Text and references to accompany Nevada Bureau of Mines and Geology Map 150

GEOLOGIC MAP OF PARTS OF THE COLORADO, WHITE RIVER, AND DEATH VALLEY GROUNDWATER FLOW SYSTEMS

NEVADA, UTAH, AND ARIZONA

by

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INTRODUCTION

The mapped area is greater than 20,000 km^2, and is largely within the Basin and Range physiographic province and its transition with the Colorado Plateau. The area is a desert, with little precipitation except in the mountains and few perennial streams and rivers besides the Colorado River and two tributaries, the Virgin and Muddy Rivers. The Colorado River is impounded by Hoover Dam, in the southwestern corner of the map area, to create Lake Mead, which volumetrically is the largest reservoir in the country. Lake Mead provides most of the culinary and agricultural water to southern California, southern Nevada, and southern Arizona, all among the fastest growing parts of the United States.

The geologic map provides a basis for understanding the complex geology and groundwater hydrology of a vast area whose population is experiencing increasingly significant water shortages (Page and others, 2003). Specifically, rapid urbanization and commercial development is taking place in the I-15 transportation corridor, from Las Vegas, Nevada, through Mesquite, Nevada, and the Arizona Strip to St. George, Utah. This growth has caused increased demand for water from surface sources and from local and regional aquifers. As a result, the geologic framework in the area needs to be described.

The main purpose of the geologic map is to provide our sponsors (National Park Service, U.S. Fish and Wildlife Service, Southern Nevada Water Authority, and Virgin Valley Water District) with digital geologic framework data used as important parameters in developing numerical groundwater flow models. These data describe the distribution, geometry, thickness, composition, and physical properties of geologic units. This information is required to define hydrogeologic units and potential aquifers and confining units. These data also describe the distribution, geometry, and characteristics of faults. Faults act as both conduits and barriers to groundwater flow depending on a variety of factors. When combined with geologic cross sections, well data, and geophysical subsurface information, these data provide a 3-dimensional geologic model characterizing the configuration of hydrogeologic units and faults in the map area that can be integrated with groundwater models using GIS analyses. The map is a printed version of an ARC/Info GIS data base. Geologic cross sections in the map area are being prepared in a separate report.

The southern half of Nevada and its adjacent states contain several huge groundwater basins, known as regional groundwater flow systems that may encompass a dozen or more of the closed topographic basins because they are interconnected in the subsurface. These regional flow systems are defined by hydrologic and geochemical evidence that indicate their groundwater flow paths pass beneath topographic barriers and continue beneath adjacent basins and ranges, referred to as interbasin flow (Eakin, 1966; Eakin and Winograd, 1965). Thomas and others (1986, 1996), Harrill and others (1988), Prudic and others (1995), and Harrill and Prudic (1998) summarized these flow systems for the Great Basin.

The main regional groundwater flow systems covered by this geologic map include parts of the Colorado flow system (Harrill and Prudic, 1998), the White River groundwater flow system (Eakin, 1964, 1966; Thomas and

Welch, 1984; and Kirk, 1987), and the Death Valley groundwater flow system (e.g., Winograd and Thordarson, 1975; Laczniak and others, 1996; Harrill and Prudic, 1998; D'Agnese and others, 2002; Workman and others, 2002, 2003). The White River flow system is contained within the much larger Colorado flow system; our map covers only the southern part of these flow systems and the eastern part of the Death Valley system (see figure on map sheet).

The primary source (recharge area) of the water in the flow systems is precipitation in the mountains surrounding basins in the map area and the numerous basins farther north and northeast. The principal discharge area for the White River flow system is Muddy River springs (Dettinger and others, 1995) (fig. 1), a series of about eight major springs (Schmidt and Dixon, 1995) that discharge 36,000 ac-ft/yr (44 hm^3/yr) to form the Muddy River. Movement of groundwater in the map area is primarily by fracture flow, that is along fractures (mostly joints; the "damage zone" of Caine and others, 1996) formed by faulting (e.g., Haneberg and others, 1999). The flow paths are generally southward, as indicated by potentiometric maps based on water levels in wells (Thomas and others, 1986; Wilson, 2001). They thus follow the general slope of the topography, from high areas in central Nevada to the low canyons of the Colorado River in southern Nevada. The flow is driven by the hydraulic head parallel to the southward topographic gradient.

