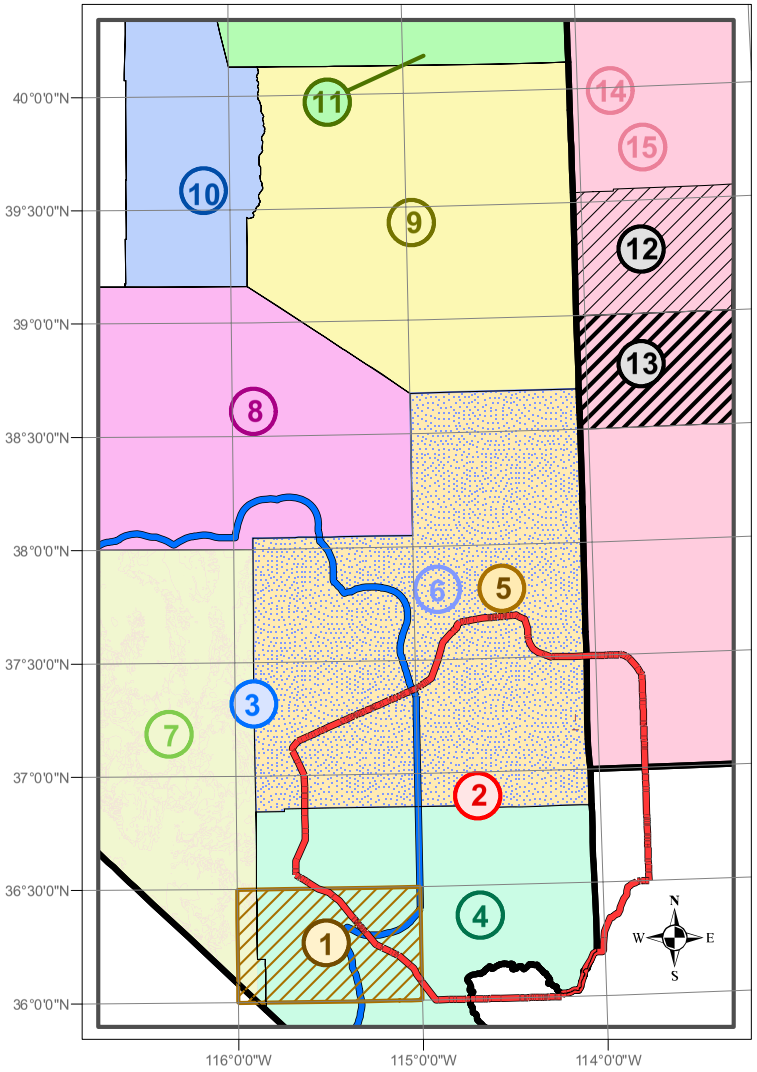
3.4 PREPARATION OF GEOLOGIC MAPS AND SECTIONS

A large portion of the map area is underlain by the WRFS (Figure 2-1). The geology of the southern part of the WRFS and adjacent systems (Figure 3-1) has been discussed by Page et al. (2005a) and in this report is digitally mapped at 1:250,000 scale (Plate 2). The digital geologic and tectonic maps of the DVFS (Figure 3-1), to the west of the WRFS, were also published at a 1:250,000 scale (Workman et al., 2002 and 2003). The DVFS includes much of the southwestern portions of Plates 1 and 2. The geologic maps of both the DVFS and southern WRFS included significant new and unpublished geologic mapping.

For the maps (Plates 1 and 2), much of the surface geology was based on county 1:250,000-scale geologic maps and the Utah 1:500,000-scale state geologic map (Hintze, 1980; Hintze et al., 2000). 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). The Utah counties covered by these maps are southwestern Tooele County, western Juab County, western Millard County (Hintze and Davis, 2002a and b, and 2003), and western Beaver County (Hintze, 1980 and 1988; Hintze and Davis, 2002a).

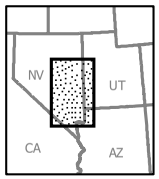
Nearly all county maps and reports were published decades ago. Many revisions and reinterpretations have been made to the geology of portions of those maps since that time. A significant part of the entire map area was compiled by Terrascan Group, Inc. (1987), but it used the same county maps used in the present map. The entire map area is also covered by state geologic maps at 1:500,000-scale (Stewart and Carlson, 1978; Hintze, 1980; Hintze et al., 2000), but some of the geology on these maps has also been subsequently revised and reinterpreted. These revisions and reinterpretations of the geology are from many more recent, commonly more detailed, published Nevada and Utah geologic maps and reports, and this new information has been incorporated into the maps of Plates 1 and 2 and in the discussions in this report. 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 7.0 of this report. Small-scale geologic maps used for the creation of Plates 1 and 2 are indexed in Figure 3-1. In addition, the present maps (Plates 1 and 2) include some new, unpublished field observations, though no new mapping was conducted specifically for this report and associated maps.

The geologic maps of Plates 1 and 2 include many changes of specific geologic units throughout the geologic study area. 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 commonly used for different counties, along with a stratigraphic column for units within western Utah. Correlations between specific geologic units are commonly given in



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., 2005b, 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., 2003, 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, 188 p.
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.
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.
9. Hose, R.K., and Blake, M.C., Jr., 1976, Geology and mineral resources of White Pine County, Nevada, Part 1, Geology: Nevada Bureau of Mines and Geology Bulletin 85, p. 1-35.
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.



MAP ID 13375 04/18/2007 JMB

FIGURE 3-1
INDEX MAP OF PREVIOUS SMALL-SCALE MAPPING USED IN THE GEOLOGIC EVALUATIONS AND TO CREATE THE GEOLOGIC AND HYDROGEOLOGIC MAPS OF Plates 1, 2, 6, AND 7

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, we accumulated, assimilated, and evaluated all available new geologic data about the area. The new data included reports, different concepts, detailed or regional maps, geophysics, and well logs, etc. Conflicts necessarily resulted over interpretations and placement of contacts and faults. Decisions on the eventual linework were based on what appeared to be scientifically the most reasonable 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. These cross sections 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 exposed geology. 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. (1987) presented associated cross sections that were referred to in making the cross sections for the maps 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 us in making our 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, so there was no need to resolve conflicts arising from other work in the area. 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 precious. Fortunately, aeromagnetic and gravity geophysical data were available for much of the area. Unfortunately, well logs and audiomagnetotelluric (AMT) 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), were used to aid in the interpretation of geologic cross sections and structure sections. Gravity maps and electromagnetic profiles were completed by USGS as part of USGS/SNWA joint funding agreements (Mankinen et al., 2006; McPhee et al., 2005 and 2007; Scheirer, 2005). The gravity data were converted to depth-to-basement data and were used to aid in constructing the cross sections.

4.0

CONCEPTUAL GEOLOGIC MODEL

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:

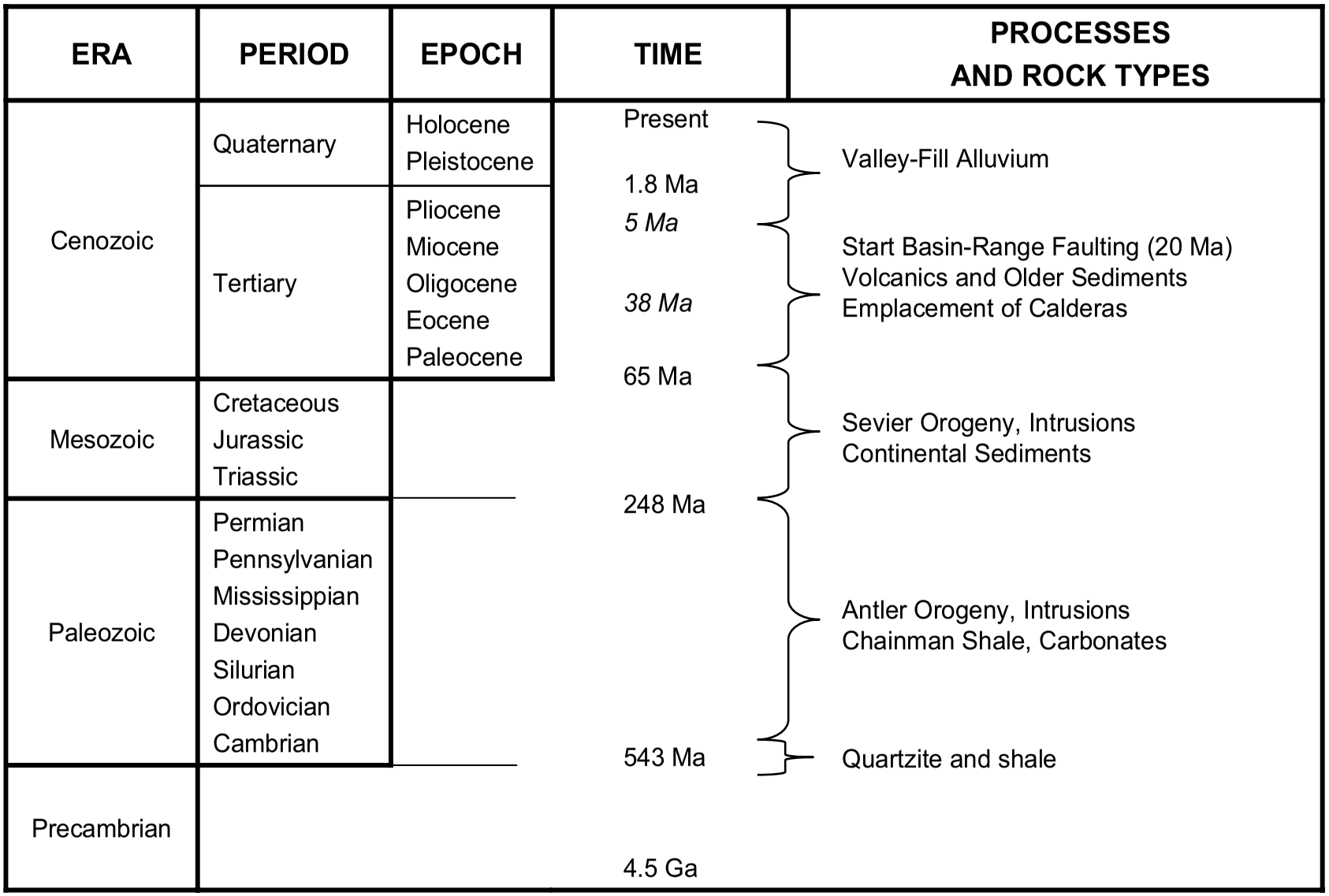
- Early to Late-Proterozoic metamorphic and igneous rocks
- Late Proterozoic to Lower Cambrian quartzite and shale
- Shale, sandstone, and conglomerate of Mississippian age
- Triassic to Cretaceous shale, siltstone, and sandstone
- Mesozoic to Cenozoic plutons.

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

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 tuff. 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 double as barriers to east or west flow in certain flow systems such as the GSLDFS.

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 and Late Proterozoic metamorphic and igneous units. These rocks are overlain by thick sequences of quartzite and subordinate shale, which are locally



Source: Adapted from Geological Society of America, 1999

FIGURE 4-1
GEOLOGIC TIME SCALE, INCLUDING ROCK TYPE AND TECTONIC EVENTS

metamorphosed to slate and schist, of Late Proterozoic age. The Proterozoic rocks pass conformably upward into rocks of similar type and thickness, though less metamorphosed, that are Late Proterozoic to Early Cambrian in age. During Middle Cambrian time, carbonate deposition was initiated, and thick sequences of marine limestone and dolomite were deposited from the Middle Cambrian through the Permian Periods. These rocks make up the carbonate aquifer of Nevada and adjacent parts of Utah and range in thickness between 5,000 and 30,000 ft throughout this area (Harrill and Prudic, 1998).

Locally, marine sandstone and shale are intertongued with the carbonates. These units generally do not form significant impediments to regional groundwater flow, with the exception of the Chainman Shale and related shale and sandstone of Late Mississippian age. This unit locally exceeds 2,000 ft in thickness, and in all but the southern part of the 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.

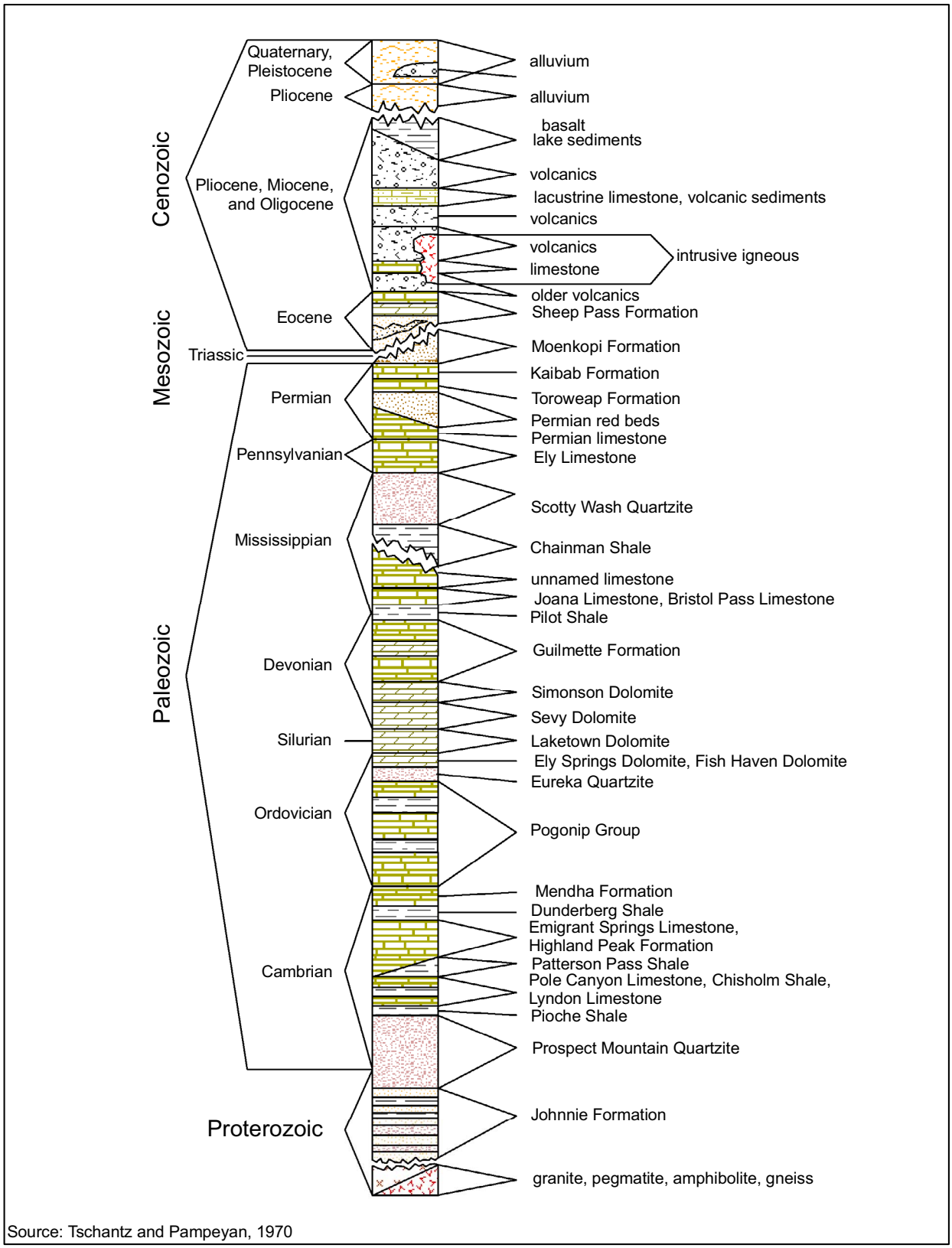
Mesozoic rocks in the geologic study area are largely clastic, nonmarine, and thin where deposited, but in most places they have been removed by erosion. Mesozoic and older rocks were deformed during the Sevier deformational event. At this time, the geologic study area was a highland, also known as a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

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

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

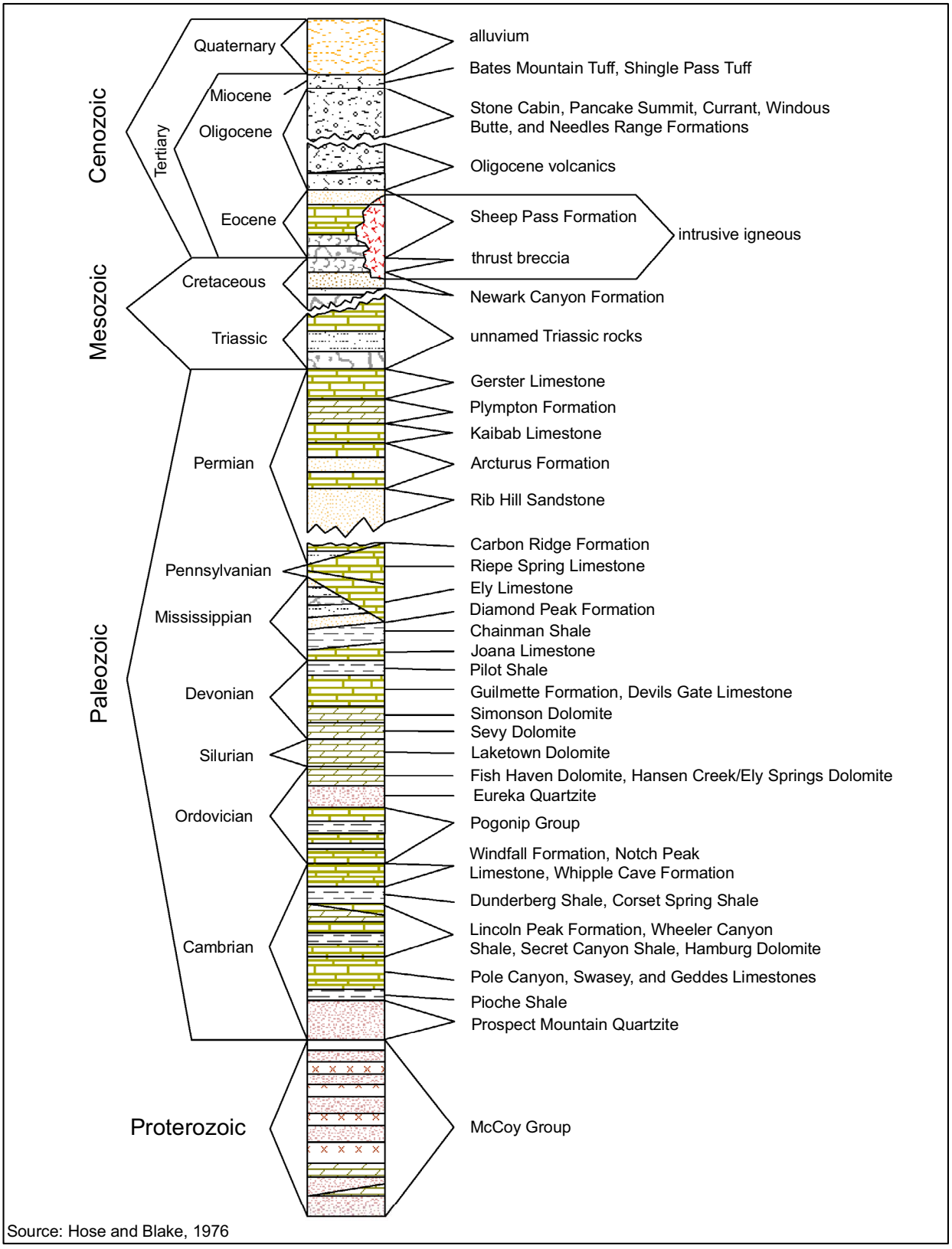
Starting at about 20 Ma ago (middle Miocene), subduction ceased and extensional deformation increased in the map area (Christiansen and Lipman, 1972; Christiansen and Yeats, 1992; Rowley and Dixon, 2001). Basin-range deformation, characterized by vertical (normal) faulting, began to form alternating mountain ranges and valley basins. The main pulse of this basin-range faulting began about 10 Ma ago, during which time the present topography formed. As valleys formed, they were filled by debris eroded from the adjacent mountain range, creating basin-fill deposits.

Individual rock units, structures, basins, and ranges are described in the 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



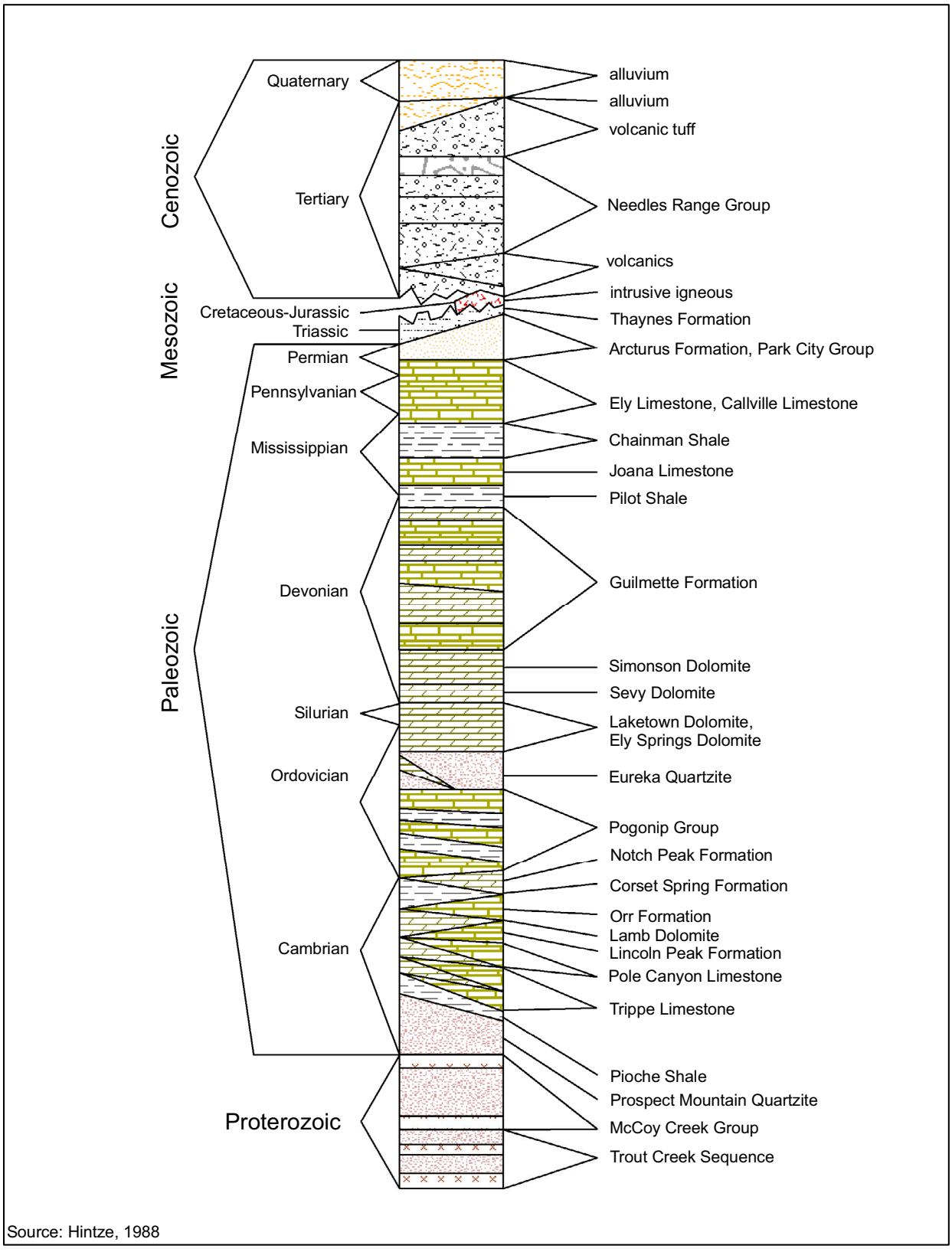
Source: Tschantz and Pampeyan, 1970

FIGURE 4-2
GEOLOGIC UNITS OF LINCOLN COUNTY, NEVADA



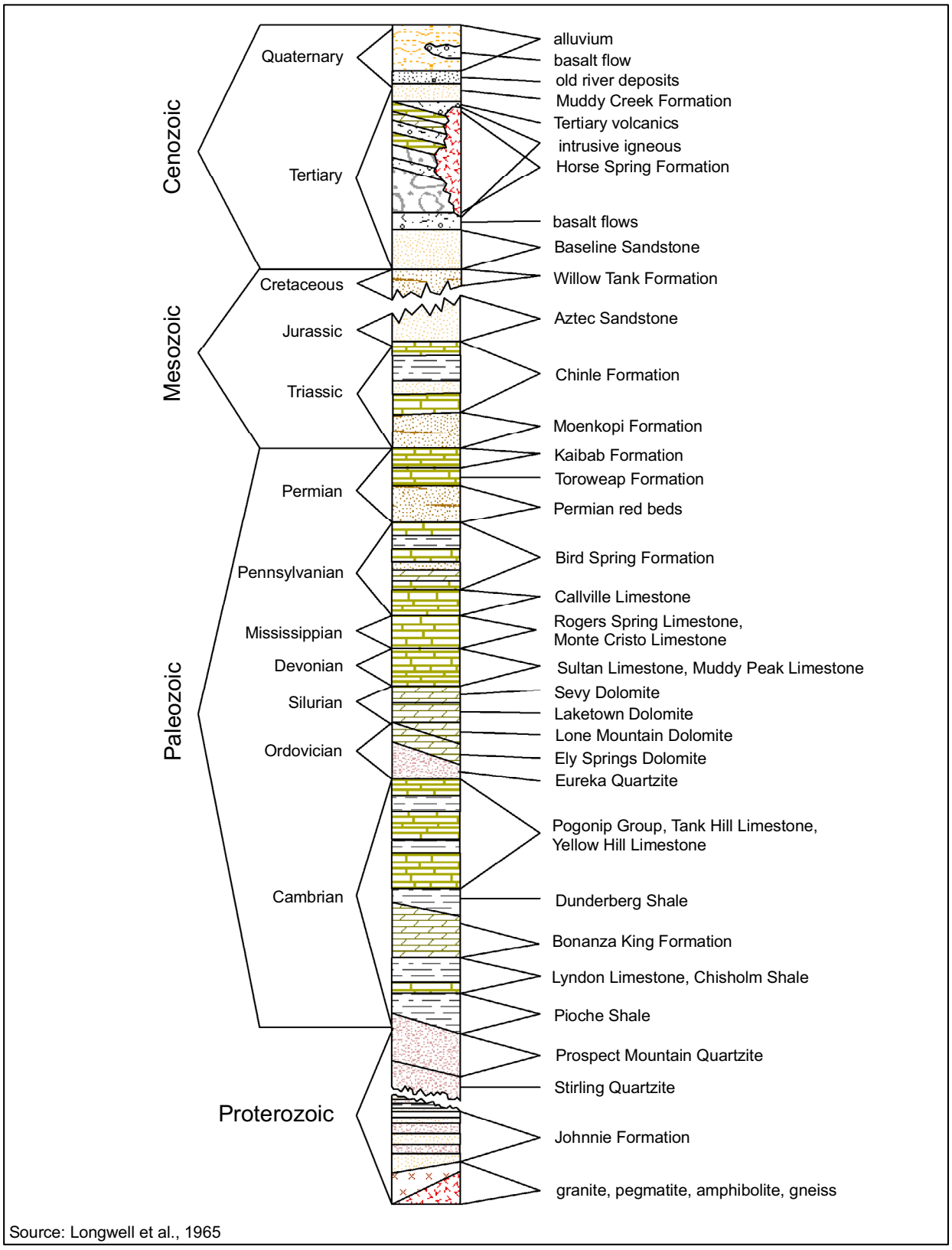
Source: Hose and Blake, 1976

FIGURE 4-3
GEOLOGIC UNITS OF WHITE PINE COUNTY, NEVADA



Source: Hintze, 1988

FIGURE 4-4
GEOLOGIC UNITS OF WESTERN UTAH



Source: Longwell et al., 1965

FIGURE 4-5
GEOLOGIC UNITS OF CLARK COUNTY, NEVADA

(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 Early Proterozoic age (Page et al., 2005a) that we have mapped as Precambrian rocks (p€). Over most of the geologic study area, however, the oldest rocks are Late Proterozoic to Lower Cambrian quartzite. These Late Proterozoic 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, 1972; Stewart, 1976).

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

4.1.3 PALEOZOIC ROCKS

4.1.3.1 CAMBRIAN ROCKS

The Prospect Mountain Quartzite (Cambrian to Precambrian sedimentary rocks, €p€s) overlies the McCoy Creek Group in White Pine County. The Prospect Mountain consists of well-bedded, resistant quartzite and subordinate shale, commonly weakly metamorphosed. It has been generally considered to be Early Cambrian, although it is not well characterized by age or correlation from place to place, and at least in the southern part of the geologic study area is partly Late Proterozoic. 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 (Late Proterozoic 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 its base is not exposed. Link et al. (1993) considered the Stirling Quartzite to postdate the Late

Proterozoic 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 Nevada Test Site and in portions of Clark County.

Cambrian carbonate rocks range in thickness from about 7,500 ft just southwest of the geologic study area to almost 5,000 ft over most of the geologic study area. The map unit is shown as the middle part of Cambrian rocks, or €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, as 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, these were originally named, from base to top, the Eldorado Dolomite, the Geddes Limestone, the Secret Canyon Shale, and the Hamburg Dolomite. In the Snake Range, these are, from base to top, the Pole Canyon Limestone, the Lincoln Peak Formation, and the Johns Wash Limestone. These latter names are now preferred in the northwestern part of the geologic study area and areas to the west. In the Cherry Creek Mountains of Nevada and in Utah, the units making up the entire sequence of Middle Cambrian carbonate rocks are, from base to top, the Dome Formation, Swasey Limestone, Wheeler Shale, Marjum Limestone, Weeks Limestone, Trippe Limestone, Wah Wah Summit Formation, Orr Formation, and others (Hose and Blake, 1976; Hintze and Davis, 2003). The overall Cm sequence is roughly equivalent to the Bonanza King Formation to the south (Longwell et al., 1965). 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 (€u); in some cross sections, the map unit is combined with €m as Cambrian carbonate rocks, undivided (€c). In White Pine County and in Utah, the €u 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 €u 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 unit 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 limestone and dolomite that is not present farther east in Lincoln and White Pine counties (Kleinhampl and Ziony, 1985). In Nye County, these units, particularly the Lone Mountain Formation, overlie and interfinger with the Roberts Mountain Formation. The Roberts Mountain is gradational to western facies deep-water sediments and is comprised of shaly limestone, dolomite, and shale with a thickness of 500 to 1,900 ft (Kleinhampl and Ziony, 1985). See Figures 4-2 to 4-5 for geologic sections in different areas of the map.

Devonian carbonate rocks over most of the geologic study area consist of, in ascending order, the Sevy Dolomite, Simonson Dolomite, and Guilmette Formation. Where combined, they are mapped as Devonian rocks, undivided (Du). In the southern part of the 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 Simonson and Sevy Dolomites (Ds) and Guilmette Formation (Dg). The Sevy Dolomite is a resistant, gray dolomite, commonly argillaceous and with a sandstone unit near the top. This dolomite increases in thickness southward across the 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 may be reduced in thickness by faulting.

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

a lower dolomite unit and an upper limestone unit with a thickness of 1,800 ft (Longwell et al., 1965). 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 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., 2003). In mapping, the Monte Cristo, Rogers Spring, and Eleana are included with the MD map unit. The map unit also includes local units Mercury Limestone and Bristol Pass Limestone (both mostly in White Pine County), Webb Formation (Elko County), 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, 2002b) in the Confusion Range as having thicknesses greater than 2,000 ft. A similar

thickness is reported from an oil-well log in Lake Valley (Hess, 2004). Although these two locations are distal from the source area, they represent localized depositional basins.

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 (IP). 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 (PIP). The rocks in the PIP 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 PIP 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 PIP 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 named for a sequence of poorly resistant, gray limestone, sandstone, and siltstone that is 2,700 to 3,400 ft thick (Hose and Blake, 1976). 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, this same 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 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, 2002b). The overlying Moenkopi Formation (Lower Triassic) is a mostly soft, red and gray, thin-bedded siltstone, limestone, sandstone, and shale, commonly gypsiferous, and locally about 2,000 ft thick in western Utah. The Thaynes and Moenkopi Formations are thin in the Nevada portion of Plate 1 and are not separated on this map. 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 (Ŧs).

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 oldest to youngest 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, Jurassic quartz monzonite and diabase 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 pluton of apparent Cretaceous and Eocene age (Best et al., 1974; Miller et al., 1999). An east-trending string of small Lower Cretaceous plutons extends from Eureka through Ely, Nevada.

4.1.5 CENOZOIC ROCKS

Cenozoic rocks in the 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 UPPER 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 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). 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). 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 generally thin, generally less than 1,000 ft, but the aggregate thickness of all of these tuffs is considerable in most places.

The outflow tuffs are interspersed with locally distributed but thick central stratovolcano deposits made up of lava flows and volcanic mudflow breccia generally deposited above their source plutons. Where these calc-alkaline flows and breccia are largely andesite, they are mapped as Ta1, Ta2, Ta3, and Ta4 based on ages that correspond to those of the ash-flow tuffs. Unit Ta4 is made up of andesitic (calc-alkaline) flows of post-18 Ma that are exposed in the southern part of the 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 of faulting and underlain by batholiths whose cupolas provide the main vent areas for the volcanic rocks. The oldest volcanic rocks in the map area belong to the Ely-Tintic igneous belt (belt names from Rowley [1998]) in the northern part of the 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-west gap in vent areas, about 30 to 60 mi wide, occurs south of Ely and Preston, Nevada, although a volcanic plain of thin outflow tuffs underlies the gap. To the south, the Pioche-Marysvale igneous belt crosses near Pioche, Nevada. The volcanic centers here are about 32 to 31 Ma on the northern side of the belt and about 28 to 27 Ma along the southern part. About 12 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 has not been found but may underlie the Red Hills or adjacent northern Spring Valley (Gans et al., 1989) near the center of deposition. Other ash-flow tuffs and lava flows underlie and overlie the Kalamazoo Tuff, and the overall thickness of the volcanic rocks in the igneous belt is about 500 to 1,500 ft. Plutons of 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, roughly 45 to 30 Ma in age (Best et al., 1974), is at the eastern end of the composite-age Kern Mountains pluton.

In the Pioche-Marysvale belt, volcanic rocks are thicker and more widespread than in the Ely-Tintic belt because calderas are more abundant and larger and the volcanic rocks are somewhat younger and thus less eroded. Most volcanic rocks are regional ash-flow tuffs from calderas, but lava flows and mudflow breccia erupted from volcanoes in and along the margins of calderas or from isolated

volcanoes 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.

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), tuff of Etna (14.0 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 bimodal sequence is made up of small basalt lava flows and cinder cones as well as small high-silica rhyolite volcanic domes, lava flows, ash-flow tuffs, and airfall tuffs. The basalts are 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 Holocene through middle Miocene alluvium (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 playa lakes are Plio-Pleistocene in age, including the latest Pleistocene Bonneville and Lahontan lakes that had water depths of as much as 1,000 ft, resulting in deposition of clay and saline sediments in many basins (Mifflin and Wheat, 1979). These lakes, however, were short lived and produced fine-grained materials that rarely exceeded a few tens of feet in thickness. Because of the vagaries of the sizes of storms, of climate changes, of integration of some basins, and of timing of the deformation of basin-bounding versus within-basin faults, the stratigraphy of basin-fill sediments is characterized by a complex intertonguing of beds of all lithologies. Within-basin faults commonly produced horsts (hills) of soft basin-range sediments that were then eroded away by streams and redeposited as younger basin-fill sediments. As with the older basin-fill sediments, Quaternary deposits are dominated by stream alluvium but also include the deposits from landslides, playas, and springs that are not individually separated in this report or on the maps due to their limited extent.

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 of 5 to 11 Ma in southern Lincoln and Clark counties. The Muddy Creek consists of locally gypsiferous sandstone, siltstone, conglomerate, and limestone. Another named unit is the Panaca Formation, about 2 to 10 Ma and located in the central part of the geologic study area (Rowley and Shroba, 1991). Others 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. They provide a bridge between geologic units and groundwater modeling units. As such, they are used to construct groundwater flow models, that is, to approximate spatially complex geology with groupings that can

be readily simulated with mathematical modeling techniques. HGUs, as given on Plates 6 and 7 and listed in Table 4-1, are a set of geologic formations that are grouped based on physical properties of the units. 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 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. Of moderate permeability where fractured.
TJi	Tertiary to Jurassic intrusive rocks - Includes all plutons. Generally impermeable except where fractured.
KTs	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.
PPc	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.
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.
€pC 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.
pCm	Precambrian metamorphic rocks - Precambrian X, Y, and Z high-grade metamorphic rocks, generally Early Proterozoic. 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, yet they follow stratigraphic procedures and principles.

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 units (aquitards) and would be of Group or Supergroup rank in formal stratigraphic terminology because they contain many 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 (pCm) consist primarily of moderately to intensely metamorphosed Precambrian "basement" rocks, forming the most significant aquitard in the geologic study area. 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 and on the western side of the Snake Range, north and south of U.S. Highway 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), map unit has the symbol pC.

4.2.2 CAMBRIAN TO PRECAMBRIAN SILICICLASTIC ROCKS

The Cambrian to Precambrian clastic rock unit (CpCs) is non-metamorphosed to moderately metamorphosed siliciclastic rock deposited in the Late Proterozoic 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 pCm and CpCs in exposed sections is considered minor, although the CpCs unit is expected to be slightly more permeable than the older pCm (Belcher and Elliott, 2001). On the geologic maps and cross sections, unit consists of the symbol CpCs.

4.2.3 CAMBRIAN CARBONATE ROCKS

The Cambrian carbonate unit (Cc) 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, 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 aquitards. Neither of these formations is considered a significant aquitard at the scale of Plates 6 to 9, and the Eureka Quartzite, where fractured, can be an aquifer nearly as permeable as the carbonates. This section of rocks also includes the Guilmette, Sultan, Sevy, and Simonson formations of Devonian Age and the Lone Mountain Dolomite of Silurian age. These rocks are predominately dolomite. 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 Nevada Test Site. 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 (KTrs) 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 Trs 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.

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, 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. 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 QTa.

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, in other words how they guide flow along and across a general flow path.

4.3.1 EVOLUTION OF THE REGIONAL STRUCTURE

Three main structural events affected the 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 the western side of 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 Late Proterozoic to middle Paleozoic rocks over Late Proterozoic to Mesozoic rocks (Armstrong, 1968). At least a half dozen large thrusts are well exposed in the Las Vegas area, each with displacements ranging from several to 20 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, the leading edges of most major thrusts are east of the map area, and the deformation created highlands within the hinterland of the map area that in turn eroded and shed clastic material primarily to the east. Some of the thrusts, including the Gass Peak, however, have been projected northward into the hinterland in the central and northern part of the 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). 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 these areas where they are known. Therefore, transverse zones are delineated as speculative zones of potential disruption on Plates 1 and 2.

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

The third structural event, the basin-range episode of extensional deformation, began at about 20 Ma and continues today. It is characterized by east-west extension and resulted primarily in

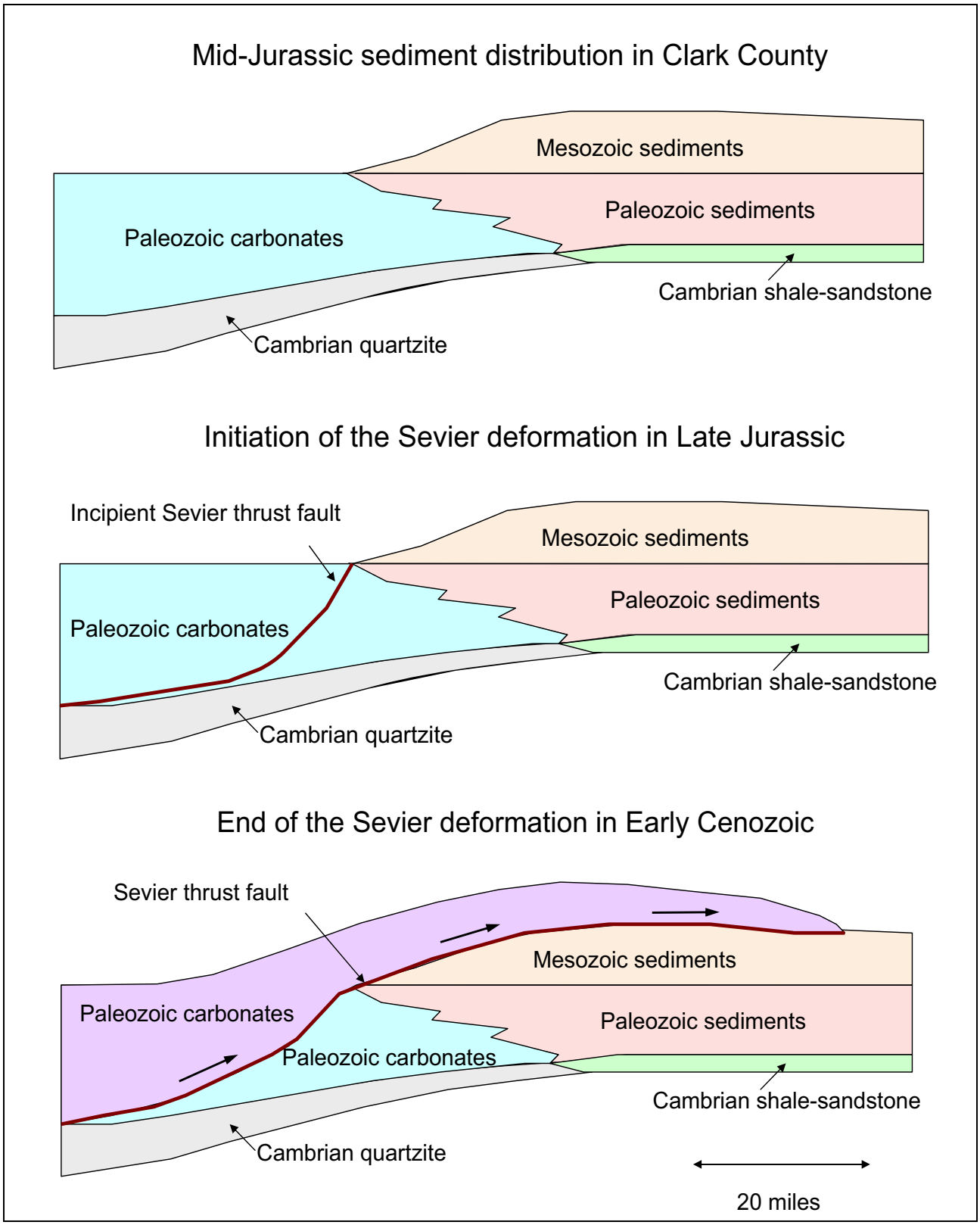
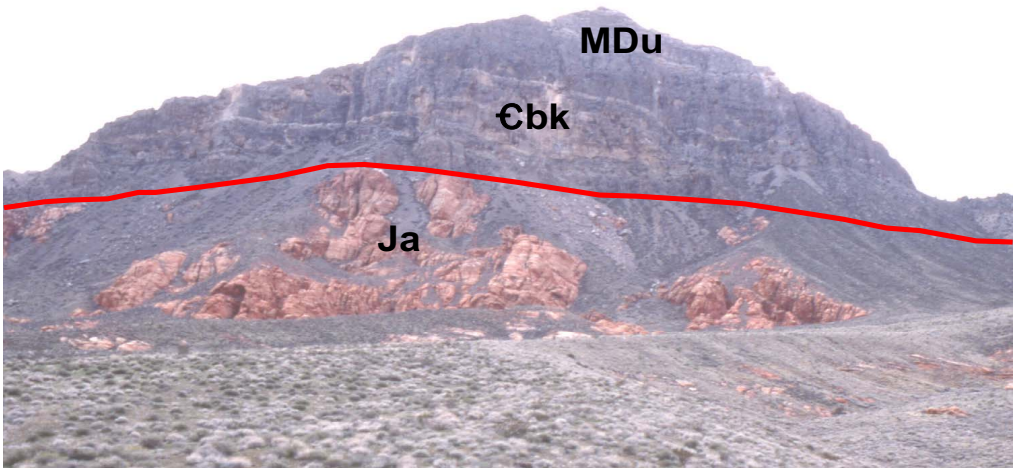


FIGURE 4-6
SCHEMATIC DIAGRAM OF SEVIER THRUST SHEETS, ILLUSTRATING THE MOVEMENT OF PALEOZOIC CARBONATES OVER CRATONIC SEDIMENTS



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

FIGURE 4-7
PALEOZOIC CARBONATES THRUST OVER JURASSIC AZTEC SANDSTONE IN THE MUDDY MOUNTAINS NEAR MUDDY PEAK

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 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 Pahranagat shear zone 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). East-striking transverse faults continued to be active at the same time, segmenting the Great Basin into broad east-trending corridors of different types and amounts of east-west pulling apart.

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

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

One major fault to which the name "detachment" fault is appropriate is the well-known Snake Range decollement. Although originally considered to be a thrust fault that placed Middle Cambrian and younger rocks over Middle Cambrian and older rocks (for example, Nelson, 1966), the fault was later mapped in greater detail and reinterpreted as an Eocene to middle Miocene low-angle fault caused by stretching and thinning during uplift of a metamorphic core complex (Miller et al., 1983; Gans et al., 1985 and 1989). This detachment may represent the ductile/brittle transition zone uplifted by the core complex, as illustrated schematically in 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, while the decollement had an older (late Eocene and early Oligocene) history, most displacement on it was middle Miocene and later, coinciding with basin-range deformation (Miller et al., 1999). The core-complex uplift that formed the decollement included the Kern Mountains and southern Deep Creek Range (Miller et al., 1999). Finally, Miller et al. (1999, p. 902) suggested that the Snake Range decollement may not be a normal fault at all but instead a "highly complex structural boundary developed above a rising and extending mass of hot crystalline rocks."

4.3.2 EFFECT OF STRUCTURES ON GROUNDWATER FLOW

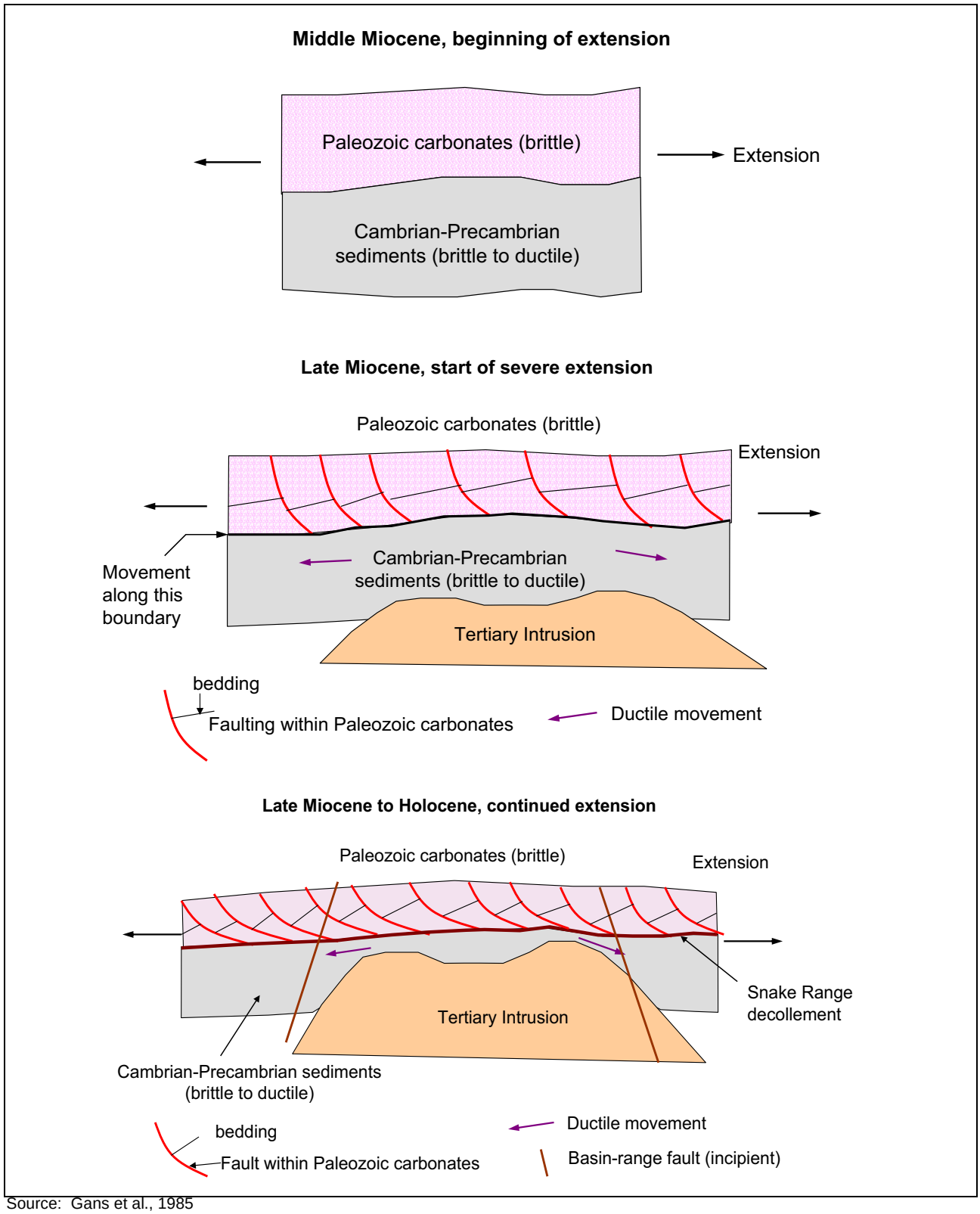
This section evaluates the effect of the three episodes of structural deformation and one episode of volcanism on the groundwater flow in the geologic study area.

4.3.2.1 THE ANTLER DEFORMATION

The Antler episode of compressive deformation probably had the least direct effect on groundwater flows 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 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 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



Source: Gans et al., 1985

FIGURE 4-8
ONE SCENARIO FOR DEVELOPMENT OF THE
SNAKE RANGE DECOLLEMENT DURING LATE CENOZOIC EXTENSION

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 structure that formed during this time are poorly known but likely included strike-slip and normal faults, including detachment faults. The region was characterized by mild extension and wrench tectonics. Strike-slip faults probably had northeast and northwest strikes. The caldera complexes and their associated ring faults and other margin structures provided mostly barriers to groundwater flow. Perhaps more important than the caldera margins 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 formed as accommodation zones during the same east-west extension also were important. 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 (Figure 4-9). Along the WRFS where flow is from north to south, parallel to these structures, flow is enhanced in the north-south direction by these faults (Figure 4-9). The hydrologic effect produced by faults largely results from joints that the faults cause, with larger-displacement faults resulting in more joints and thus greater fracture flow. However, for brittle rocks such as carbonates, ash-flow tuff, and basalt flows, even small faults—which are many times more abundant in the Great Basin than the large faults we have mapped—will create rock fractures, acting like a hammer on a plate of glass. 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).