Aquifers in the flow systems consist of Paleozoic carbonate rocks and subordinate volcanic rocks and basin-fill sediments (e.g., Plume and Carlton, 1988; Dettinger and others, 1995; Prudic and others, 1995; Burbey, 1997; Harrill and Prudic, 1998). In fact, the importance of the Paleozoic carbonate-rock aquifer to the flow systems that cover much of southern Nevada and adjacent states is so significant that many regional hydrologic reports have focused on the distribution and features of this aquifer (e.g., Dettinger and others, 1995; Burbey, 1997; Wilson, 2001).

METHODS AND DATA SOURCES

The geologic map contains greater detail and more recent compilations than existing regional geologic maps in the study area and provides stratigraphic and structural continuity across county and state boundaries. It was assembled by compiling all available regional and detailed geologic maps in the area. These maps were modified by the authors, as required to apply new information and concepts about the geology. The sources of geologic mapping are shown in figures 2 and 3. Figure 2 lists detailed map sources at 1:24,000-scale and figure 3 includes regional map sources from 1:50,000 to 1:250,000 scale. In a few remote areas not covered by existing geologic maps, we compiled the geology using reconnaissance scale county geologic maps (Longwell and others, 1965; Tschanz and Pampeyan, 1970) in combination with Landsat and aerial photo interpretation.

Geophysical studies have been completed in many of the major basins of the map area in order to understand the subsurface geology. These studies mainly applied gravity and magnetic methods in combination with analyses of seismic reflection data. Subsurface studies are especially significant in locating buried faults that may control groundwater flow and in modeling basins to better understand interbasinal groundwater flow. Bohannon and others (1993) interpreted subsurface faults and stratigraphic units in the Virgin Valley area based mostly on seismic reflection and well data. Jachens and others (1998) interpreted subsurface faults and other geologic features in the Virgin Valley and Tule Springs Hills areas based on high-resolution aeromagnetic studies. Langenheim and others (2000, 2001a, b, c) modeled the Virgin Valley, Las Vegas Valley, and California Wash basins using seismic reflection and gravity data. Phelps and others (2000) interpreted subsurface faults in the Coyote Spring Valley area based on gravity data.

ACKNOWLEDGMENTS

Funding for this geologic map was provided by the Southern Nevada Water Authority, U.S. Fish and Wildlife Service, National Park Service, and Virgin Valley Water District. We are grateful to Ernie Anderson, Bob Scott, and Van Williams of the USGS for their unpublished map data. Vicky Langenheim, Geoff Phelps, Bob Morin, Bob Jachens, and Tom Hildenbrand conducted geophysical surveys in the map area. We also thank Mel Kuntz of the USGS, Jim Faulds of the Nevada Bureau of Mines and Geology, Grant Willis of the Utah Geological Survey, and an anonymous reviewer for their technical reviews of the manuscript. Terry Katzer and David Donovan of the Southern Nevada Water Authority provided helpful suggestions to improve the manuscript.

STRATIGRAPHY

Proterozoic and Paleozoic Rocks

The oldest rocks in the map area are Early Proterozoic metamorphic and intrusive rocks consisting of gneiss, granite, and schist that are about 1.7 Ga (Quigley and others, 2002); their surface distribution is shown in figure 4. These crystalline rocks form both geologic and hydrologic basement and are considered barriers to groundwater flow because of their low permeability. The crystalline rocks may be locally permeable where highly fractured, but fractures in these rocks are generally poorly connected (D'Agnese and others, 1997). Early Proterozoic rocks exposed in the Beaver Dam and Virgin Mountains form the eastern boundary of the flow systems. Early Proterozoic rocks also form the core of the Mormon Mountains in the central part of the map area (fig. 4), where they act as a local barrier to groundwater flow (Burbey, 1997), although through-going, north-striking faults in the eastern Mormon Mountains may provide conduits for some component of southward groundwater flow through the mountain range.

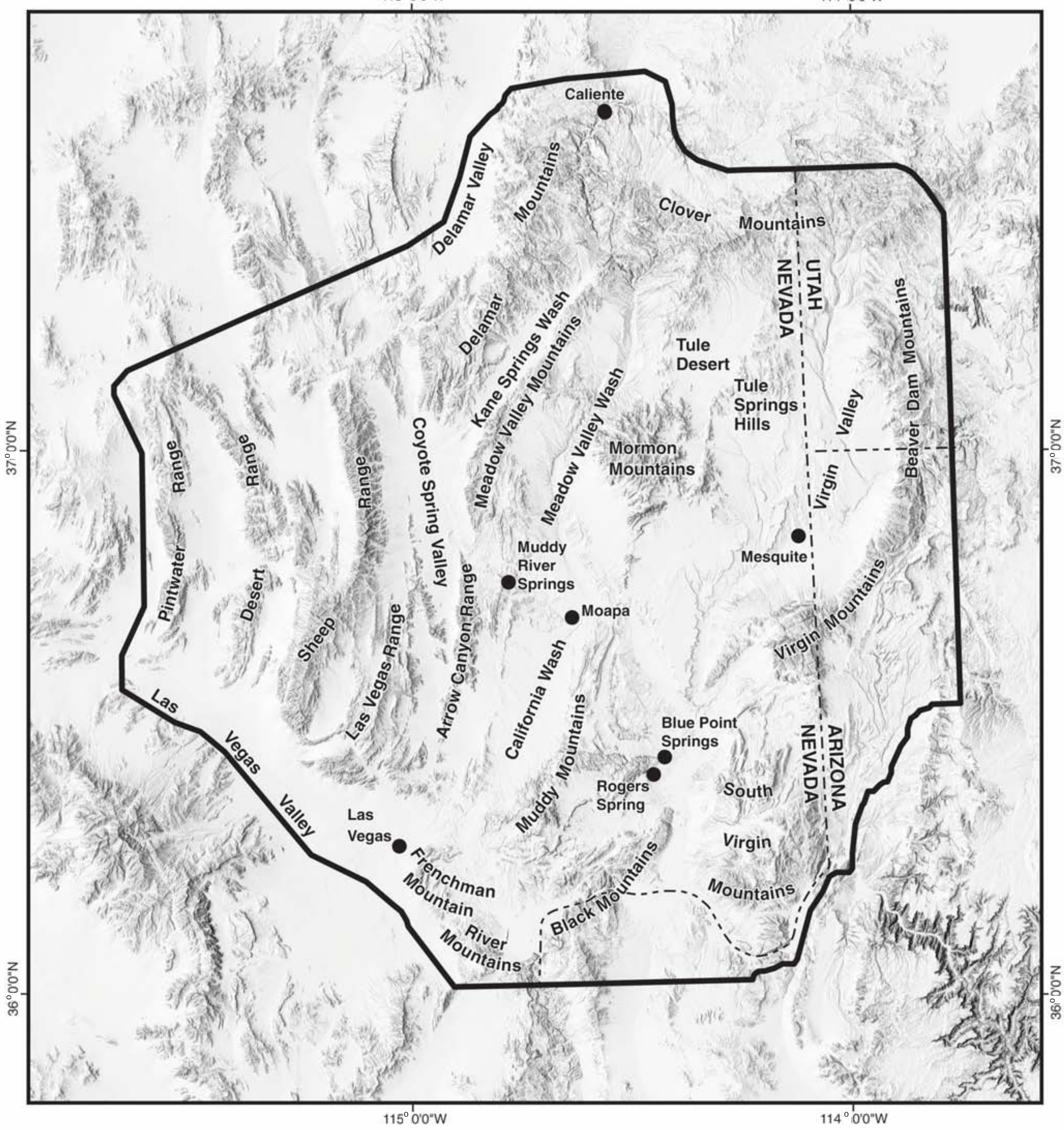


Figure 1. Index map showing major physiographic features in the map area.