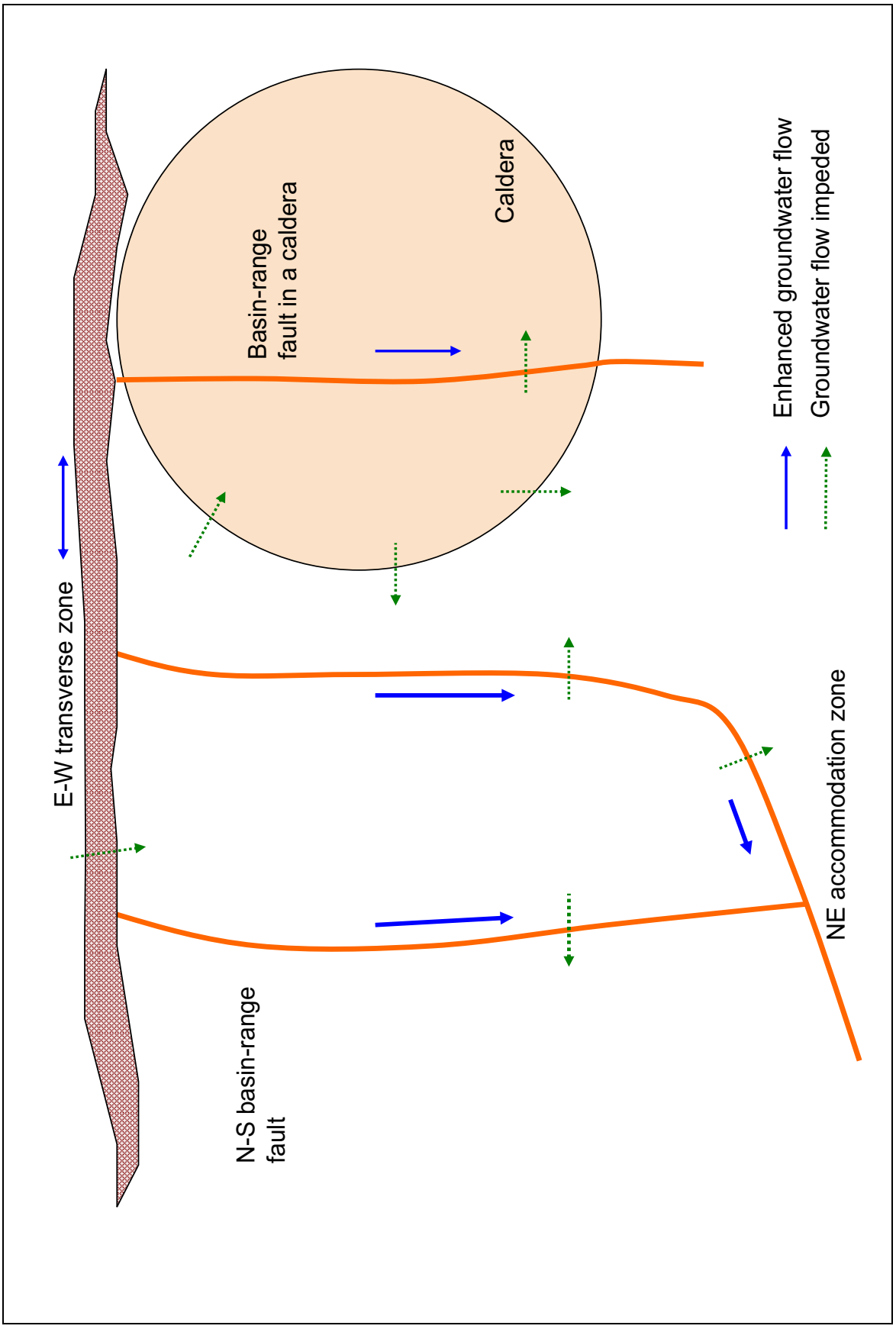


FIGURE 4-9
DIAGRAMMATIC MAP SHOWING ENHANCEMENT OR IMPEDANCE OF GROUNDWATER FLOW ALONG OR ACROSS FAULTS, TRANSVERSE ZONES, AND CALDERAS

Some normal faults are low-angle—that is, detachment or attenuation faults. Their effect on groundwater flow is much less important than that from high-angle faults. These detachment zones may be either from brittle or plastic deformation, resulting respectively in gouge or mylonitic zones along the faults. Gouge and mylonite may provide barriers to groundwater flow. An example is the Snake Range decollement that formed as the Snake and Schell Creek ranges were uplifted and intruded. The detachment faults of the Snake Range decollement 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 section describes basins and ranges and the potential for interbasin groundwater flow between the basins within a series of hydrologic regional flow systems. Most flow systems were defined by Harrill et al. (1988) and Harrill and Prudic (1998). The most extensive flow systems within and adjacent to the geologic study area are the WRFS and DVFS, the boundaries of which are defined on Figures 2-1 and 3-1, respectively, and the GSLDFS, part of the boundary for which is defined on Figure 2-1. Adjacent to these flow systems are the Penoyer Valley, Newark Valley, Railroad Valley, Diamond Valley, Humboldt, Ruby Valley, Goshute Valley, Virgin River, and Sevier Lake flow systems (Figure 2-1). The MVFS is considered a separate system by some workers, but in this report, this flow system is interpreted to be part of the WRFS to which it is tributary. In subsequent sections, the MVFS is included in the WRFS.

This study concentrated on specific basins or hydrographic areas within or adjacent to the model area, which includes the WRFS, the MVFS, and the southwest portion of the GSLDFS. Mountain ranges adjacent to these 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. Basins and bounding mountain ranges in adjacent flow systems are shown to give regional context and are described in less detail.

Basins and ranges are described in this section to better understand their structure and extent within individual flow systems. The features are first described for the WRFS and MVFS, going from west to east and north to south, starting in the northwestern part of the map. For adjacent flow systems, basins and ranges are described for the western edge north to south, then the eastern edge north to south.

The potential for interbasin groundwater flow is discussed within the text and is illustrated by Figure 4-10. The figure shows the likelihood of interbasin groundwater flow based on lithology and structure. The potential for interbasin groundwater flow was classified, geologically, 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.

As defined, boundaries of the flow systems are inferred from available water-level data, mass-balance calculations, geochemical signatures, and geologic features that control groundwater movement. Probable flow pathways of the flow systems are defined by geologic features, which are critical in understanding flow routing between the valleys of the flow systems.

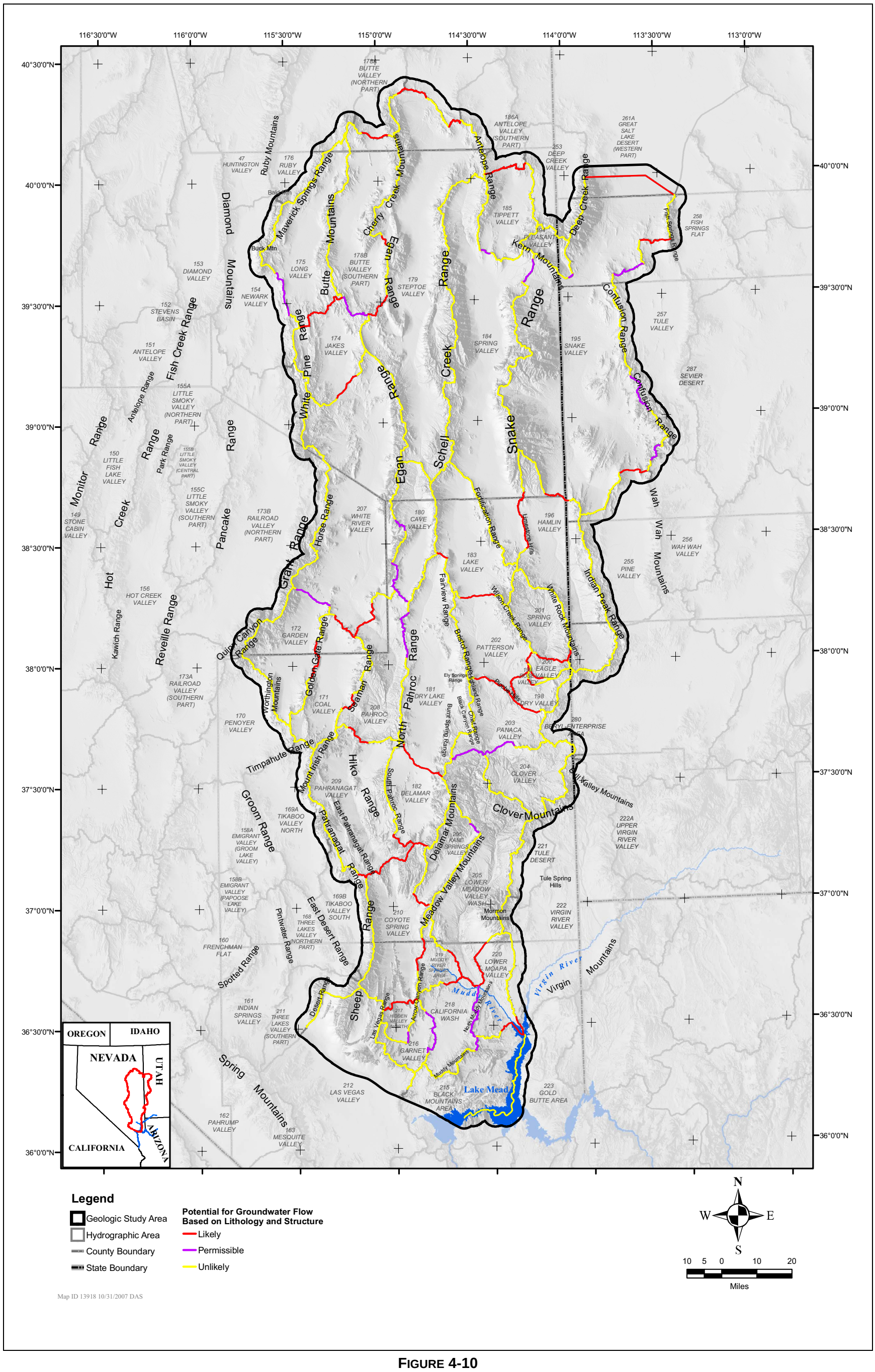


FIGURE 4-10
POTENTIAL FOR INTERBASIN GROUNDWATER FLOW WITHIN THE GEOLOGIC STUDY AREA

4.4.1 BASINS AND RANGES ALONG AND WITHIN THE WHITE RIVER FLOW SYSTEM

This section discusses the geology and hydrogeology of basins and ranges along the sides and interior of the WRFS. Basins and ranges of the MVFS are included in the discussion. The order of ranges is generally from north to south and west to east.

4.4.1.1 RUBY MOUNTAINS, BALD MOUNTAIN, AND BUCK MOUNTAIN

The mountain ranges at and near the northwestern parts of the WRFS are the southern Ruby Mountains, Bald Mountain, and Buck Mountain. These ranges bound Long Valley, the northernmost valley of the WRFS; Ruby Valley, the southernmost valley of the Ruby Valley Flow System; Huntington Valley, a southern valley in the Humboldt River Flow System; and Newark Valley, the northern and downstream end of the Newark Valley Flow System (Figure 2-1). 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 (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 Cambrian aquitards.

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 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 (Figure 4-10). The intrusions provide a barrier to flow across Bald Mountain, thereby allowing separation of the Ruby, White River, and Newark flow systems at this location.

Ruby Valley is a deep graben bounded by the Ruby Mountains to the west, the Maverick Springs Range (Section 4.4.1.2) to the east, and Bald Mountain to the south. 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 4.4.1.3. Seismic profiles disclose Sevier thrusts beneath the basin-fill deposits (Dobbs et al., 1994).

4.4.1.2 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 forms part of the northern edge of the WRFS and 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 northern end of the WRFS, 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 through Mooney Basin to the western side of Long Valley and is potentially a conduit for groundwater flow between southern Ruby Valley and Long Valley. Groundwater in Long Valley flows southward along north-trending faults and fractures in the valley, then is permissible to move along faults and fractures of the same trend in the northern White Pine Range, then into Jakes Valley to the southeast (Figure 4-10) (Harrill et al., 1988).

4.4.1.3 BUTTE MOUNTAINS AND WHITE PINE RANGE

The Butte Mountains is located east of Long Valley along the northeastern margin of the WRFS. The range is a 40-mi-long, north-trending horst of east-dipping to anticlinically folded, upper Paleozoic sedimentary rocks. 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 and Tertiary volcanics rocks. The southern end of the Butte Mountains also joins with the Egan Range (Section 4.4.1.9) to the east across a similar low range of hills. At this divide, flow is likely to the southeast into Steptoe Valley and permissible to the southwest into Jakes Valley (Figure 4-10).

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 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 doubtless is responsible for the high relief of the range here (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 geologically likely that the graben may be a groundwater conduit between Jakes Valley and the White River Valley (Figure 4-10), respectively, west and south of the caldera. The siliciclastic and intrusive rocks of the White Pine Range form a groundwater barrier between the White River Valley and Railroad Valley, and east-dipping sedimentary rocks may allow recharge to flow preferentially eastward from the range into the White River Valley.

Basins surrounding the Butte Mountains and White Pine Range include the previously described Long Valley, southern Butte Valley, Jakes Valley, northern White River Valley, and southern Newark Valley. Butte Valley, east of the Butte Mountains, is a graben similar to Long Valley but is part of the GVFS. Butte Valley contains upper Paleozoic rocks at 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, 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'). 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. Jakes Valley is the second northernmost valley within the WRFS.

West of the White Pine Range, Newark Valley is a shallow graben, narrowing and becoming shallower to the south; it is further described in Section 4.4.1.1. West of the southern end of the White Pine Range, Newark Valley opens out southward into Railroad Valley, a broad deep graben and the upper eastern end of the Railroad Valley Flow System. East of the axis of the White Pine caldera, the White Pine Range is dropped down by many down-to-the-east normal faults that also create White River Valley to the east, which is part of the WRFS. Although relatively shallow at this latitude, near Preston and Lund, Nevada, the White River Valley widens and becomes a deep, broad graben to the south, with a depth of more than 5,000 ft (see Section 4.4.1.4).

4.4.1.4 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. All these ranges are bounded on the west by the deep graben of Railroad Valley. The crests of the Horse, Grant, and Quinn Canyon ranges thus define the boundary between the Railroad Valley Flow System to the west and the WRFS to the east. On the east, the Horse and Grant ranges are bounded 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 (E.B. Ekren, 2002 to 2004, unpublished mapping), 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. Geologically permissible 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. White River Valley is a broad, deep graben within the WRFS. Gravity surveys on its eastern side (Scheirer, 2005) suggest that it is underlain by many thousands of feet of basin-fill sediments and volcanic and carbonate rocks. We interpret that the White River Valley contains as much as 5,000 ft of valley fill (Plates 4 and 8, Cross Section T—T'). It is geologically permissible that groundwater passes from southwestern White River Valley to Garden Valley.

4.4.1.5 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 is mostly 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 two ranges form the boundary between the WRFS on the east and the Penoyer Valley Flow System on the west. 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 Tem Piute 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 is possible through the carbonate rocks of the southern Worthington Mountains 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 4-10). 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.

4.4.1.6 GOLDEN GATE RANGE, MOUNT IRISH, PAHRANAGAT RANGE, AND NORTHERN SHEEP RANGE

The Golden Gate Range is a 40-mi-long, low string of north-trending faulted hills that passes southward into Mount Irish, a 10-mi by 10-mi massif 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 related gaps that would allow groundwater to flow in a west to east direction into Coal Valley.

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 that occur in the Timpahute Range (Plates 4 and 8, Cross Section 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 between Coal Valley and Pahranagat Valley to the south.

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 on the east. 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 left-lateral Pahranagat shear zone. The southern splay is the Maynard Lake fault zone (Plates 5 and 9, Cross Section A—A') (Jayko, 1990). The western part of the splay is interpreted to join the main north-south normal fault that defines the western side of the Sheep Range. Under this interpretation, the Maynard Lake zone is an accommodation or transfer fault that transfers east-west 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 oblique (left-lateral and normal) movement. The Pahranagat Range 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.

The northern Sheep Range is a simple, narrow, and abrupt horst of Cambrian and Ordovician sedimentary rocks. The Pahranagat and Sheep ranges are the boundary between the WRFS on the east and the DVFS on the west, so flow between them is generally unlikely. It is geologically likely, however, that the subparallel faults of the Pahranagat shear zone provide conduits from southern Pahranagat Valley through the Pahranagat Range to Tikaboo Valley South.

4.4.1.7 SOUTHERN SHEEP RANGE, LAS VEGAS RANGE, AND ELBOW RANGE

The southern Sheep Range is generally composed of Cambrian through Devonian carbonate rocks that dip mostly eastward (Plates 5 and 9, Cross Sections G—G', H—H', and I—I') (Guth, 1980). The range is a large horst block defined by north-striking, normal basin-range faults on its eastern and western sides, the eastern fault having the greatest offset. Within the range, minor north-striking faults dominate, but some cross-faults that strike east to east-northeast also have been mapped. The low-angle Gass Peak thrust underlies most of the range. It has transported Late Proterozoic to Cambrian quartzite and Cambrian to Ordovician carbonate rocks eastward over Cambrian to Mississippian rocks.

A small north-trending range, the northern end of which terminates against the Maynard Lake fault zone, lies just east of the northern end of the Sheep Range. This basin-range tilt block consists largely of east-dipping volcanic rocks (Jayko, 1990) that rest unconformably on Pennsylvanian and Permian carbonate rocks. North-striking normal faults on its western side and within this range pass into the Maynard Lake fault zone and transfer the normal slip to oblique slip. The buried north-striking trace of the Gass Peak thrust fault passes beneath the normal faults. In concert with the faults of the Pahranagat shear zone, it is likely that the normal faults carry groundwater from southern Pahranagat Valley to Coyote Spring Valley.

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 Section F—F') (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). The folds and thrusts in the Las Vegas and Elbow ranges strike north and it is geologically likely that they provide conduits for groundwater flow.

4.4.1.8 CHERRY CREEK RANGE

The Cherry Creek Range is in northern White Pine and southern Elko Counties, just northeast of the WRFS. 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. The high range separates two north-flowing basins, with the Ruby Valley Flow System on the west and the GVFS on the east. Butte Valley is part of the GVFS (Harrill et al., 1988).

A thin sliver of bedrock cored by a Tertiary intrusion connects the Cherry Creek Mountains with the northern Egan Range. A northeast-striking oblique-slip, also left-lateral and down-to-the-west, cuts through the southern end of this sliver. It is geologically permissible that this fault provides an avenue for minor groundwater to flow between Butte Valley South and Steptoe Valley (Figure 4-10). The Tertiary intrusion north of this fault localized the Cherry Creek mining district, which produced gold, silver, and base metals. 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 Mountains would facilitate flow of recharge westward toward Butte Valley.

4.4.1.9 NORTHERN EGAN RANGE

Like the Cherry Creek Mountains 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 detachment 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, lead, zinc, silver, and gold associated with a Cretaceous pluton. Barren Tertiary plutons 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 Heidrich, 1966; Brokaw and Barosh, 1968; Brokaw, 1973, Brokaw et al., 1973; Jones, 1996). 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 in the WRFS to the west and southern Steptoe Valley to the east.

Steptoe Valley is a deep graben with as much as 8,000 ft of basin-fill sediments in it. Thus, it is one of the deepest grabens in the central Great Basin. Steptoe Valley is part of the GVFS, in which groundwater flows north (Harrill et al., 1988).

4.4.1.10 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 forms the southern end of Steptoe Valley and the northern end of Cave Valley, which continues southward. 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 east 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'). 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 is part of the WRFS and 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 with mostly east-dipping Cambrian rocks at shallow depth and containing relatively thin basin-fill sediments (Plates 4 and 8, Cross Section U—U'). It is geologically permissible that the fault at Shingle Pass provides a conduit for groundwater flow from northern Cave Valley into White River Valley (Figure 4-10). Gravity data (Scheirer, 2005) and oil test well logs (Hess, 2004) indicate that the base of combined basin-fill sediments and volcanic rocks is about 3,000 ft below the valley floor.

The other portion of the valley, southern Cave Valley in Lincoln County, is a tilt block bounded by the high fault scarp of the Schell Creek Range to the east. In other words, the east-dipping Cambrian through Permian succession of the Egan Range passes beneath the valley to terminate against the range-front fault of the Schell Creek Range (Plates 4 and 8, Cross Section R—R'). Nonetheless, a groundwater connection between northern and southern Cave Valley is likely because of the north-striking range-front fault of the Egan Range; however, the southeast-dipping strike ridge south of the Shingle Pass fault continues across Cave Valley and contains the Chainman Shale based on oil test well drilling and gravity surveys (Hess, 2004; Mankinen et al., 2006; Scheirer, 2005). 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 northwest-trending right-lateral faults forms the boundary between southern Cave Valley, northern Pahroc Valley, and northern Dry Lake Valley. These faults provide permissible groundwater pathways out of southern Cave Valley into northern Pahroc Valley, and then potentially into northern Dry Lake Valley.

4.4.1.11 SEAMAN RANGE

The 35-mi-long, heavily-faulted Seaman Range, located in Nye and Lincoln counties, trends north and northwest and joins the Golden Gate Range at the northern end of both ranges (Section 4.4.1.6).

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 (du Bray 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 and subordinate tuffs and a central plug (du Bray and Hurtubise, 1994). The Seaman Range is within the central part of the WRFS, and it is geologically likely that northwest-trending faults along Seaman Wash (southern end of the range) likely form conduits for movement of groundwater between Coal Valley and Pahroc Valley (Figure 4-10).

4.4.1.12 NORTH PAHROC, SOUTH PAHROC, AND HIKO RANGES

The North Pahroc Range extends south from the junction with the southern Egan and Schell Creek ranges for 40 mi. It is separated from the smaller South Pahroc Range by an east-trending belt of faulted rocks of low relief formed by the east-striking Timpahute transverse zone. The belt of faulted rocks is the boundary between Dry Lake Valley to the north and Delamar Valley to the south. The Seaman (Section 4.4.1.11) and the North Pahroc ranges join together at their southern ends, and 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 extends southward from 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 flows from White River Valley 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 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 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 Pahranagat shear zone, 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 North Pahroc Range that contains in most places 3,000 to 5,000 ft of basin-fill sediments (Mankinen et al., 2006) 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) but locally as much as 5,000 ft of sediments and underlying downfaulted volcanic and carbonate rocks (Scheirer, 2005). All

these basins and ranges are within the WRFS. Groundwater flow is southward in Dry Lake and Delamar valleys (Brothers et al., 1996).

4.4.1.13 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 detachment transported Middle Cambrian and younger rocks 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 (Plates 4 and 8, Cross Section U—U') the rocks are mostly Late Proterozoic 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 within the GSLDFS that is discussed in Section 4.4.2.4. 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. Spring Valley continues southeast on the eastern side of the Fortification Range. South of the thin carbonate ridge is Lake Valley, 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). Lake Valley is part of the MVFS, a subsystem of the WRFS. At the thin 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 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 unlikely. 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. The only geologically possible groundwater routes between these valleys is around the northern end of the Schell Creek Range, along the faults that define and continue northeast from Duck Creek Valley, or through middle to upper Paleozoic carbonate rocks at and south of Conners Pass where U.S. Highway 50 crosses the range, but we consider significant flow as unlikely. On the eastern side of northern Cave Valley, the Schell Creek Range is also cored by Precambrian to Cambrian quartzite, creating a likely barrier to

flow between northern Cave Valley and Lake Valley (Figure 4-10). South of 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 likely inhibit this flow.

Northern Dry Lake 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. It is geologically likely 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 4-10). It is permissible that groundwater locally follows paths in carbonate rocks, cross faults, and the caldera margin in the northern Fairview Range (Rowley, 1998). From northern Dry Lake Valley, groundwater passes south along fault conduits into the main part of Dry Lake Valley (Harrill et al., 1988).

4.4.1.14 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 separated 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 detachment 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 west-dipping, west-verging, moderately dipping 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. 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 (Rowley et al., 1994).

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 detachment 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, consists 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. 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 thick (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 Late Proterozoic to Cambrian quartzite results in a likely barrier to groundwater flow between Lake, Patterson (southern Lake) and Panaca (Meadow) valleys to the east and Dry Lake Valley to the west (Figure 4-10). In the Fairview Range, a likely barrier to flow may result from the Indian Peak caldera complex due to probable subsurface intracaldera intrusions and their contact metamorphic and hydrothermal products. Geologically likely conduits to flow through and around the Fairview Range include the faults between Lake and northern Dry Lake valleys, through Muleshoe Pass (Figure 4-10). East-striking faults of the Blue Ribbon transverse zone are mapped between the Fairview and Bristol ranges; however, their hydrologic significance is unknown (Prudic et al., 1995; Rowley, 1998; Rowley et al., 2001). The Pioche Hills could likely form a partial flow barrier due to the presence of Proterozoic to Cambrian shale and quartzite in the range, but this barrier is localized and likely serves only to direct groundwater around the Pioche Hills along fault zones bounding and within the range.