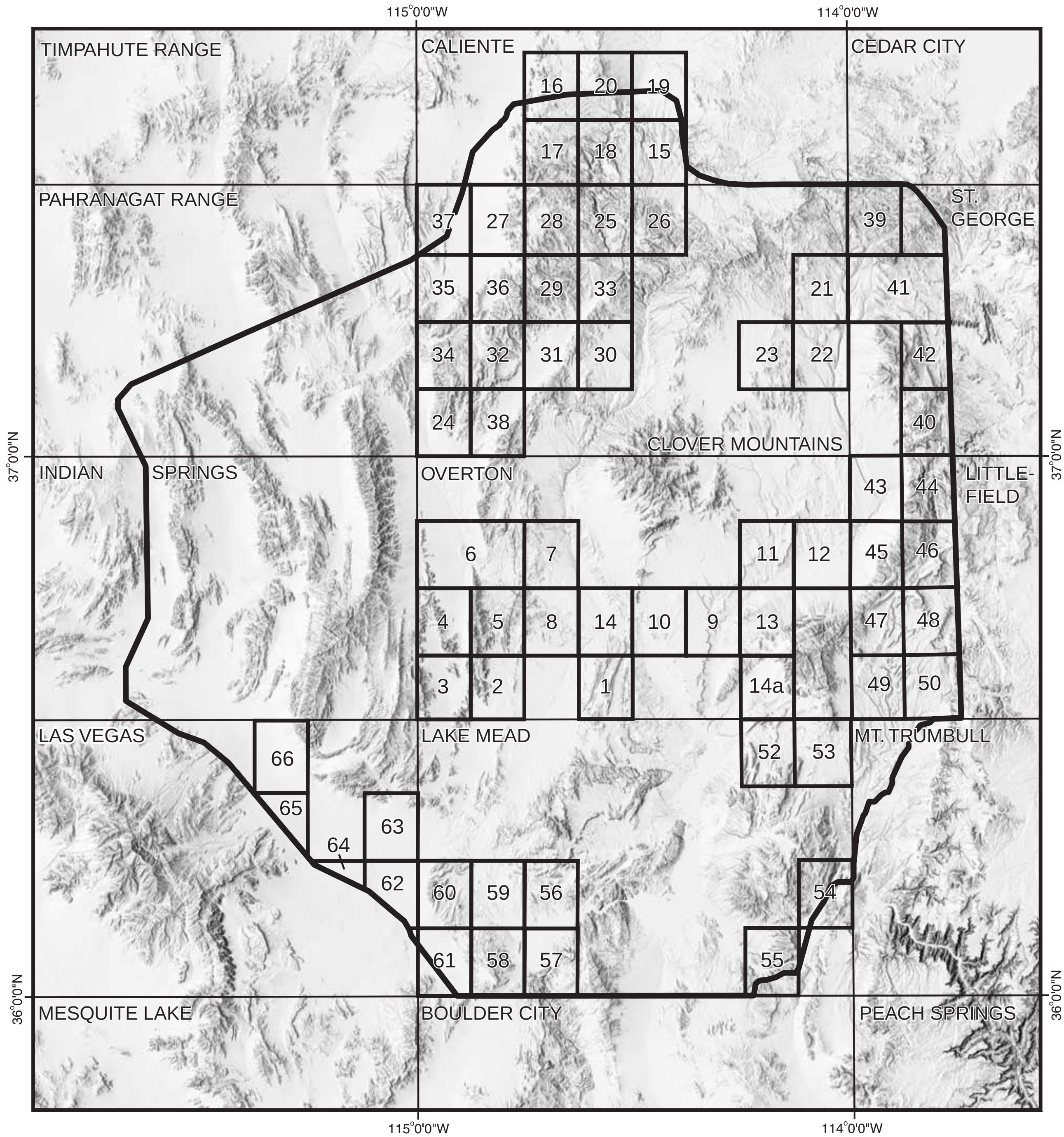


Figure 2. Index to 1:24,000-scale geologic mapping sources. See table 1 for quadrangle names and references.

Table 1. Geologic mapping sources for the study area. Locations of the 1:24,000-scale geologic maps are shown in figure 3.

Overton 30 x 60 Quadrangle

1. Weiser Ridge (Bohannon, 1992a)
2. Arrow Canyon SE (W.R. Page, unpub. mapping, 1999)
3. Arrow Canyon SW (W.R. Page, unpub. mapping, 1999)
4. Arrow Canyon NW (Page, 1998)
5. Arrow Canyon (Page, 1992)
6. Wildcat Wash SE and Wildcat SW (Page and Pempeyan, 1996)
7. Farrier (Schmidt, 1994)
8. Moapa West (Schmidt and others, 1996)
9. Overton NE (V.S. Williams, unpub. mapping, 1999)
10. Overton NW (V.S. Williams, unpub. mapping, 1999)
11. Flattop Mesa (V.S. Williams, unpub. mapping, 2000)
12. Mesquite (Williams, 1996)
13. Riverside (Williams and others, 1997a)
14. Moapa East (Williams and others, 1997b)

14a. Whitney Pocket (Beard, 1993)

Caliente 30 x 60 Quadrangle

15. Eccles (P.D. Rowley, unpub. mapping,1993)
16. Caliente NW (P.D. Rowley, unpub. mapping,1993)
17. Chokecherry Mtn. (P.D. Rowley, unpub. mapping,1993)
18. Caliente (P.D. Rowley and others, unpub. mapping,1993)