4.4.1.15 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 western extension of 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 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. 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 Late Proterozoic 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). 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 Pahranagat shear zone (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 Pahranagat shear zone and north-striking normal faults into Pahranagat and Coyote Springs valleys (see Figure 4-10).

Late Proterozoic 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 4-10). 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 Pahranagat and Coyote Springs Valleys.

4.4.1.16 MEADOW VALLEY MOUNTAINS

The Meadow Valley Mountains constitute 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).

It is likely that the Tertiary caldera, north-northeast-striking oblique faults, and thrusts prevent groundwater flow between Kane Springs Valley and the valley of Meadow Valley Wash east of the Mormon Mountains.

4.4.1.17 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).

The range is within the WRFS. Coyote Spring Valley, on the western side of the Arrow Canyon Range, is underlain by thin basin-fill sediments, generally less than 1,000 ft deep (Plates 5 and 9, Cross Sections L—L', E—E', F—F', and G—G'). Groundwater moves south beneath Coyote Spring Valley (Harrill et al., 1988). It also flows southeast, passing north of the Arrow Canyon Range as well as through the range in its carbonate rocks. The southeast-flowing groundwater is the principal source of the Muddy River Springs Area and the Muddy River (Schmidt and Dixon, 1995).

4.4.1.18 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 4.4.1.13. Geological reasons for the ridge being a groundwater divide is that it 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 restricts groundwater flow through the northern half of the range.

The southern half of the Fortification Range consists of east-dipping volcanic rocks (Loucks et al., 1989), part of which we interpret 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 range likely marks a groundwater divide between the WRFS and the GSLDFS. 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, so it is geologically possible that some groundwater moves along it.

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 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 a major 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 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. 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 319, is a pass through these hills of outflow volcanic rocks.

Because of its underlying intracaldera intrusions, it is geologically likely that the Indian Peak caldera complex 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 4-10).

4.4.1.19 CLOVER MOUNTAINS AND BULL VALLEY MOUNTAINS

The Clover Mountains, Bull Valley Mountains, and Delamar Mountains represent a poorly defined, broad, east-trending, 60-mi-long massif 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 massif. The Clover Mountains extends from Rainbow Canyon on the west to 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 massif 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 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 massif is heavily cut by north- and northwest-trending faults, so it is geologically possible that these provide conduits to some flow. Rainbow Canyon allows surface water to move southward via Meadow Valley Wash.

4.4.1.20 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 Early Proterozoic 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 argued for Tertiary extension along high-angle normal faults and explained Wernicke's low-angle structures as representing gravity slides. These interpretations have been largely adopted by Page et al. (2005a) and by this report.

The broad valley of Meadow Valley Wash, to the west and northwest of the Mormon Mountains, is underlain by about 3,000 ft of valley-fill sediments (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'). In this part of lower Meadow Valley Wash, the basin-fill sediments are about 2,000 ft thick. 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 massif represents a barrier to groundwater flow between the eastern side of Meadow Valley Wash and the Tule Desert to the east. However, the low divide north of the Mormon Mountains may provide geological structures that make flow possible in this area. Northwest of the Mormon Mountains, thrust faults may also likely restrict groundwater flow to the east. Southwest of the Mormon Mountains, flow is likely from lower Meadow Valley Wash to the Glendale basin (Section 4.4.1.21) to the south.

4.4.1.21 NORTH MUDDY MOUNTAINS, MUDDY MOUNTAINS, AND DRY LAKE RANGE

The southeastern end 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 separate the Glendale basin on the west from the Mesquite basin on the east. The Muddy Mountains occupy 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 just southwest 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 (Glendale basin) are not connected with those in the Las Vegas Valley and, based on limited mapping in the area, 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), and the east-west gap between the two ranges, now occupied by Tertiary and Quaternary basin-fill sediments, likely also is underlain by fractures of the same strike. The northern Muddy Mountains and North Muddy Mountains contain significant Jurassic sedimentary rocks

(Bohannon, 1983), 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 4-10) (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). Bohannon interpreted this structure as the northern continuation of the Keystone thrust zone, which has been displaced approximately 40 mi right laterally by the Las Vegas Valley shear zone. 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).

The southeastern edge of the geologic study area, where the Muddy and Virgin rivers enter the Overton Arm of Lake Mead, is probably an area of groundwater discharge. Basin-fill sediments, dominated at the surface by resistant Quaternary calcretes, underlie Mormon Mesa and its northward extension. This prominent calcrete is underlain by Pliocene to upper Miocene basin-fill deposits making up the southwestern end of the Mesquite basin. The Black Mountains and Gold Butte areas, respectively west and east of Lake Mead, contain Proterozoic metamorphic rocks that extend northward to the southwestern Virgin Mountains. Numerous fault zones have been mapped here and in the northeastern end of the Muddy Mountains, including northeast-striking faults that are discharge points for Rogers and Blue Point springs in the Lake Mead National Recreation Area. These faults most likely are related to a series of faults that strike northeast, have oblique-slip (left-lateral and normal) motion, and are part of the Lake Mead fault zone (Anderson and Barnhard, 1993).

4.4.2 BASINS AND RANGES WEST AND EAST OF THE WHITE RIVER FLOW SYSTEM

This section discusses the geology and hydrogeology of basins and ranges outside the WRFS and MVFS. The areas are described generally from north to south and west to east.

4.4.2.1 ANTELOPE RANGE, WHITE PINE COUNTY

The Antelope Range, in northeastern White Pine County, Nevada, is a relatively small, low range of faulted, mostly Tertiary volcanic rocks that unconformably overlie mostly 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 are as much as 5.5 km. The Antelope Range and its bounding valleys are within the GSLDFS. The range likely is a barrier to groundwater flow through it (Figure 4-10), for flow in northern Spring Valley appears to head mostly south, whereas flow in Tippett Valley appears to head mostly north (Harrill et al., 1988).

4.4.2.2 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. 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 that erupted lava flows occurs on the southeastern side of the range (Gans et al., 1989). A small north-trending range north of the western side of the Kern Mountains and east of Tippett (Antelope) Valley consists mostly of Tertiary volcanic rocks. A small 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'). Another valley south of the Kern Mountains appears to be shallow.

The Kern Mountains and associated ranges are within the GSLDFS. 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 may take place along east-striking fault conduits and carbonate rocks south of the mountain block (Figure 4-10).

4.4.2.3 DEEP CREEK RANGE, UTAH

The Deep Creek Range is a 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 to the southeast. The fault on the eastern side of the Deep Creek Range appears to be the main basin-range fault controlling the range, but the basin-range fault on the western side is also significant, for it drops down 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 Late Proterozoic quartzite and schist of the McCoy Creek and Trout Creek groups. These Precambrian units have a combined thickness estimated at 19,000 ft (Hintze, 1988; Nutt et al., 1990). West of the southern part of the range, Paleozoic sedimentary rocks dip westward. These rocks range from Late Proterozoic 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 as a core complex (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 4-10). Nonetheless, the range and its bounding valleys are part of the GSLDFS. 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 the flow system (Harrill et al., 1988).

4.4.2.4 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 Great Basin National Park. 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 horst, bounded on both sides by major high-angle normal fault zones. Spring Valley, west of the Snake Range, is a major graben defined by basin-range faults of at least 10,000 ft of vertical displacement. Snake Valley, east of the Snake Range, is a graben containing about 5,000 ft of basin-fill deposits but local holes in the basin contain deposits thicker than this (Plates 4 and 8, Cross Sections X—X', W—W', V—V', and U—U') (Allmendinger et al., 1983; Saltus and Jachens, 1995; Kirby and Hurlow, 2005). Hamlin Valley, southeast of the Snake Range and south of Snake Valley, is similar to Snake Valley in structural size. The Limestone Hills is a narrow, low, heavily faulted cuesta extending about 20 mi south of the Snake Range.

Except for the southern end, the Snake Range is cored by Late Proterozoic to Cambrian quartzite, intruded by a massive batholith of apparent Jurassic age (Whitebread, 1970; Miller et al., 1994 and 1995). The range is a metamorphic core complex, which rose rapidly and formed the Snake Range decollement, a detachment fault (Miller et al., 1999). This low-angle Tertiary detachment formed over an extended period as the range uplifted and stretched the roof rocks apart (Figure 4-8) (Gans, 2000b). The fault 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. The decollement is exposed on the top and eastern side of the northern half of the range. The central part of the Snake Range is narrower and lower. On the eastern side of Sacramento Pass, north-striking, down-to-the-east listric normal faults drop down a thick section of Tertiary volcanic and basin-fill rocks (Gans et al., 1989; Miller et al., 1994, 1995, and 1999). The southern end of the range consists of south-plunging tilt blocks of Paleozoic rocks as young as Mississippian. These tilt blocks become 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 4.4.1.18). The southern end of the Limestone Hills forms part of the northern wall of the Indian Peak caldera complex.

Spring Valley is a 100-mi-long, broad, deep graben containing about 6,000 ft of basin-fill sediments (Plates 4 and 8, Cross Sections X—X', W—W', V—V', and U—U'). Snake Valley is a similarly long, broad, deep graben that passes southward into Hamlin Valley. Basin-fill sediments are locally more than 5,000 ft thick beneath Snake Valley (Plates 4 and 8, Cross Sections X—X', W—W', and V—V') (Davis, 2005).

The Snake Range and Spring, Hamlin, and Snake valleys are part of the GSLDFS. In northern Spring Valley, groundwater flows partly along north-striking basin-range faults and related fractures but appears to pool in northern Spring Valley (Harrill et al., 1988). Gravity data support a groundwater divide between northern and central Spring Valley, coinciding with a surface-water divide (Mankinen et al., 2006). McPhee et al. (2005 and 2007) used gravity data and an AMT profile across southern Spring Valley, west from the Limestone Hills, to identify many previously unknown faults in the basin-fill sediments, which here are as thick as 3,000 ft. Some of the groundwater in southern Spring Valley flows east through the Limestone Hills into Hamlin Valley (Harrill et al., 1988). From Hamlin Valley, groundwater flows mostly northward into Snake Valley (Davis, 2005) then farther northward to the Great Salt Lake Desert (Harrill et al., 1988). 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 possible that minor groundwater might flow through it along an east-striking fault and adjacent carbonate and volcanic rocks near Osceola, Nevada. But we consider such flow unlikely because any flow would be at least 1,500 ft below the surface at Osceola. The carbonate rocks and faults that form the Limestone Hills provide the only significant pathway for groundwater flow from southern Spring Valley to Hamlin Valley and from there to southern Snake Valley (Figure 4-10). Hood and Rush (1965) estimated a flow of 4,000 afy through the Limestone Hills.

Fracture flow, as elsewhere in the Great Basin, explains movement of groundwater in Snake Valley. In other words, we interpret that northward groundwater flow beneath Snake Valley is along mostly high-angle, north-striking normal faults in both the basin-fill and carbonate-rock aquifers, few of which can be shown on Plates 1 and 4 because of the scale. We also interpret that these faults formed Snake Valley, resulting in a deep graben, as supported by geophysics and logs of oil wells. Allmendinger et al. (1983) and Kirby and Hurlow (2005), however, suggested that the eastern frontal fault of the Snake Range, separating the range from Snake Valley, is the low-angle Snake Range decollement. The straight range front argues for our interpretation of a high-angle normal fault. Miller et al. (1999), who have studied the Snake Range decollement in the most detail, agree with us and showed (Miller et al., 1999, Figure 10) such a high-angle fault cutting the decollement (Plates 4 and 8, Cross Section W—W').

4.4.2.5 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. 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. Tule Valley is east of the Confusion Range. 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 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 folded, thrusted, and attenuated, middle to upper Paleozoic rocks that together form a synclinorium, in other words a combination of synclines and

anticlines that overall appear as a broad syncline (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. Basin-range faults cut all these ranges, but most are of small magnitude so individual stratigraphic units are remarkably coherent and continuous over this large area. The most significant basin-range fault 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 Confusion Range and adjacent ranges and valleys are within the GSLDFS. The Chainman Shale underlies at shallow depth all of these areas accept the southern Confusion Range. In fact, the Chainman is folded along north-striking trends so it is repeated over the area. 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 faults, which provide conduits for northward flow. 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).

4.4.2.6 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, near the eastern margin 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, 2002a). Locally lower Paleozoic carbonate rocks are thrusted over upper Paleozoic carbonate rocks (Best et al., 1987a and b). Most of the Needle Range, however, consists of east-dipping outflow ash-flow tuffs derived primarily from the Indian Peak caldera complex. The eastern caldera margin passes through much of the southern part of the range (Williams et al., 1997). The Needle Range is a faulted horst, with the main basin-range fault 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, consists of gently folded and locally thrusted, lower to middle Paleozoic carbonate rocks. Farther south,

east-dipping Late Proterozoic to Cambrian quartzite and overlying Cambrian carbonate rocks form most of the range (Hintze and Davis, 2002a). 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).

Hamlin, Pine, and Wah Wah valleys are part of the GSLDFS, likely with northward groundwater flow into Snake Valley (Harrill et al., 1988). Except for their southern edges, the Needle Range and Wah Wah Mountains also are within the GSLDFS. These southern edges and the Escalante Desert are part of the Sevier Lake Flow System of Harrill et al. (1988), where groundwater flow is eastward then northward to its sump at Sevier Lake, east of the House Range. Groundwater flow from Pine Valley to Wah Wah Valley is permissible through the northern Wah Wah Mountains because of its carbonate rocks and perhaps even through the southern part of the Wah Wah Mountains because of its outflow volcanic rocks and local cross faults (Harrill et al., 1988). The presence of Late Proterozoic to Cambrian quartzite in the central part of the range, however, likely prevents flow through the range here. Wah Wah Valley may receive flow from the Sevier Lake Flow System to the east (Harrill et al., 1988). Nonetheless, northward flow likely dominates in all these valleys, following conduits provided by the basin-range faults.

4.4.2.7 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 contains basin-fill sediments that in most places are 1,000 to 2,000 ft thick (Plates 4 and 8, Cross Sections W—W' and V—V') but have been estimated to be locally more than 6,000 ft thick (Davis, 2005).

The Fish Springs Range is a highly faulted but generally gently west-dipping horst consisting of lower Paleozoic carbonate rocks (Plates 4 and 8, Cross Section X—X') (Hintze, 1980; Hintze et al., 2000). The range is bounded by large basin-range faults on its western and eastern sides. The high House Range is a tilt block, bounded on the western side by a major basin-range fault beneath eastern Tule Valley. The fault uplifts the range and tilts it several degrees east (Hintze and Davis, 2002b). 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.

The Fish Springs Range and the valleys east (Fish Springs Flat) and west (Tule Valley) of it are within the GSLDFS. The House Range marks the eastern side of this flow system. Late Proterozoic 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. Some eastward groundwater flow, however, is permissible through Sand Pass between the Fish Springs and House ranges (Harrill et al., 1988). Southern Tule Valley receives flow from the Sevier Lake Flow System to the east (Harrill et al., 1988). Northward flow, of course, likely dominates in this entire area in conduits provided by basin-range faults, including the fault zone along the western side of the Fish Springs and House ranges (Stephens, 1977). In northern Tule Valley, this northward flow is shown as likely, and northwestward flow is considered permissible (Figure 4-10).

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GEOPHYSICS

5.1 GRAVITY

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

USGS collected gravity observations at 1,013 new sites to supplement about 5,000 previous stations in this area (Snyder et al., 1981; Bol et al., 1983; Snyder et al., 1984; Ponce, 1992 and 1997; Scheirer, 2005; Mankinen et al., 2006). 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.

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

Gridded isostatic gravity anomaly data were used to guide the gravity analysis in two modes: (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 involves two steps: (1) to separate contributions to the isostatic gravity anomaly that arise from Cenozoic sedimentary and volcanic deposits and those from pre-Cenozoic rocks and (2) to convert the contributions from the lower density deposits into a model of basin depth (Jachens and Moring, 1990).

Because available gravity data for the study area were made by many different observers at different times, the data set was examined to remove duplicate entries. Major station elevations were compared with elevations interpolated from 10- and 30-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). The resulting isostatic gravity field emphasizes features that reflect local density variations in the middle and upper crust. Gravity lows (cool colors) generally indicate low-density sedimentary and volcanic rocks in basin fill; gravity highs (warm colors) generally reflect pre-Cenozoic basement rocks in the basin.

The isostatic residual gravity field reflects a pronounced contrast between dense pre-Cenozoic rocks and significantly less dense overlying strata. Because of this relationship, the gravity inversion method (Jachens and Moring, 1990) can be used to separate the isostatic residual anomaly into

pre-Cenozoic "basement" and younger "basin" fields, thus allowing an estimate of thickness of Cenozoic alluvial fill and underlying Tertiary volcanic rocks within the area. The accuracy of thickness estimates derived by the gravity inversion technique is dependent on (1) the assumed density-depth relation of the Cenozoic valley 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 Late Precambrian through upper Paleozoic marine carbonate and siliciclastic sedimentary rocks. Subvolcanic Cenozoic intrusions are included here as part of the basement because their physical properties are similar to most of the older rocks, and they differ strongly from those of the eruptive and basin-fill sequences. The density-depth function used here is the same as used in an earlier basin-depth analysis of the Basin and Range province (Saltus and Jachens, 1995). The gravity inversion method also allows the input of basement depths determined from deep drill-holes and seismic data.

5.1.1 Gravity Data for Spring and Snake Valleys

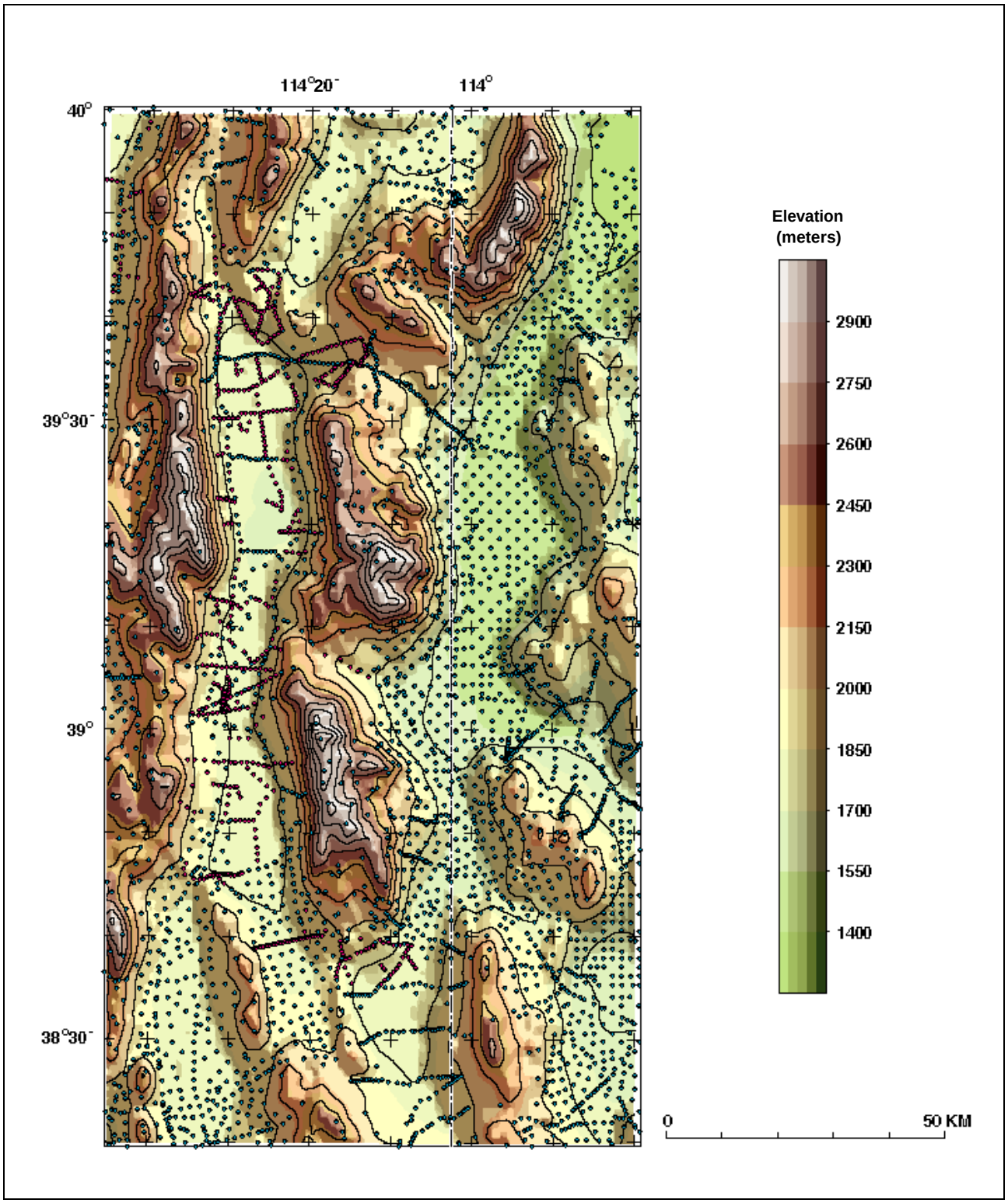
As discussed by Mankinen et al. (2006 and 2007), a total of 545 new gravity stations (Figure 5-1) were collected for Spring and Snake valleys (Figure 5-2). The isostatic gravity field for Spring and Snake valleys is shown on Figure 5-3. The depth to basement, calibrated by oil and gas wells (dots in Figure 5-4) is shown on Figure 5-4. The topographic contour interval in these figures is 200 m.

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

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

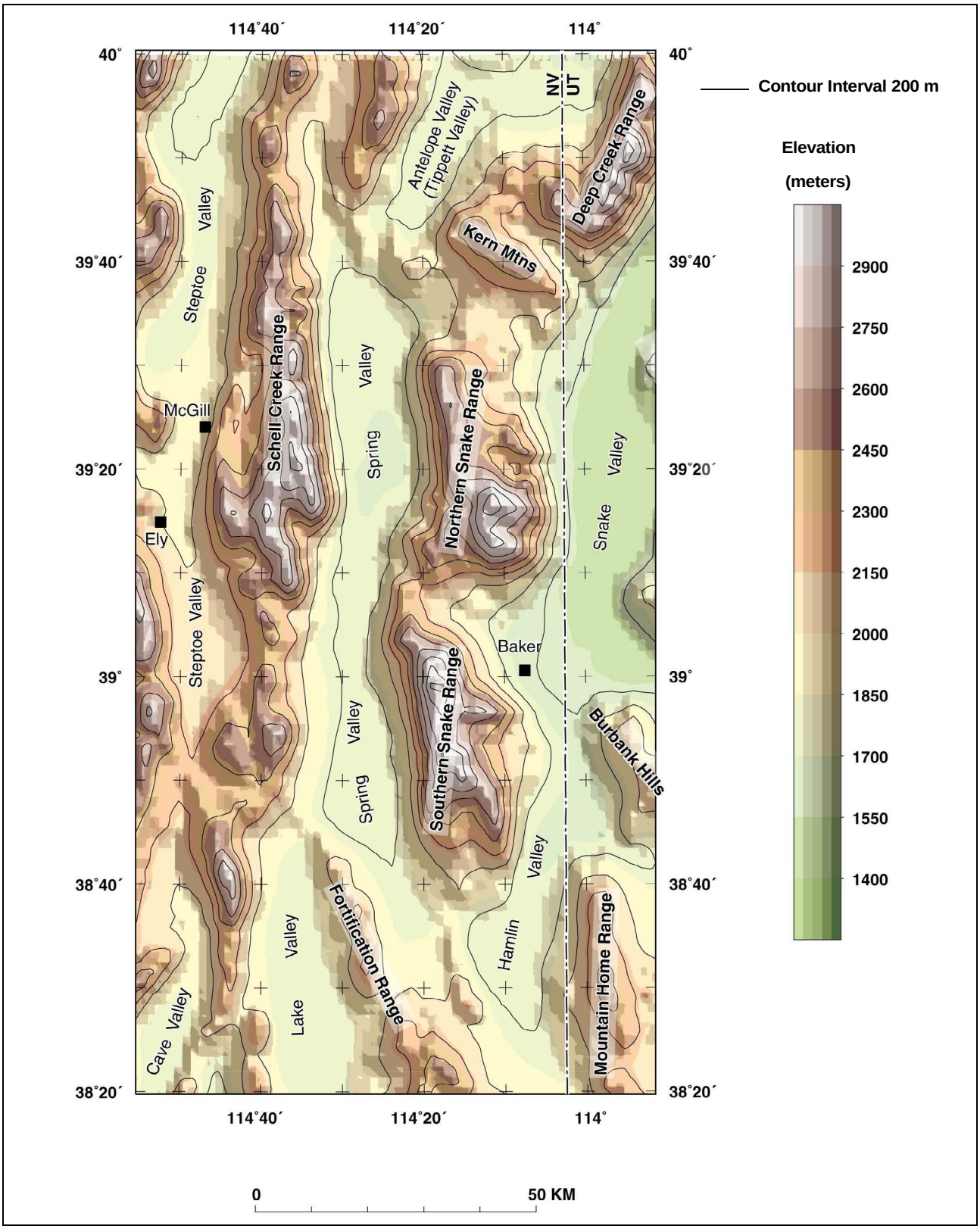
In 2003 and 2004, USGS collected gravity observations at 468 new sites (Scheirer, 2005; Mankinen et al., 2006 and 2007) in Cave, Dry Lake, and Delamar valleys to supplement the prior compilation of ~3,500 stations in this area (Figure 5-5) (Snyder et al., 1981; Bol et al., 1983; Snyder et al., 1984; and Ponce, 1992 and 1997).

Analysis of gravity anomalies in Cave, Dry Lake, and Delamar valleys defines the shape of their basins, estimates the depth to pre-Cenozoic basement rocks, and identifies buried faults (Figure 5-6 [Scheirer, 2005, Figure 2]). In all cases, the basins are asymmetric in their cross section and in their placement beneath the valley, reflecting the extensional tectonism that was initiated during Miocene time in this area. Absolute values of basin depths are estimated using a density-depth profile calibrated by deep oil and gas wells and one MX well (red and white dots and red triangle, respectively, in Figures 5-5 and 5-6), some of which penetrated pre-Cenozoic basement. In Figure 5-6, the red and white dashed lines show the outlines of the alluvial valleys. The left image of Figure 5-6 shows the basin gravity anomaly derived from the depth-to-basement algorithm, the



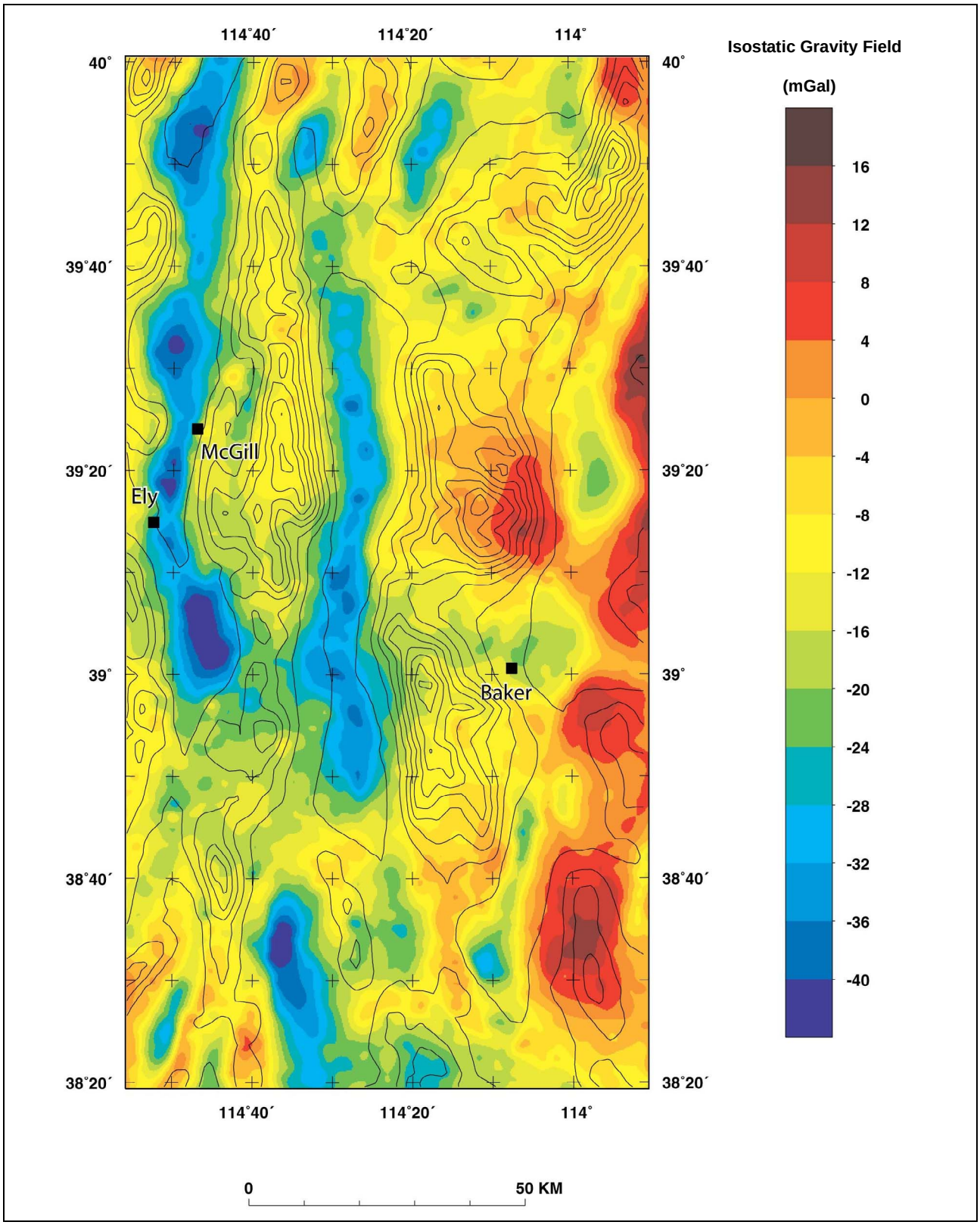
Source: after Mankinen et al., 2006

FIGURE 5-1
PREVIOUSLY AVAILABLE GRAVITY STATIONS (GREEN DOTS) AND GRAVITY STATIONS ESTABLISHED DURING THE 2004/2005 FIELD SEASONS (RED DOTS) IN SPRING AND SNAKE VALLEYS, NEVADA AND UTAH



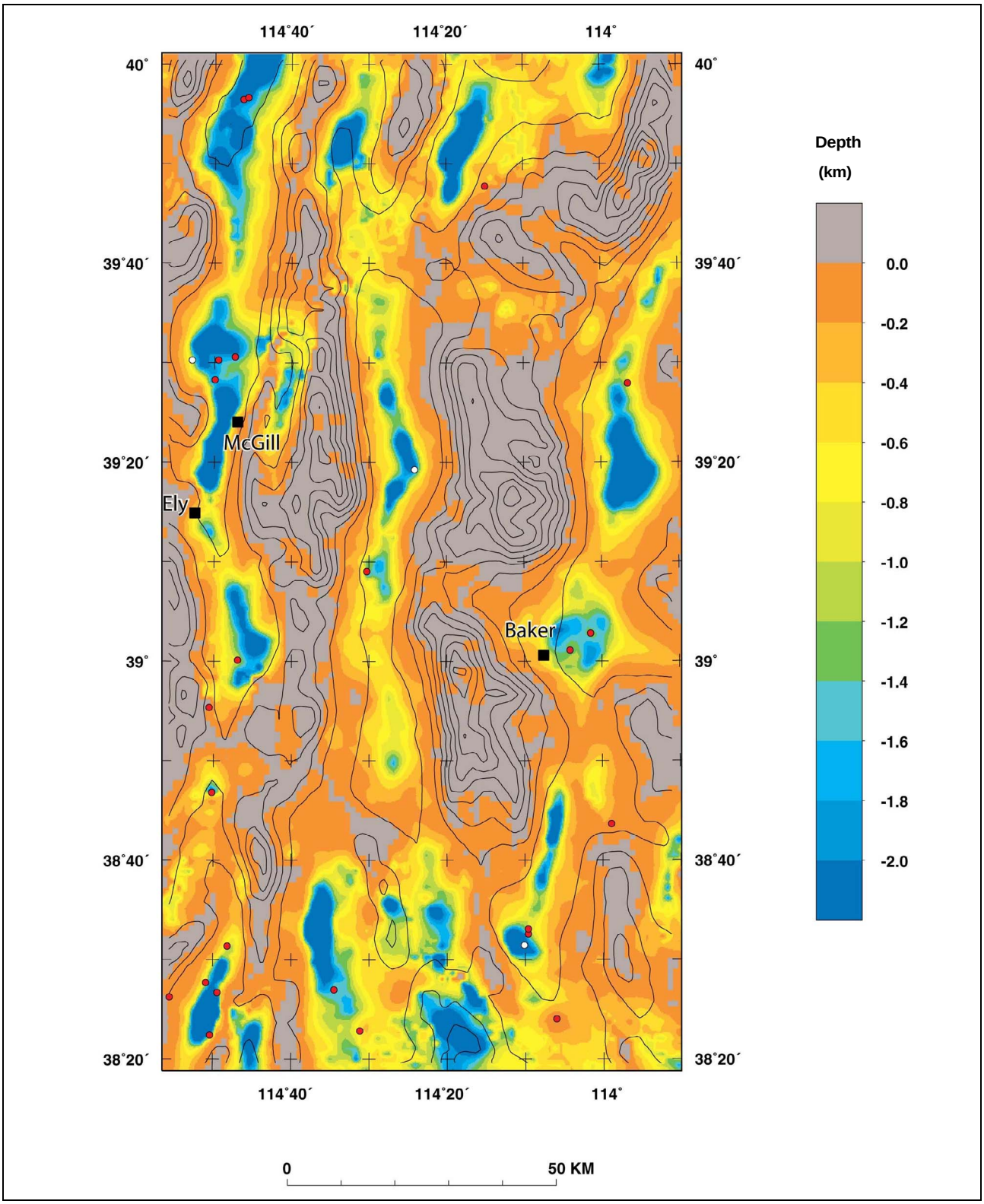
Source: after Mankinen et al., 2006

FIGURE 5-2
INDEX MAP TO THE SPRING VALLEY, NEVADA, STUDY AREA



Source: after Mankinen et al., 2006

FIGURE 5-3
ISOSTATIC RESIDUAL GRAVITY FIELD



Note: Red dots are drill holes that encountered pre-Cenozoic basement; white dots are holes in alluvium.
Source: after Mankinen et al., 2006

FIGURE 5-4
DEPTH TO PRE-CENOZOIC BASEMENT IN THE SPRING VALLEY STUDY AREA

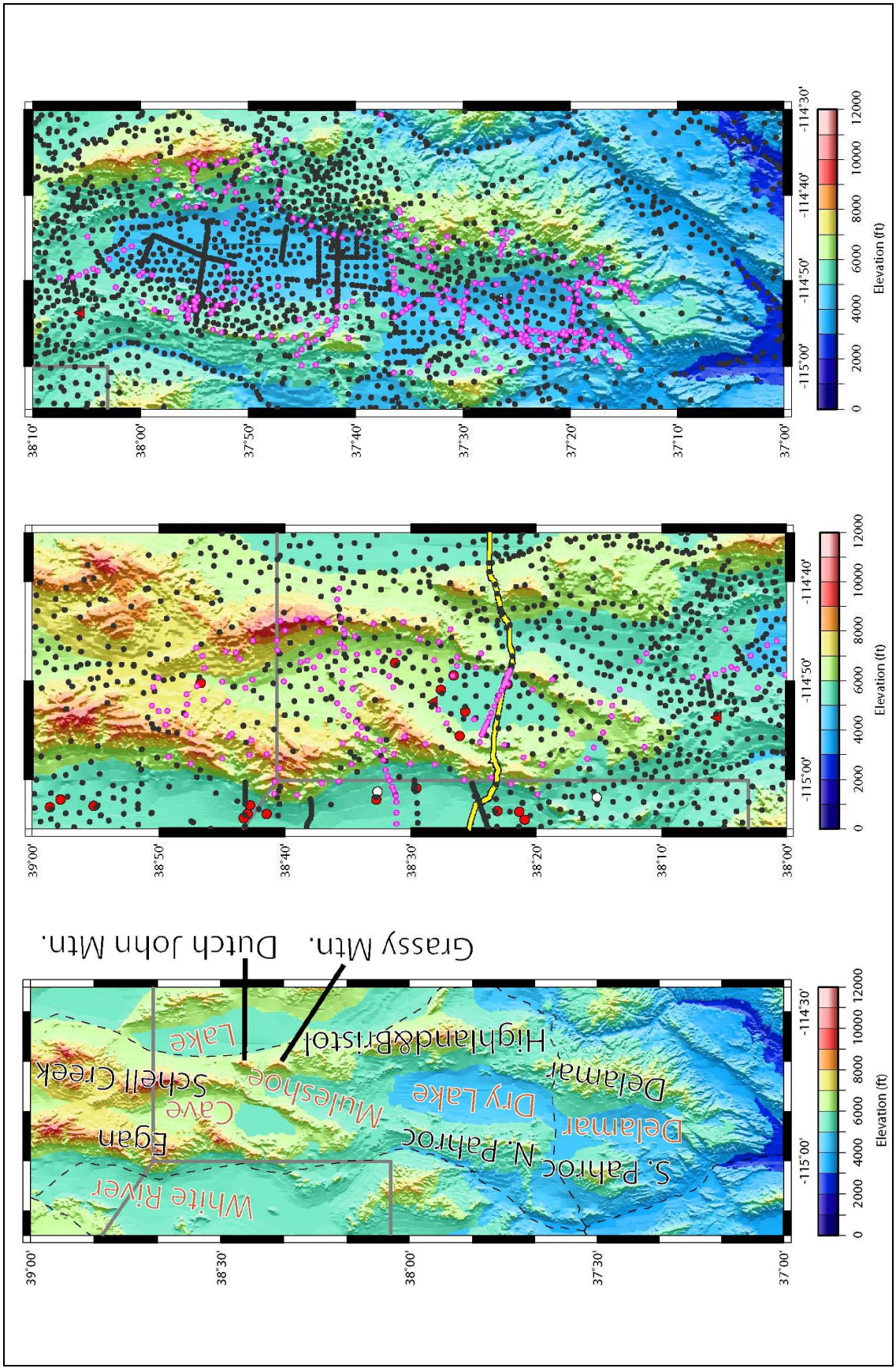
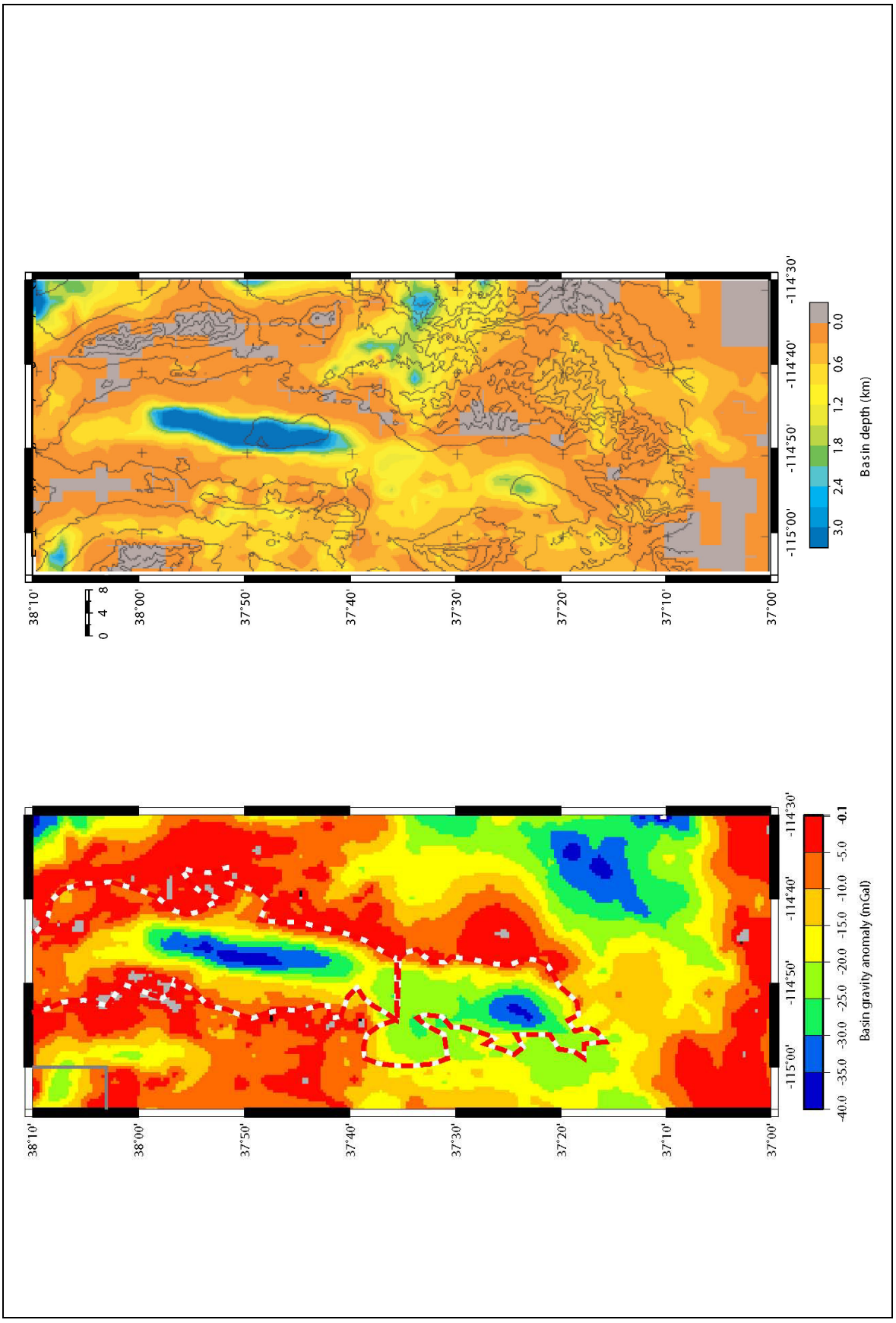


FIGURE 5-5
INDEX MAP, SHOWING GRAVITY STATIONS, OF CAVE, DRY LAKE, AND DELAMAR VALLEYS WITHIN THE GEOLOGIC STUDY AREA

Note: Black dots are previous stations, pink dots are new stations, large red and white dots are oil and gas drill holes, red triangle is MX well.
Source: after Scheirer, 2005



Source: after Scheirer, 2005; Mankinen et al., 2006 and 2007.

FIGURE 5-6

CAVE, DRY LAKE, AND DELAMAR VALLEY BASIN GRAVITY ANOMALIES DERIVED FROM DEPTH-TO-BASEMENT ALGORITHM

image shows the calculated basin depth based on the basin gravity anomaly. The basin beneath southern Cave Valley extends down to 3 to 5 km, that beneath Dry Lake Valley to 3 to 5 km, and that beneath Delamar Valley to 2 to 3 km. The ranges surrounding Dry Lake and Delamar valleys are dominated by volcanic units that may produce lower-density basin infill, which, in turn, would make the maximum depth estimates somewhat less. 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. Significant portions of the basins are shallow (less than 1 km deep) as are the transitions between each of these valleys. A seismic reflection image across southern Cave and northern Dry Lake (Muleshoe) valleys (yellow line in central image of Figure 5-5) confirms the basin shapes inferred from gravity analysis. The architecture of these basins inferred from gravity aided in interpretation of the hydrogeologic framework of Cave, Dry Lake, and Delamar valleys by placing estimates on the volume and connectivity of potential unconsolidated alluvial aquifers and by identifying faults buried beneath basin deposits.

5.1.3 GRAVITY DATA FOR COYOTE SPRING VALLEY

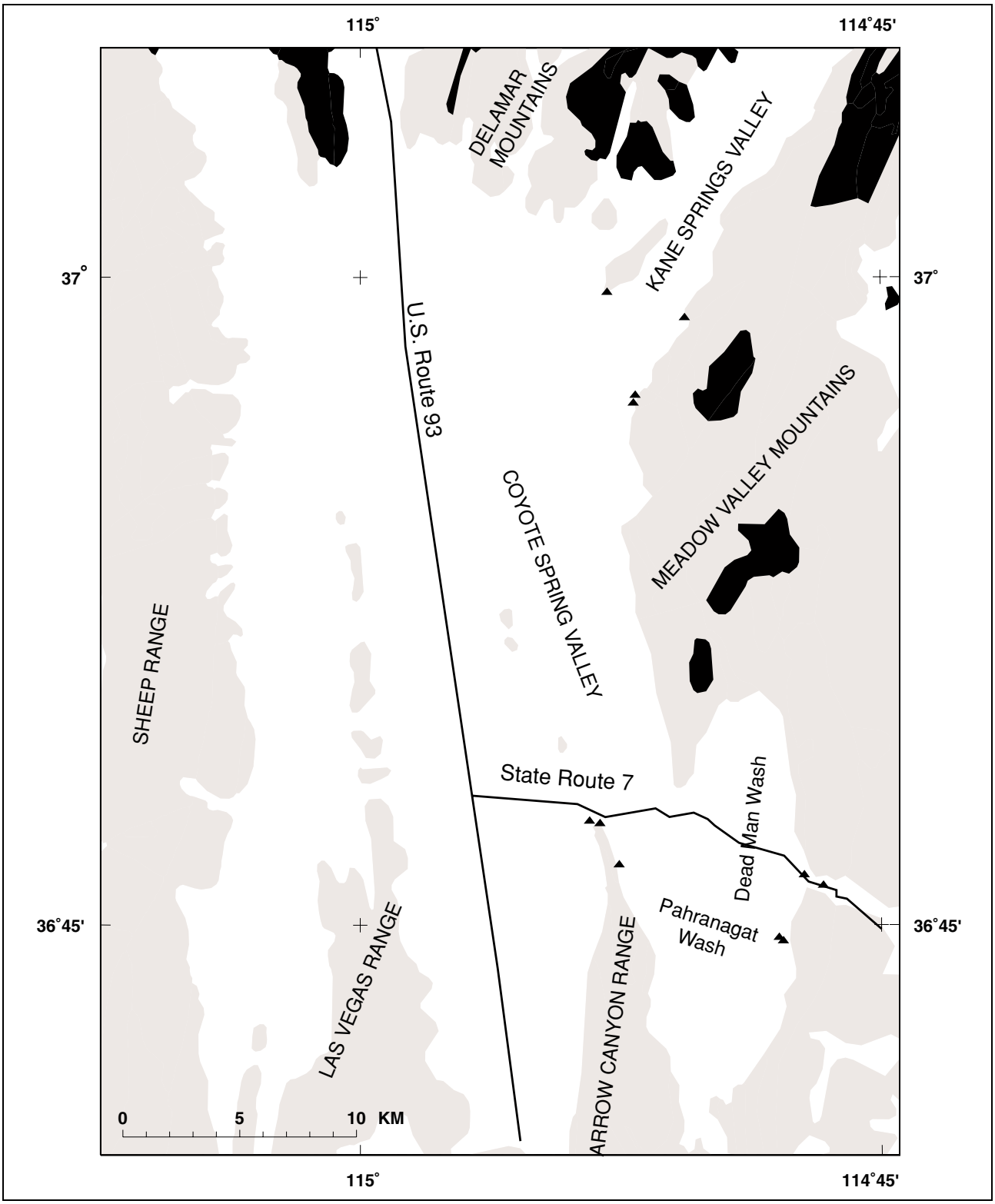
USGS conducted gravity surveys in the Coyote Springs Valley and vicinity in Clark and Lincoln counties, Nevada (Phelps et al., 2000). These gravity measurements (224 measurements spaced 660 ft apart) were made along 5 profiles across parts of the Coyote Spring Valley to aid in modeling the depth and shapes of the underlying basins and to locate faults concealed beneath the basin fill (Figure 5-7).

The isostatic residual gravity field defined by the new data is shown in Figure 5-8. The results of the depth to pre-Cenozoic basement analysis are shown in Figure 5-9. The results show two deep basins (the northern crossed by profile N2 and the southern crossed by profiles S1 and S3) beneath the axis of Coyote Spring Valley, both reaching maximum depths greater than about 3,300 ft. The deepest parts of both basins are aligned north-south and are separated from each other by a north-northwest-trending, shallowly-buried, bedrock edge that is the northward continuation of the Arrow Canyon Range. A smaller basin (maximum depth of about 1,600 ft) lies beneath the valley containing Dead Man Wash and part of Pahranagat Wash and appears to be the southern continuation of the northern basin beneath Coyote Spring Valley.

5.2 AUDIOMAGNETOTELLURICS STUDIES

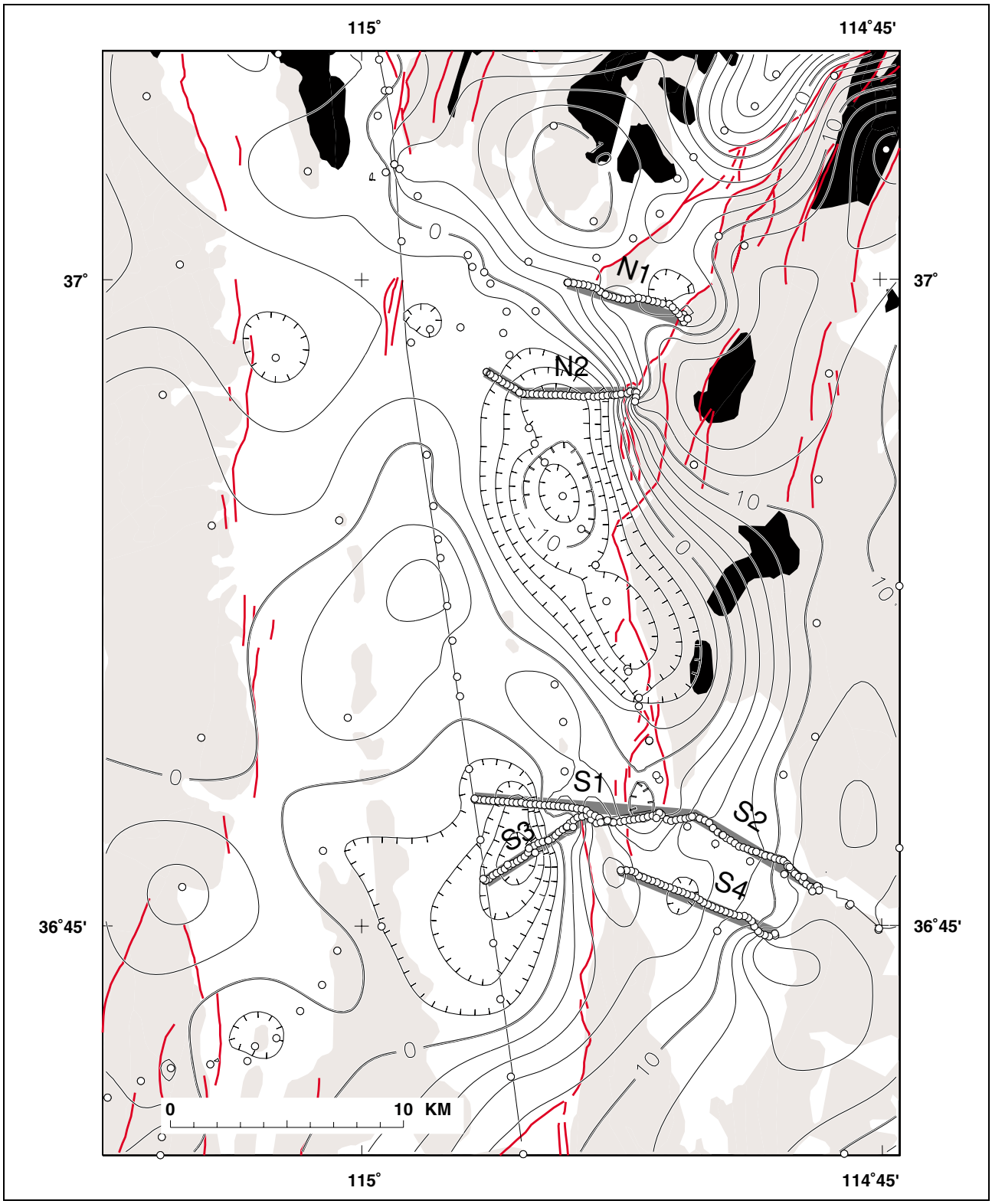
In conjunction with the gravity studies of Scheirer (2005), Mankinen et al. (2006), and Phelps et al. (2000), AMT technology was tested to see whether it is a feasible approach for mapping the structure and to contribute to the regional hydrological model in a typical Basin and Range setting. In particular, faults and stratigraphy within the valleys, as well as estimates of depth to pre-Cenozoic basement, are valuable targets. AMT technology is used to detect variations in shallow, subsurface electrical resistivity, which is largely dependent on the fluid content, porosity, fracturing, and conductive mineral content of the subsurface geology. We concluded that it may serve as a valuable tool for mapping subsurface faults and lithology at shallow levels of basins (~1,000 m).

The AMT data were collected along two profiles in Spring Valley by McPhee et al. (2005) and shown on Figure 5-10. The models along Profile A (Figure 5-11) and Profile B (Figure 5-12) in Spring Valley show detailed fault structure (black lines in Profile A, red lines in Profile B) revealed by the inversion model within the alluvial basin. A clear transition between unsaturated (200 to 500 ohm-m)



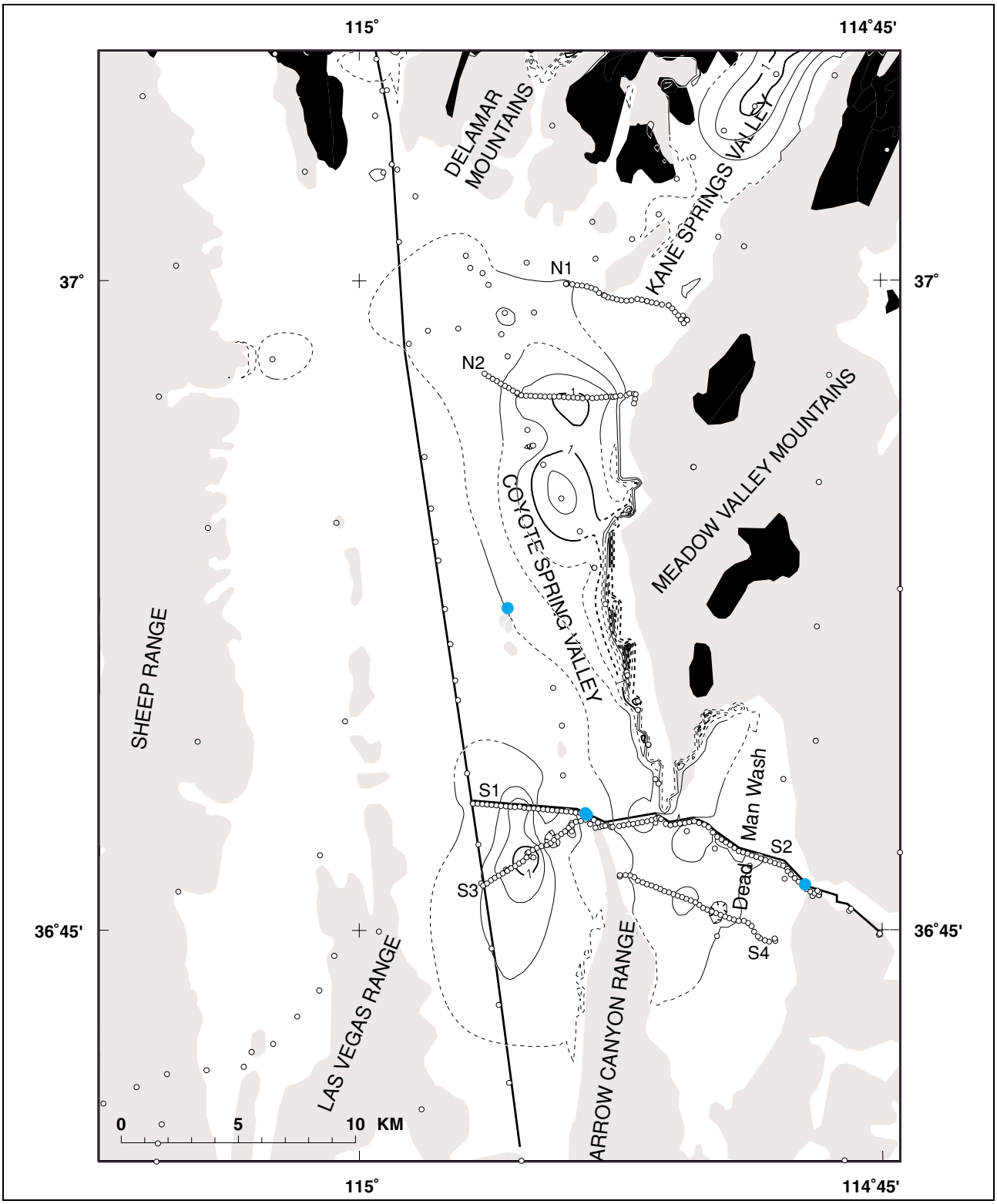
Note: Black areas have outcrops of Cenozoic volcanic rocks, pink areas have outcrops of Paleozoic rocks, and white areas indicate areas covered by Cenozoic basin fill. Solid triangles indicate locations where samples of Paleozoic rock were collected for density measurements. Source: after Phelps et al., 2000

FIGURE 5-7
INDEX MAP SHOWING COYOTE SPRING VALLEY STUDY AREA AND VICINITY



Note: Contour interval = 2 mGal. Open circles show gravity stations. Bands labelled N1-N2 and S1-S4 are detailed gravity profiles that were modeled to define basin shape. Red lines indicate faults mapped by Dohrenwend et al. (1996). See Figure 5-7 for geology and culture. Source: after Phelps et al., 2000

FIGURE 5-8
ISOSTATIC RESIDUAL GRAVITY CONTOURS FOR COYOTE SPRING VALLEY AND VICINITY



Note: Contour intervals, 250 m, 1 km. Open circles show gravity stations. Bands labelled N1-N2 and S1-S4 are detailed gravity profiles that were modeled to define basin shape. Contours dashed where poorly constrained. Blue dots, wells that penetrate pre-Cenozoic basement. See Figure 5-7 for geology and culture. Source: after Phelps et al., 2000

FIGURE 5-9
BASIN THICKNESS MAP OF THE STUDY AREA

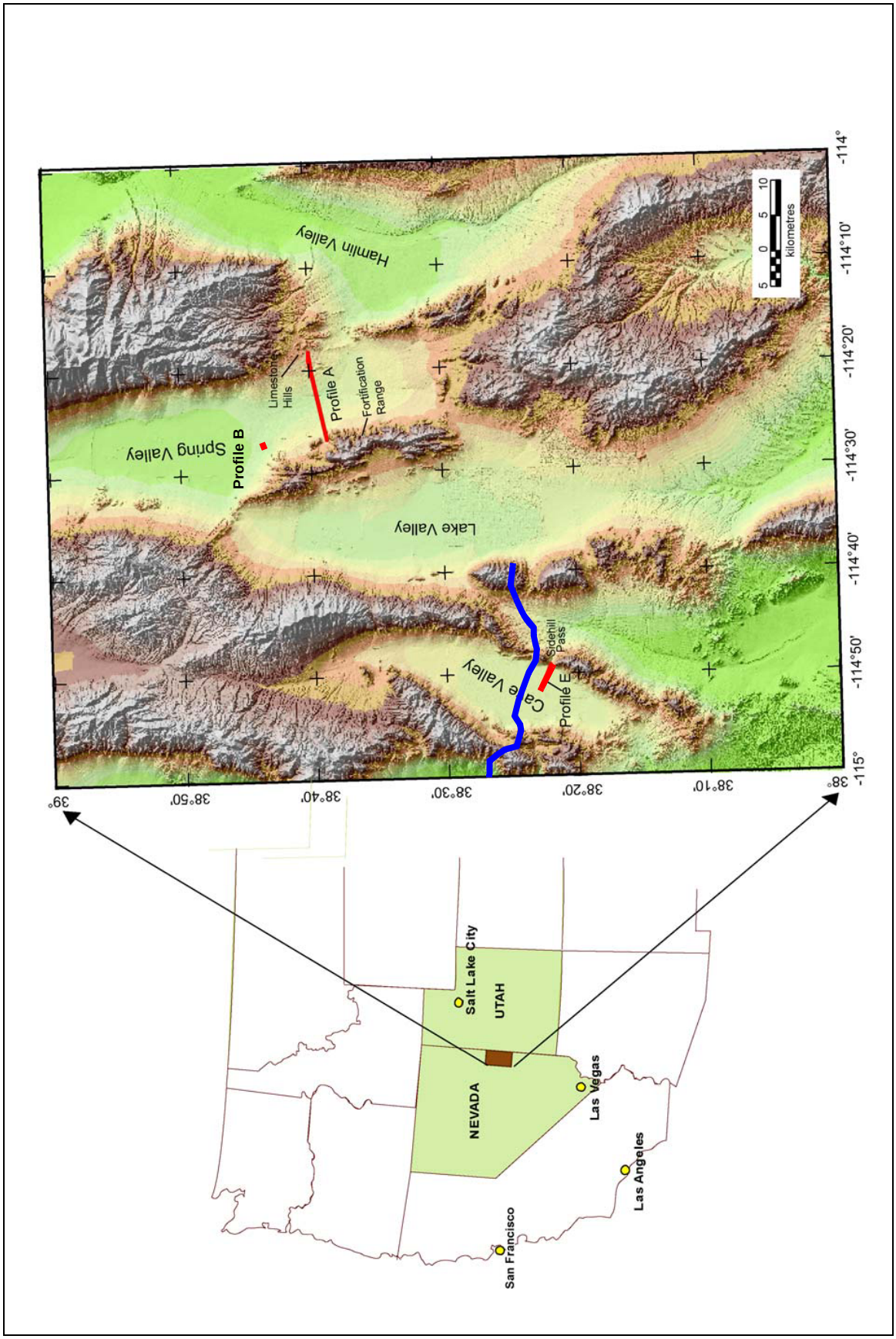
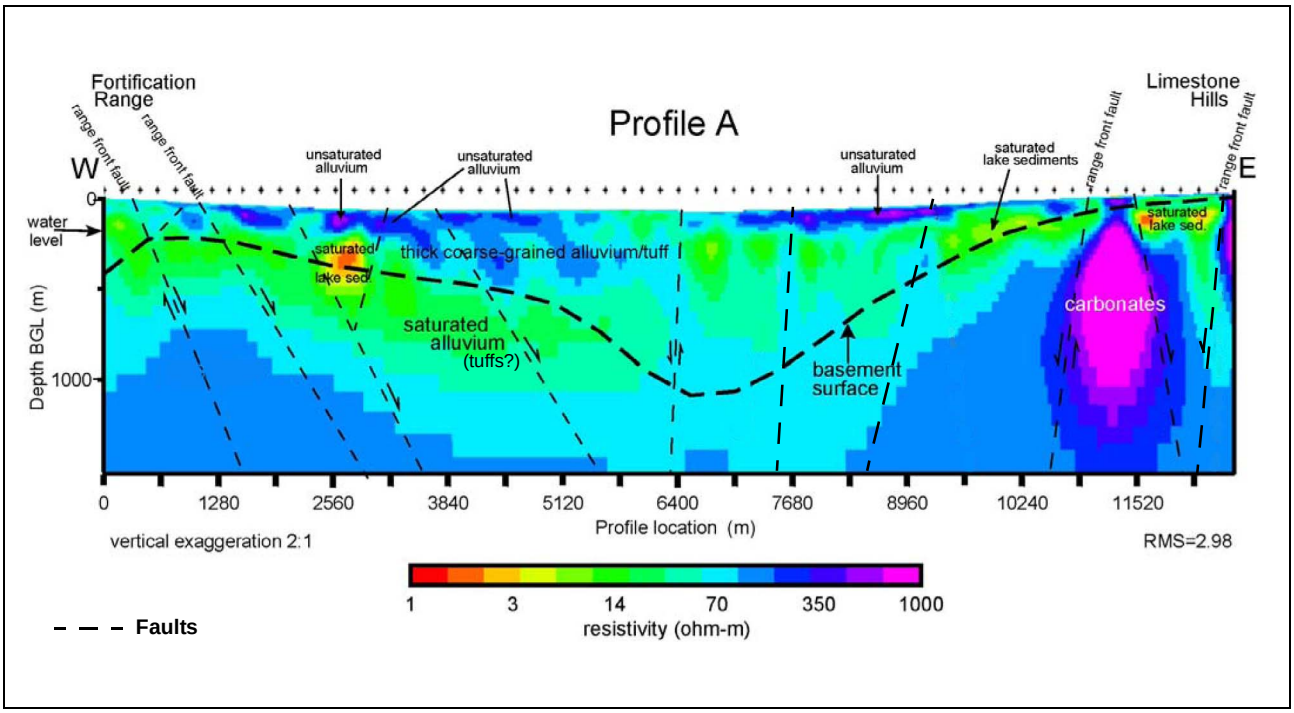


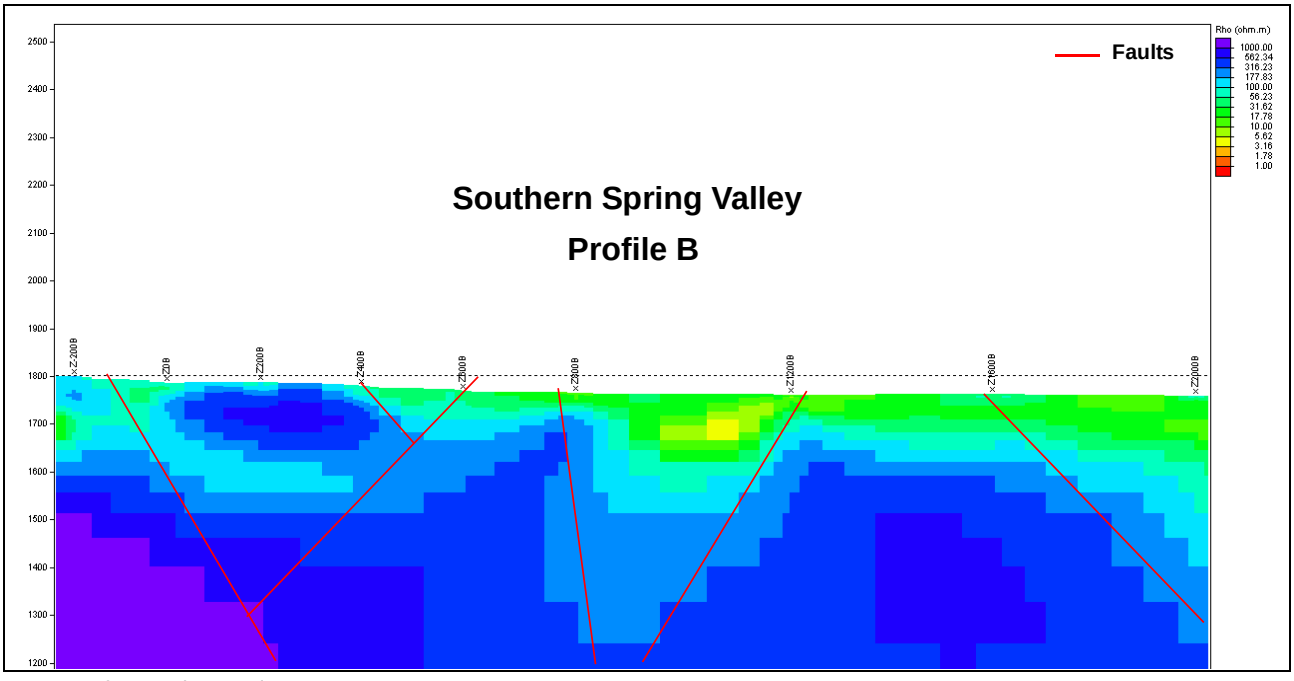
FIGURE 5-10
LOCATIONS OF AMT PROFILES (RED) AND ECN-01 SEISMIC LINE (BLUE) PERFORMED IN THE GEOLOGIC STUDY AREA

Source: after McPhee et al., 2005



Source: after McPhee et al., 2005

FIGURE 5-11
AMT MODEL ALONG PROFILE A ACROSS SOUTHERN SPRING VALLEY, NEVADA

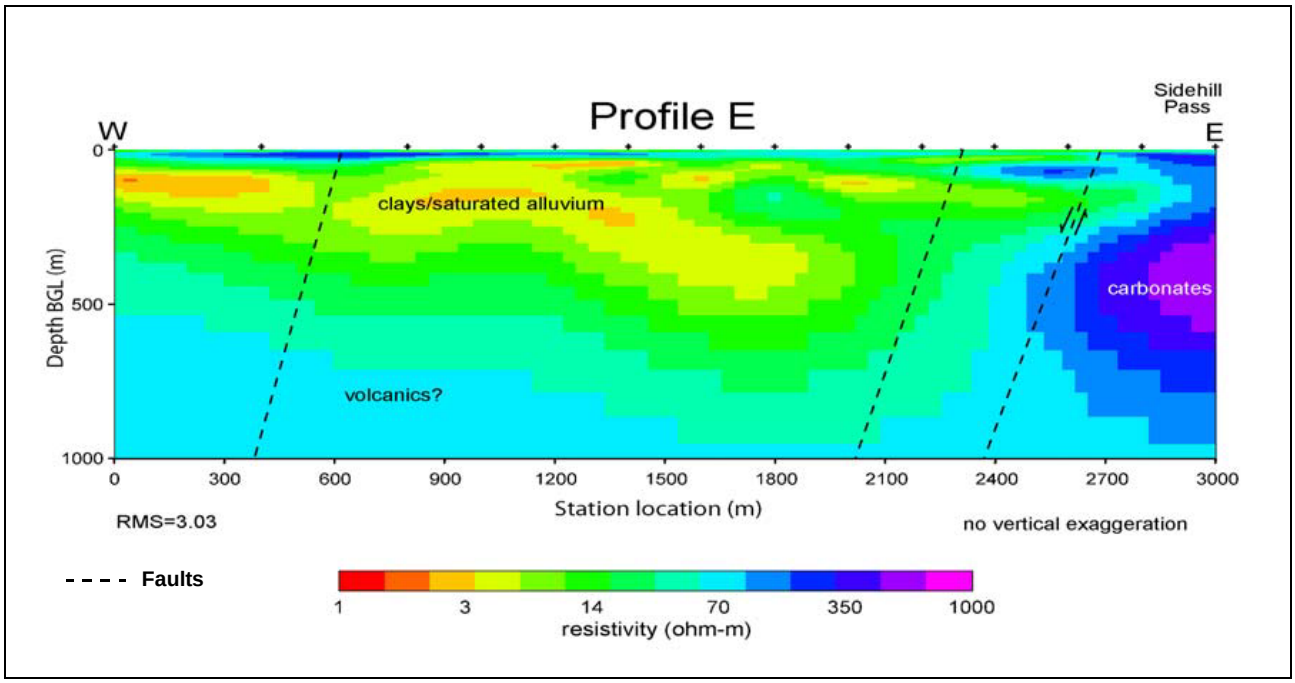


Source: after McPhee et al., 2005

FIGURE 5-12
AMT MODEL ALONG PROFILE B ACROSS SOUTHERN SPRING VALLEY, NEVADA

and saturated alluvium/volcanic rocks (20 to 50 ohm-m) is present at roughly 100 m depth in Profile A. High-resistive (greater than 1,000 ohm-m) carbonate rocks are clearly defined at the eastern end of Profile A under the Limestone Hills, and the locations and dips of several range-front and interbasin faults that lack surface expression can be interpreted throughout the upper 1-km portion of the section image. The interpreted surface of the pre-Cenozoic basin is shown by the heavy dashed line in Figure 5-11.

McPhee et al. (2005 and 2007) provided information on faults on the eastern side of the southern part of Cave Valley, based on AMT profiles (Figure 5-10 and Figure 5-13). The data collected along this Profile E (Figure 5-13) were "noisier" than those collected along Profiles A and B in Spring Valley. The upper several hundred meters of the valley shows more conductive alluvial fill (3 to 20 ohm-m) than was observed in Spring Valley, perhaps due to the additional presence of clays in the valley. Clearly delineated structure within the basin includes other interbasin faults as well.



Source: after McPhee et al., 2005

FIGURE 5-13
AMT MODEL ALONG PROFILE E ACROSS CENTRAL CAVE VALLEY, NEVADA

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

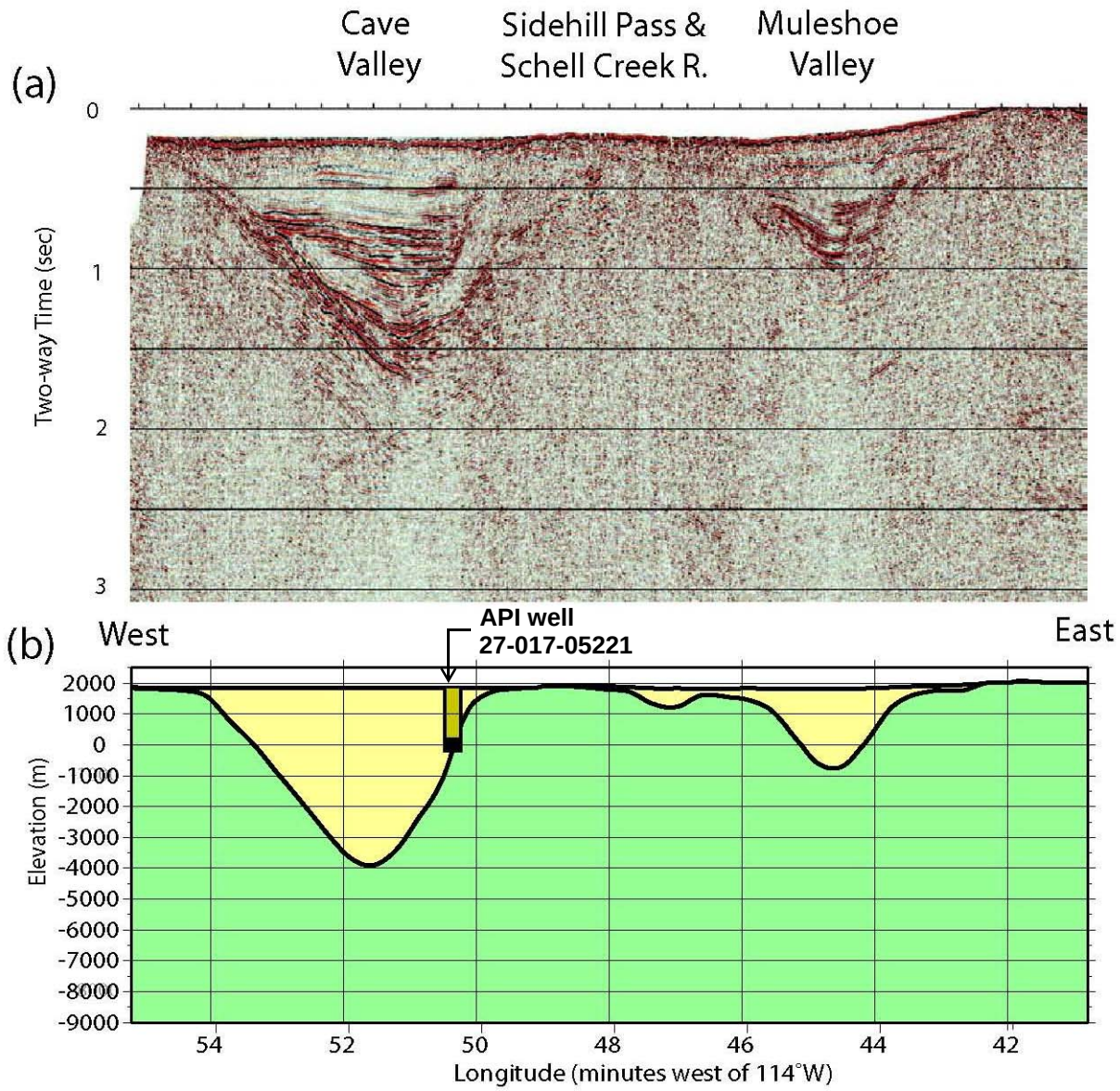
When compared to the basement-surface estimates derived from the inversion of the gravity data (Scheirer, 2005; Mankinen et al., 2006), AMT technology proves successful at estimating the depth to bedrock. That the AMT data is consistent with the gravity data enhances confidence in these depth estimates.

Several AMT profiles were attempted in Coyote Spring Valley, but due to significant electronic noise from local construction activities, no usable data were obtained.

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 5-14a). 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 5-14b) 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 5-14b to illustrate its general agreement with the gravity depth-to-basement estimate and to show its position with respect to the seismic structures.



(a) Cross section of southern Cave and northern Muleshoe valleys ECN-01 seismic reflection section displayed in time. (b) Results of gravity depth-to-basement inversion with low-density basin fill in yellow. 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 5-14
(A) ECN-01 SEISMIC REFLECTION SECTION DISPLAYED IN TIME
(B) RESULTS OF GRAVITY DEPTH-TO-BASEMENT

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6.0

SUMMARY

6.1 GENERAL GEOLOGY OF THE STUDY AREA

Eastern Nevada and adjacent parts of Utah were the sites of deposition of thick quartzite and other clastic rocks in Late Proterozoic and Early Cambrian time. These rocks, the initial deposits of the Cordilleran miogeocline, were deposited in shallow marine water along a passive continental margin of what is now western North America. Middle Cambrian through Lower Permian rocks record a shift in deposition to predominantly carbonate sedimentation, resulting in 30,000 ft or locally more of mostly limestone and dolomite, the great carbonate aquifer. All these rocks can be grouped into two facies that are gradational over time and place: (1) a western facies of the Cordilleran miogeocline, now exposed in most of the map area, that represents a Late Proterozoic through Devonian offshore carbonate shelf and intertidal environment of deposition and an overlying Mississippian to Permian carbonate platform; and (2) a thinner eastern facies that includes cratonic platform rocks (Colorado Plateau) in the extreme southeastern part of the geologic study area that are mostly shallow marine but includes near-shore through continental environments of deposition.

In Late Devonian to Late Mississippian time, thrust faults and folds of the Antler compressive deformational event transported deeper-marine rocks eastward to about the longitude of Eureka, Nevada, and created a highland there. Clastic sediments, which included the Chainman Shale, were deposited in a foreland marine basin east of the Antler Highland. Carbonate deposition resumed by Late Mississippian time and continued through the Pennsylvanian and into the Permian.

Triassic, Jurassic, and Cretaceous rocks in the geologic study area are mostly continental clastic units deposited only in the eastern part of the area. In fact, the entire geologic study area was characterized by erosion during and after deposition of these units, so they are spotty in distribution and collectively were less than several thousand feet thick. From Middle Jurassic through the early Paleocene, thrust faults, folds, and intrusions of the Sevier compressive deformational event were emplaced. The thrusts transported western facies rocks eastward onto thinner eastern, more cratonic facies. A series of thrusts are well exposed throughout the southern part of the area, and some of these continue into the central and northern part of the map area. But most thrusts strike north-northeast and therefore pass east of the northern part of the map area. The deformation created a highland over most of the area that shed clastic sediment eastward.

During and following the waning stages of the Sevier deformation in the Paleocene, erosional stripping of the Sevier highland that included the northern part of the map area led to sedimentation mostly east of the map area. Only the post-deformational Sheep Pass Formation in mostly White Pine County and the Claron Formation in the extreme southeastern part of the area remain as patches in the geologic study area. These rocks, as well as the deeply eroded underlying Paleozoic and Mesozoic rocks, were inundated by voluminous Eocene to Miocene calc-alkaline, subduction-related volcanic rocks. Most of these rocks are ash-flow tuff, derived from many scattered calderas in the area, but andesitic to dacitic lava flows and mudflow breccia from stratovolcanoes were also deposited. Depositional thickness of overall outflow ash-flow tuffs and flows ranged from about 1,000 to 6,000 ft thick over most of the area, but intracaldera tuffs were thicker. Intrusions, the ultimate sources of the volcanic rocks, are abundant. The locations and types of post-Sevier faults that

deformed the lower to middle Tertiary sedimentary and volcanic rocks are uncertain but doubtless included oblique-slip high-angle faults. East-trending transverse zones, which began to form in the Mesozoic, deformed the calc-alkaline rocks and continued throughout the Cenozoic.

By middle to late Miocene, subduction ceased and the area began to be deformed by extensional tectonics, during which time the rocks were pulled apart in an east-west direction. North-trending normal basin-range faults began to form. By about 10 Ma ago, this deformation intensified and the present topography began to form. North-trending ranges were, and continue to be, uplifted on one side as tilt blocks or on both sides as horsts, and north-trending basins similarly went down as tilt blocks or grabens. The ranges were stripped by erosion and the basins were filled by the erosional debris. The resulting basin-fill sediments accumulated to many thousands of feet thick until the present time. Bimodal (basalt and rhyolite) volcanic rocks, generally thin, are intertongued with the basin-fill sediments.

6.2 GENERAL HYDROGEOLOGY OF THE STUDY AREA

Each succeeding episode of deposition and deformation had increasingly greater effects on the hydrogeology of the study area. Most of the hydrogeologic effects for Paleozoic events, including the Antler deformational event, resulted from deposition of the various sediments that would become the aquifers and aquitards of eastern Nevada. The greatest of these aquifers is the carbonate aquifer. On the other hand, deposition of clastic sediments predominated throughout the Mesozoic, resulting primarily in aquitards or low-permeability sedimentary rocks. The Sevier deformational event created barriers to groundwater flow in the southern part of the geologic study area.

During the middle Cenozoic, emplacement of calderas and associated intracaldera intrusions created areas of low permeability within the region but, especially where fractured ash-flow tuffs dominate, the thick calc-alkaline volcanic rocks are major aquifers. Some volcanic rocks sandwiched between valley fill above and carbonate rocks below may have reduced the interconnection of the carbonate aquifer and the valley fill in a few basins. The result is that carbonate aquifers beneath the volcanic rocks may be under artesian pressure or at least have a piezometric head higher than that of the basin fill. Some springs may result from this. During Mesozoic to late Cenozoic time, east-west transverse zones developed. These zones may provide potential conduits or barriers to groundwater flow, but their hydrologic significance is unknown at this time.

From middle Miocene to Holocene time, basin-range extensional tectonics resulted in the dominantly north-south faults of the Great Basin. These north-trending structures are excellent conduits to north or south groundwater flow. Gouge in the core zone of these north-south faults acted as partial to complete barriers, however, to east or west flow. During this tectonism, all rocks became fractured, but brittle units such as ash-flow tuffs, carbonate rocks, and basalt and rhyolite flows became shattered throughout and thus became local to regional aquifers. In carbonate rocks, groundwater dissolution resulted in even larger and more interconnected fracture conduits.

7.0

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Appendix A

General Photos of the Study Area



View northwest of Jackmans Narrows cut into folded and faulted Permian carbonate rocks. Towns of Glendale and Moapa in the background.



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



View overlooking Muddy River Springs Complex.



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



View north into southern Delamar Valley. Delamar Lake 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.



View west from the Meadow Valley Mountains across the oblique-slip fault scarp of the Kane Springs fault zone at the Kane Springs Wash caldera complex in the Delamar Mountains.



View 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.



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



View to the south looking at springs in White River Valley.

Plates

Legend

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
- Js — Jurassic sedimentary rocks, undivided
- Ts — 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
- PP — Permian and Pennsylvanian Riepe Spring Limestone and Ely Limestone, undivided
- P — 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
- DC — Devonian to Upper Cambrian sedimentary rocks, undivided
- DS — Devonian and Silurian sedimentary rocks, undivided
- Du — Devonian carbonate sedimentary rocks, undivided
- Dd — Upper and Middle Devonian Devils Gate Formation
- Dg — Upper and Middle Devonian Guilmette Formation
- Dn — Middle and Lower Devonian Nevada Formation
- Ds — Middle and Lower Devonian Simonson and Sevy Dolomites
- SOu — Silurian and Upper Ordovician dolomite, undivided
- Ol — Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
- €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.
- Transverse Zone (Zone of possible disruption)

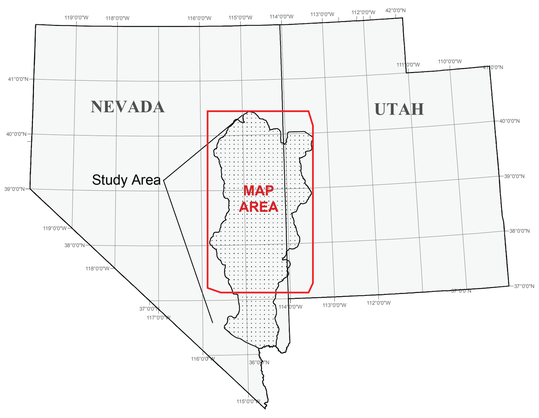
Subsidiary Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Strike-slip Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Thrust Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Detachment Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain

- Strike and Dip of Beds
- Caldera Boundary — Solid where known; dashed where concealed
- 5000 — Elevation Contours - 1,000 ft
- Cross Sections (Plates 4 and 5)
- Oil Well Data Used in Cross Sections — Nevada: Nevada Bureau of Mines and Geology; Utah: Utah Division of Oil, Gas and Mining

SCALE 1:250,000

N W E S



10 5 0 10 20 30 Kilometers

10 5 0 10 20 30 Miles

Projection: UTM Zone 11 NAD83

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

Southern Nevada Water Authority

MAP ID 13872 11/06/2007 JMB

Legend

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 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
Ŧrs	Triassic sedimentary rocks, undivided
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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
€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.
- **Reverse Fault** — Solid where known; Dashed where inferred; dotted where concealed. Bar and ball on downthrown side.
- Transverse Zone (Zone of possible disruption)
- Las Vegas Shear Zone

Subsidiary Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Strike-slip Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Thrust Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Detachment Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain

- Strike and Dip of Beds
- Caldera Boundary — Solid where known; dashed where inferred; dotted where concealed
- Elevation Contours - 1,000 ft
- Cross Sections (Plates 4 and 5)
- Oil Well Data Used in Cross Sections — Nevada: Nevada Bureau of Mines and Geology

SCALE 1:250,000

N W E S

Projection: UTM Zone 11 NAD83

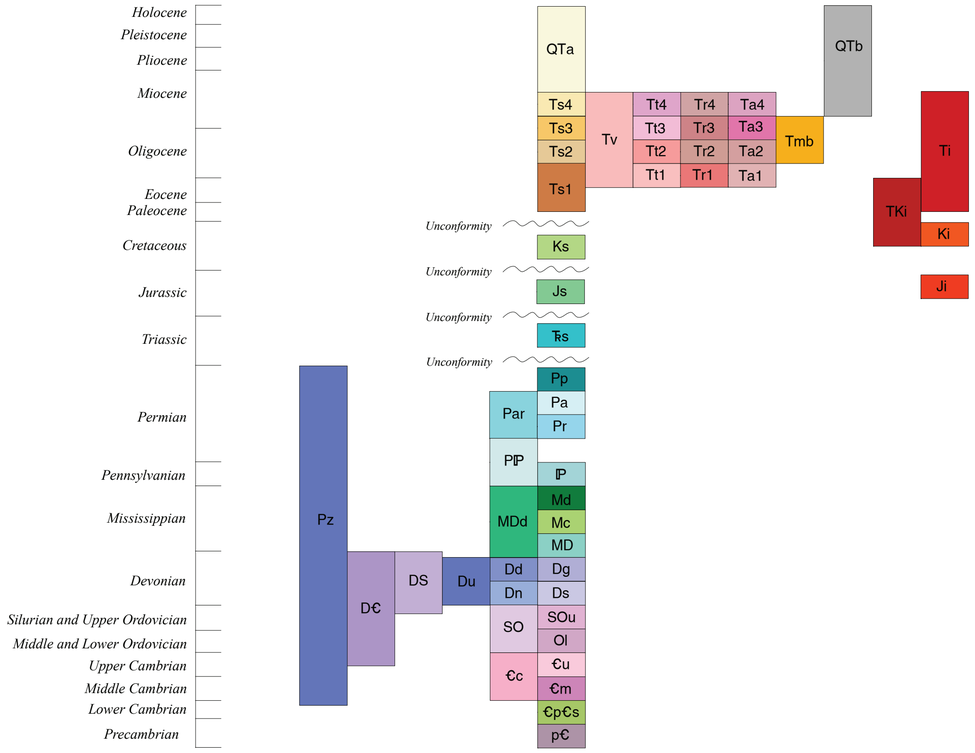
10 5 0 10 20 30 Kilometers

10 5 0 10 20 30 Miles

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

MAP ID 13873 11/01/2007 JMB

Southern Nevada Water Authority



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

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.

Ts — 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 rocks are mostly clastic.

Pz — 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)—Mostly in the northern part of Plate 1, thickening eastward.

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

PP — 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.

P — 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.

D€ — Devonian to Upper Cambrian sedimentary 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.

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

€u — Upper part (Lower Ordovician? and Upper Cambrian)—Includes the Notch Peak Limestone, Orr Formation, Windfall Formation, Nopah Limestone, Dunderberg Shale, and Corset Spring Shale. In the extreme southwestern part of Plate 2, includes the Emigrant Formation (Upper and Middle Cambrian).

€m — Middle part (Upper and Middle Cambrian)—Mostly the Highland Peak Formation and its southwestern equivalent, the Bonanza King Formation. 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.

€p€s — Lower part (Middle Cambrian to Late Proterozoic)—Chisholm Shale (Middle Cambrian), Lyndon Limestone (Middle Cambrian), Pioche Shale (Middle and Lower Cambrian), Carrara Formation (Middle and Lower Cambrian), Stella Lake Quartzite (Lower Cambrian), Prospect Mountain Quartzite (Lower Cambrian and Late Proterozoic), and Johnnie Formation (Late Proterozoic). The Prospect Mountain, in turn, has been subdivided into the Zabriskie Quartzite (Lower Cambrian), Wood Canyon Formation (Lower Cambrian), and Sterling Quartzite (Lower Cambrian and Late Proterozoic). Locally includes the Reed Dolomite (Lower Cambrian) and underlying Wyman Formation (Lower Cambrian?) in the southwestern part of Plate 2.

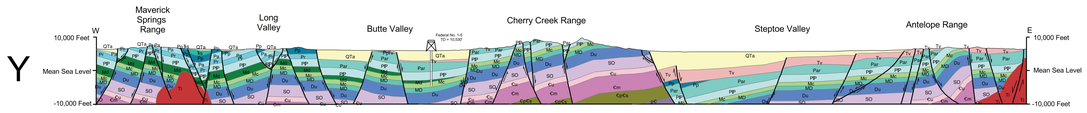
p€ — Metamorphosed and crystalline Precambrian basement rocks (Late to Early Proterozoic)—Throughout most of Plates 1 and 2, consists of metamorphosed quartzite of Late Proterozoic age, namely the McCoy Creek Group and, in Utah, also the underlying Trout Creek Group. Locally, in the southern part of Plate 2, includes crystalline basement rocks.

Open Water

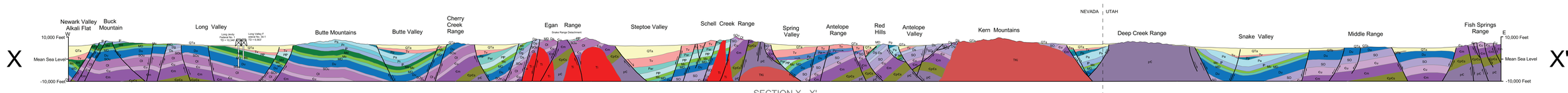
PLATE 3. EXPLANATION OF GEOLOGIC UNITS FOR THE MAPS AND CROSS SECTIONS OF PLATES 1, 2, 4, AND 5.

MAP ID 13874 11/05/2007 JMB

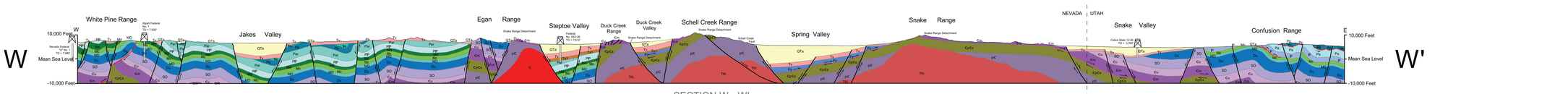
Southern Nevada Water Authority



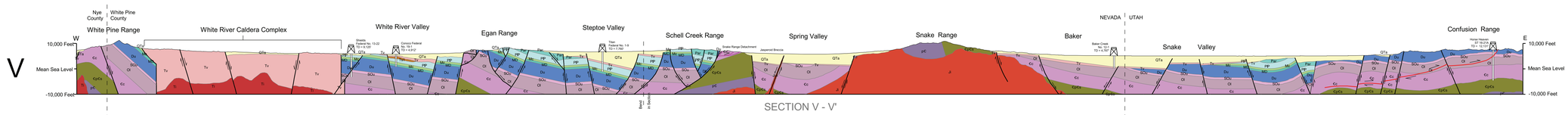
SECTION Y - Y'



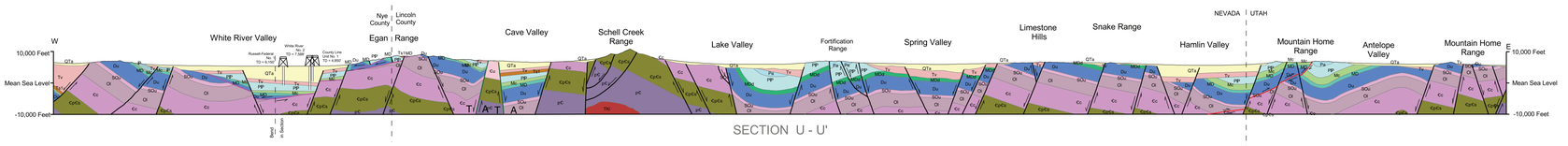
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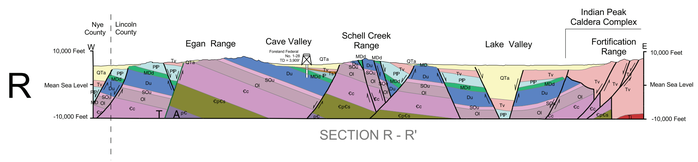
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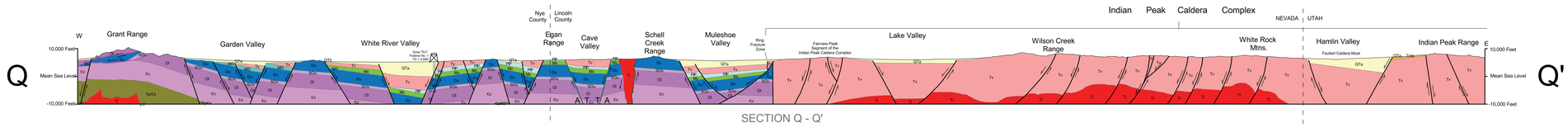
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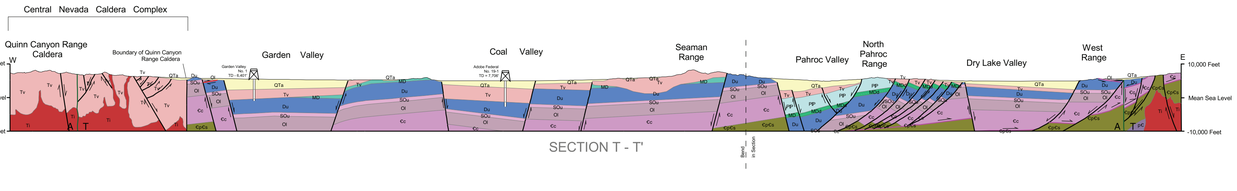
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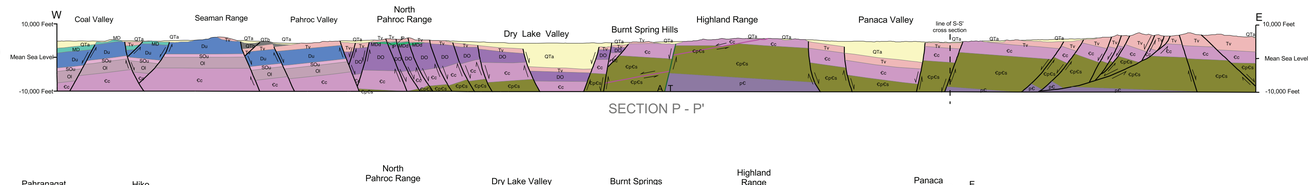
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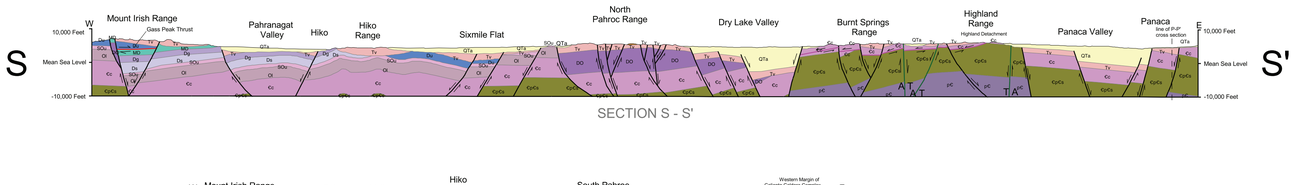
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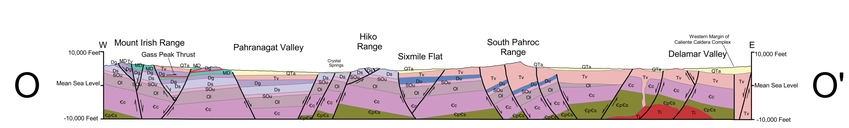
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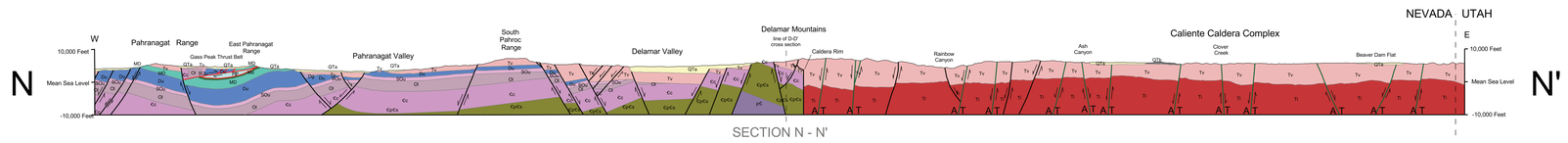
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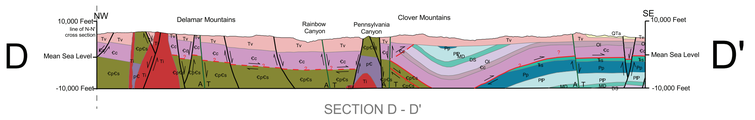
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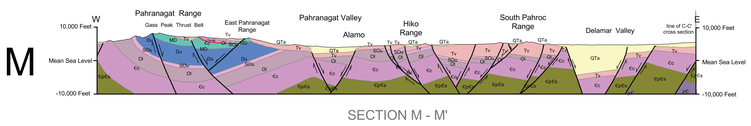
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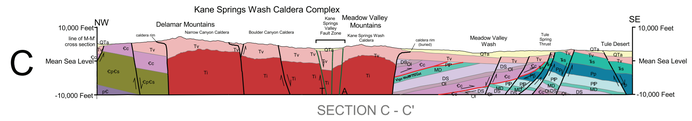
SECTION N - N'



SECTION D - D'



SECTION M - M'



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
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
Pz	Paleozoic 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
DC	Devonian to Upper Cambrian sedimentary rocks, undivided
DS	Devonian and Silurian sedimentary rocks, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Dd	Upper and Middle Devonian Devils Gate Formation
Dg	Upper and Middle Devonian Guilmette Formation
Dn	Middle and Lower Devonian Nevada Formation
Ds	Middle and Lower Devonian Simonson and Sevy Dolomites
SO	Silurian and Ordovician sedimentary rocks, undivided
SOu	Silurian and Upper Ordovician dolomite, undivided
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
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
- Thrust Fault
- Strike-Slip Fault
- Detachment Fault
- Formation Contact
- Projection

Well Name
TD= 1,234

Oil Well Data Used in Cross Sections

TD= total depth

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

SCALE 1:250,000
NO VERTICAL EXAGGERATION

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

MAP ID 13875 11/01/2007 JMB

Southern Nevada Water Authority

Explanation of Geologic Units Shown on Cross Section

QTa	Quaternary and Tertiary basin-fill deposits
QTb	Quaternary and Tertiary thin basalt flows and cinder cones
Tv	Tertiary volcanic ash-flows, flows and ash-fall tuffs
Ts1	Tertiary fluvial and lacustrine sediments
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
Pz	Paleozoic 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
DC	Devonian to Upper Cambrian sedimentary rocks, undivided
DS	Devonian and Silurian sedimentary rocks, undivided
Du	Devonian carbonate sedimentary rocks, undivided
Dd	Upper and Middle Devonian Devils Gate Formation
Dg	Upper and Middle Devonian Guilmette Formation
Dn	Middle and Lower Devonian Nevada Formation
Ds	Middle and Lower Devonian Simonson and Sevy Dolomites
SO	Silurian and Ordovician sedimentary rocks, undivided
SOu	Silurian and Upper Ordovician dolomite, undivided
Ol	Middle and Lower Ordovician, mostly Eureka Quartzite and the Pogonip Goup
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

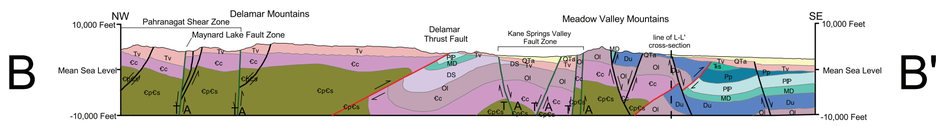
- Normal Fault
- Thrust Fault
- Strike-Slip Fault (T / A)
- Detachment Fault
- Formation Contact
- Projection

Well Name TD= 1,234

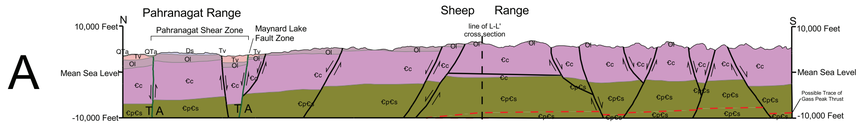
Oil Well Data Used in Cross Sections

TD= total depth

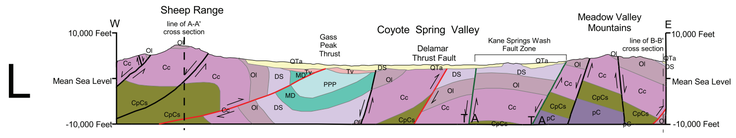
SCALE 1:250,000
NO VERTICAL EXAGGERATION



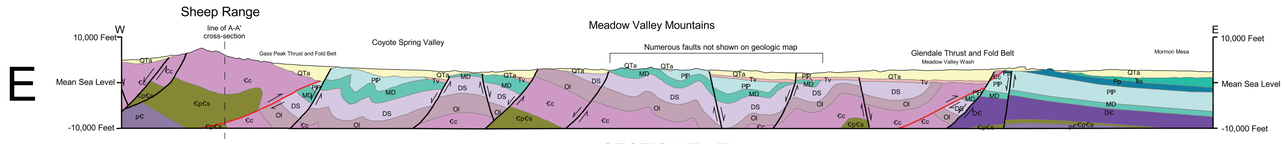
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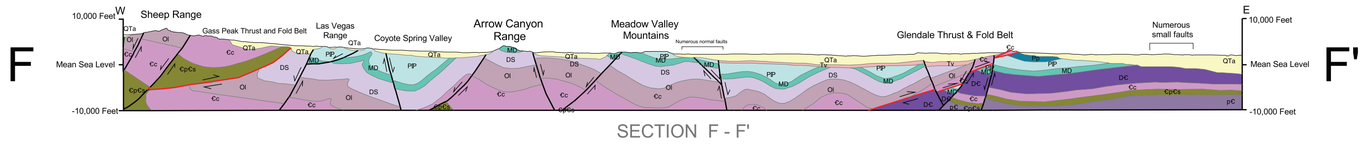
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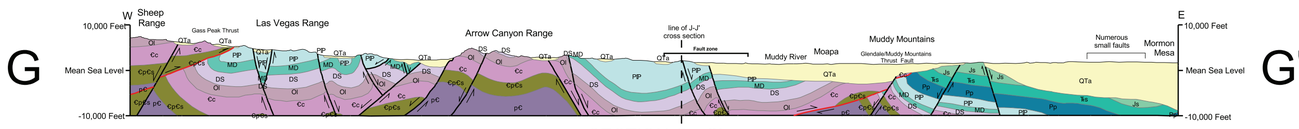
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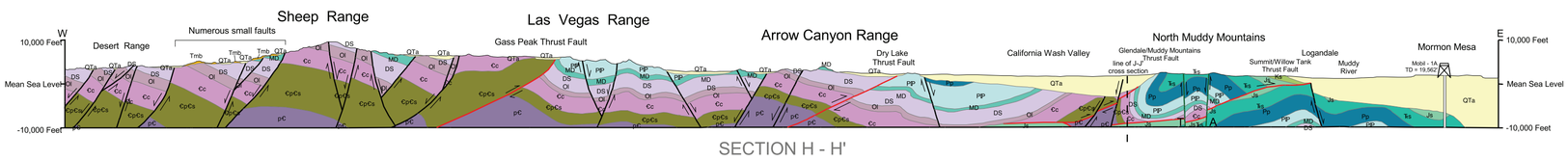
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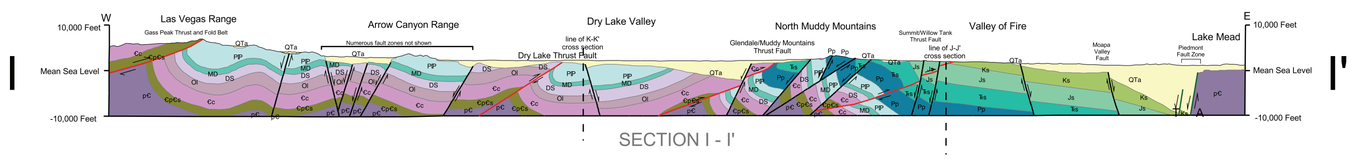
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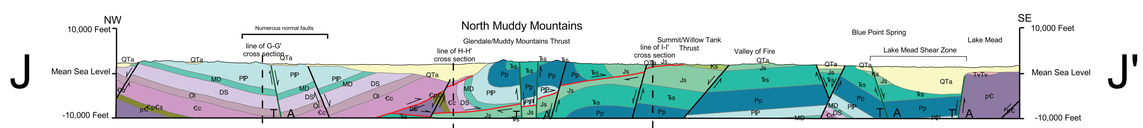
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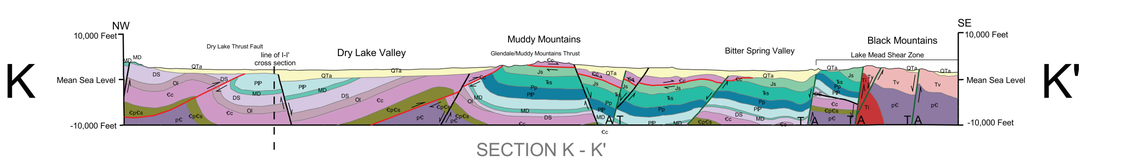
SECTION H - H'



SECTION I - I'



SECTION J - J'



SECTION K - K'

Southern Nevada Water Authority

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

MAP ID 13876 11/01/2007 JMB

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

Legend

Hydrogeologic Units

- QTs — Quaternary-Tertiary sediments
- QTb — Quaternary-Tertiary basalts
- Tv — Tertiary volcanic rocks
- Tos — Tertiary older sediments
- TJi — Tertiary-Jurassic intrusive rocks
- KTrs — Cretaceous-Triassic clastic rocks
- PIPc — Permian-Pennsylvanian carbonate rocks
- Ms — Mississippian clastic rocks
- MOc — Mississippian-Ordovician carbonate rocks
- €c — Cambrian carbonate rocks
- €pCs — Cambrian-Precambrian clastic rocks
- pCm — Precambrian metamorphic 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.
- Transverse Zone (Zone of possible disruption)

Subsidiary Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Strike-slip Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Thrust Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Detachment Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain

- Strike and Dip of Beds
- Caldera Boundary — Solid where known; dashed where inferred: dotted where concealed
- Elevation Contours - 1,000 ft
- Cross Sections (Plates 8 and 9)
- Hydrographic Basin (e.g. 158 BASIN NAME)
- Oil Well Data Used in Cross Sections — Nevada: Nevada Bureau of Mines and Geology; Utah: Utah Division of Oil, Gas and Mining

SCALE 1:250,000

N / W / E / S

Study Area — NEVADA / UTAH — MAP AREA

10 5 0 10 20 30 Kilometers

10 5 0 10 20 30 Miles

Projection: UTM Zone 11 NAD83

MAP ID 13877 11/01/2007 JME

Southern Nevada Water Authority

Legend

Hydrogeologic Units

QTs	Quaternary-Tertiary sediments
QTb	Quaternary-Tertiary basalts
Tv	Tertiary volcanic rocks
Tos	Tertiary older sediments
TJi	Tertiary-Jurassic intrusive rocks
KTs	Cretaceous-Triassic clastic rocks
PIPc	Permian-Pennsylvanian carbonate rocks
Ms	Mississippian clastic rocks
MOc	Mississippian-Ordovician carbonate rocks
€c	Cambrian carbonate rocks
€p€s	Cambrian-Precambrian clastic rocks
p€m	Precambrian metamorphic 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.
- Reverse Fault — Solid where known; Dashed where inferred; dotted where concealed. Bar and Ball on downthrown side.
- Transverse Zone (Zone of possible disruption)
- Las Vegas Shear Zone

Subsidiary Faults

- Normal Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Strike-slip Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Thrust Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain
- Detachment Fault — Solid where known; dashed where inferred; dotted where concealed; dotted and queried where uncertain

- Strike and Dip of Beds
- Caldera Boundary — Solid where known; dashed where inferred; dotted where concealed
- Elevation Contours - 1,000 ft
- Cross Sections (Plates 8 and 9)
- Hydrographic Basin (e.g. 123 BASIN NAME)
- Oil Well Data Used in Cross Sections — Nevada: Nevada Bureau of Mines and Geology

SCALE 1:250,000

N W E S

Projection: UTM Zone 11 NAD83

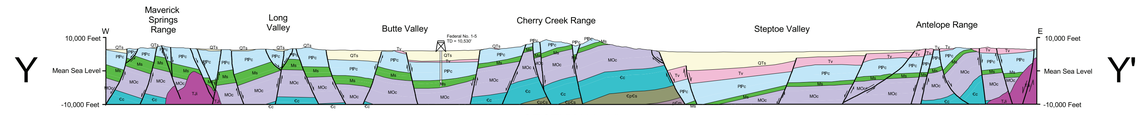
10 5 0 10 20 30 Kilometers

10 5 0 10 20 30 Miles

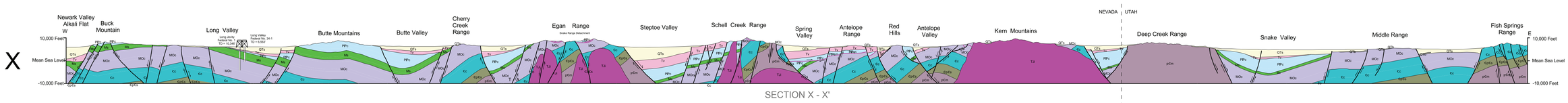
PLATE 7. HYDROGEOLOGY OF SOUTHERN LINCOLN AND NORTHERN CLARK COUNTIES, NEVADA, AND ADJACENT AREAS, ARIZONA

MAP ID 13878 11/01/2007 JMB

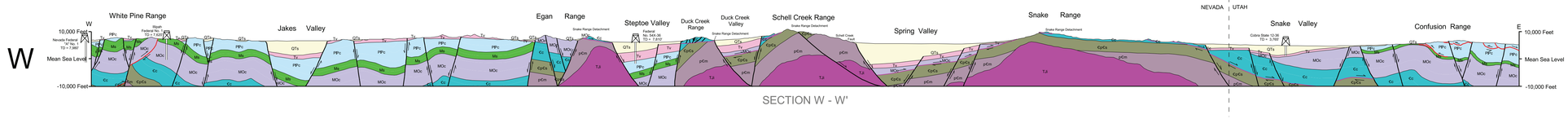
Southern Nevada Water Authority



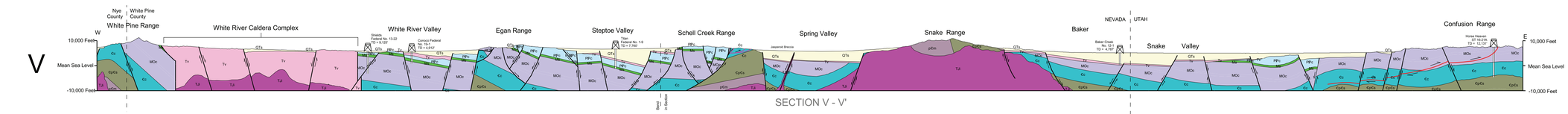
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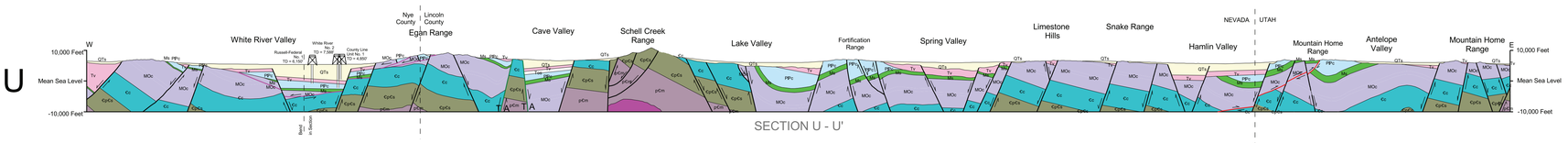
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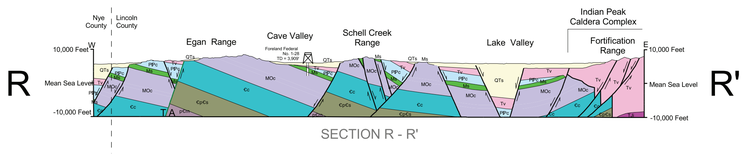
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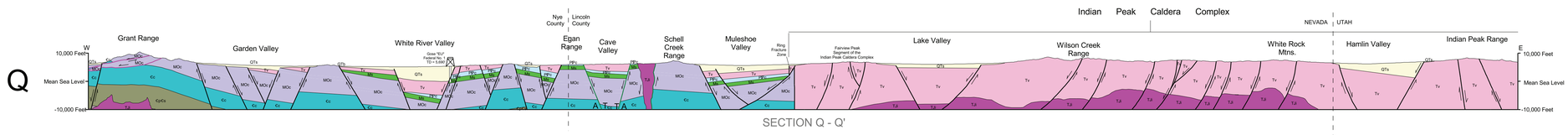
SECTION V - V'



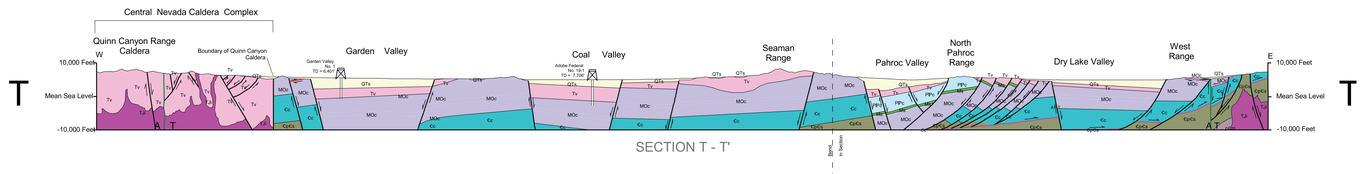
SECTION U - U'



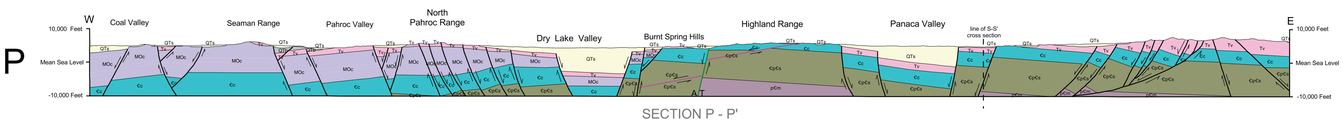
SECTION R - R'



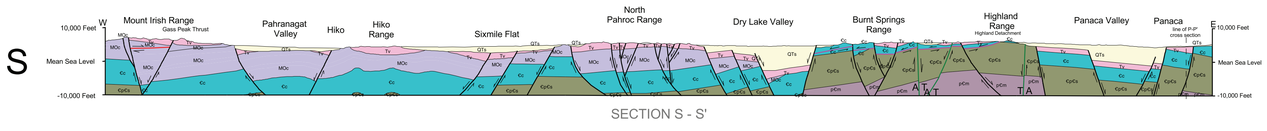
SECTION Q - Q'



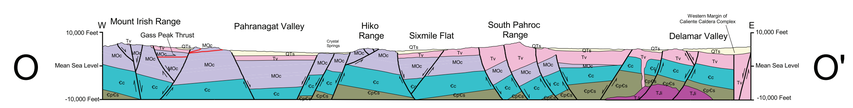
SECTION T - T'



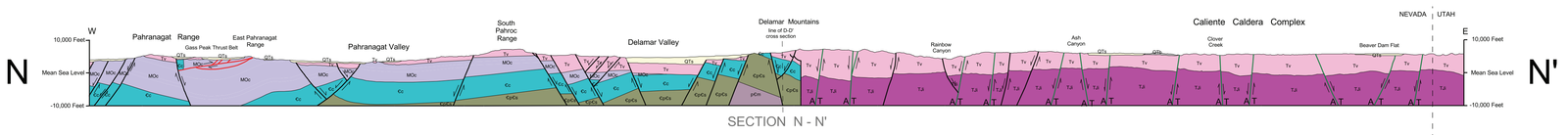
SECTION P - P'



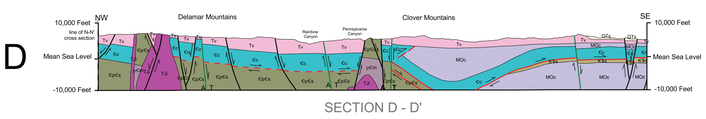
SECTION S - S'



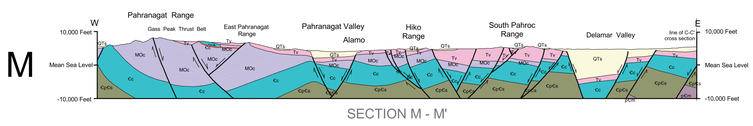
SECTION O - O'



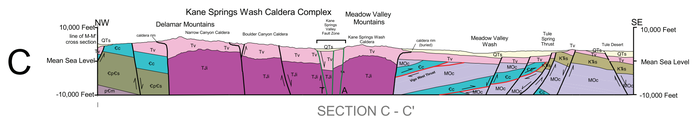
SECTION N - N'



SECTION D - D'



SECTION M - M'



SECTION C - C'

Explanation of Hydrogeologic Units Shown on Cross Section

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

Geologic Structure

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

Oil Well Data Used in Cross Sections

Well Name
TD= 1,234

TD= total depth
Nevada: Nevada Bureau of Mines and Geology
Utah: Utah Division of Oil, Gas and Mining

SCALE 1:250,000
NO VERTICAL EXAGGERATION

Southern Nevada Water Authority

MAP ID 13879 11/01/2007 JMB

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

Explanation of Hydrogeologic Units Shown on Cross Section

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

Geologic Structure

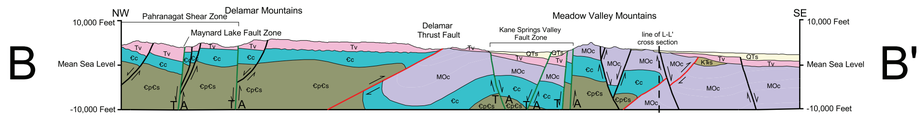
- Normal Fault
- Thrust Fault
- Strike-Slip Fault
- Detachment Fault
- Projection
- Hydrogeologic Contact

Well Name
TD= 1,234

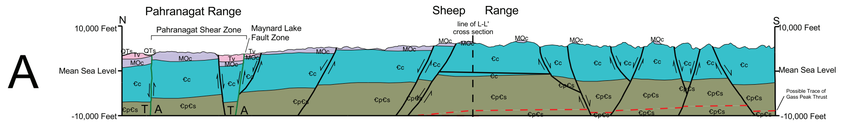
Oil Well Data Used in Cross Sections

TD= total depth

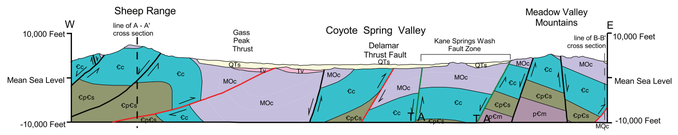
SCALE 1:250,000
NO VERTICAL EXAGGERATION



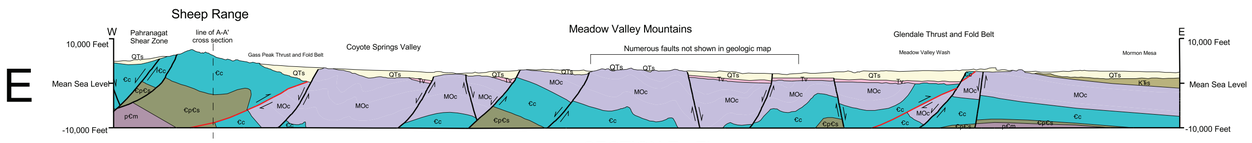
SECTION B - B'



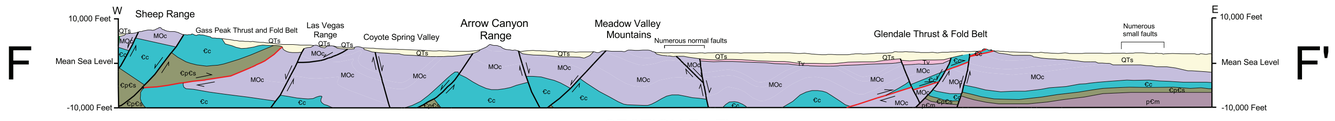
SECTION A - A'



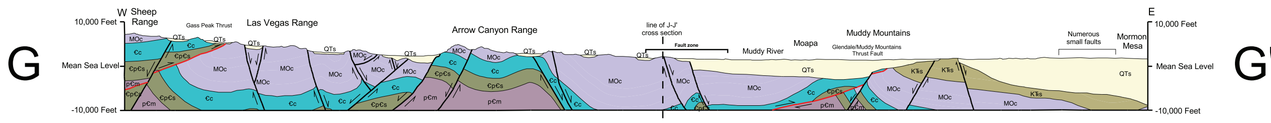
SECTION L - L'



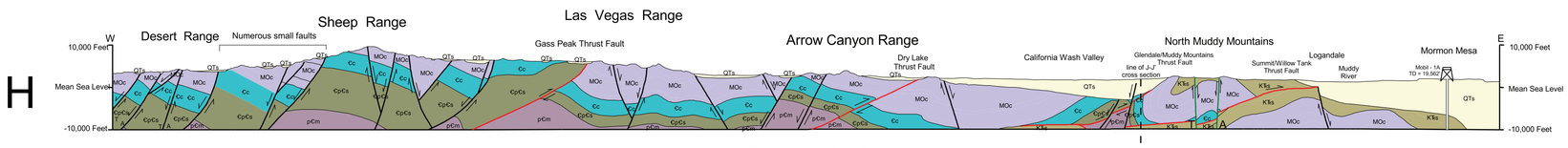
SECTION E - E'



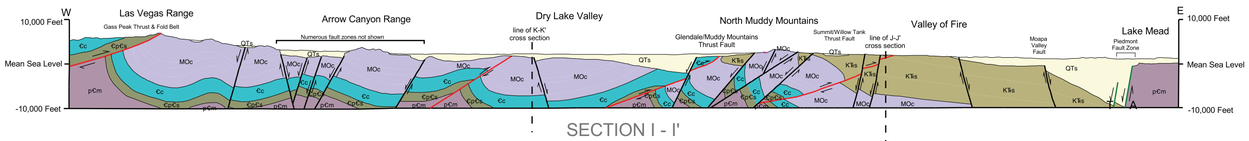
SECTION F - F'



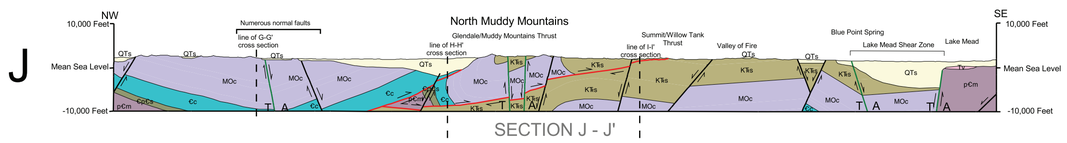
SECTION G - G'



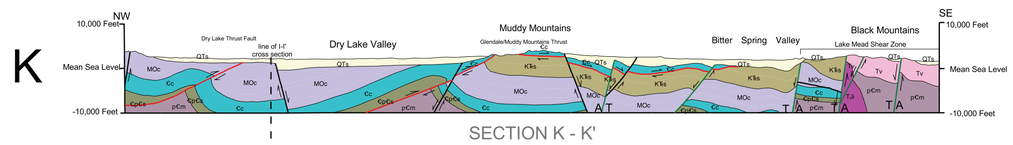
SECTION H - H'



SECTION I - I'



SECTION J - J'



SECTION K - K'

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

MAP ID 13880 11/01/2007 JMB