19. Indian Cove (Rowley and Shoba, 1991)
20. Chief Mountain (Rowley and others, 1994)

Clover Mountains 30 x 60 Quadrangle

21. Dodge Spring (Anderson and Hintze, 1993)
22. Scarecrow Peak (Hintze and Axen, 1995)
23. Lime Mountain (Hintze and Axen, 2001)
24. Delamar 3 SW (Page and others, 1990)
25. Elgin NE (P.D. Rowley, unpub. mapping, 1994)
26. Ella Mountain (P.D. Rowley, unpub. mapping, 1994)
27. Delamar (P.D. Rowley, unpub. mapping, 1995)
28. Slidy Mountain (P.D. Rowley and R.B. Scott, unpub. mapping, 1994)
29. Elgin SW (R.B. Scott, unpub. mapping, 1994)
30. Vigo NE (R.B. Scott and A. Harding, unpub. mapping, 2003)
31. Vigo NW (Scott and others, 1991a)
32. Delamar 3 NE (Scott and others, 1990a)
33. Elgin (R.B. Scott and P.D. Rowley, unpub. mapping, 1993)
34. Delamar 3 NE (Scott and others, 1990b)
35. Delamar Lake (Scott and others, 1993)
36. Gregerson Basin (Scott and others, 1991b)
37. Delamar NW (Swadley and Scott, 1990)
38. Delamar 3 SE (Swadley and others, 1994)

St. George 30 x 60 Quadrangle

39. Goldstrike (R.E. Anderson, unpub. mapping, 1993)
40. Jarvis Peak (Hammond, 1991)
41. Motoqua and Gunlock (Hintze and others, 1994)
42. Shivwits (Hintze and Hammond, 1994)

Littlefield 30 x 60 Quadrangle

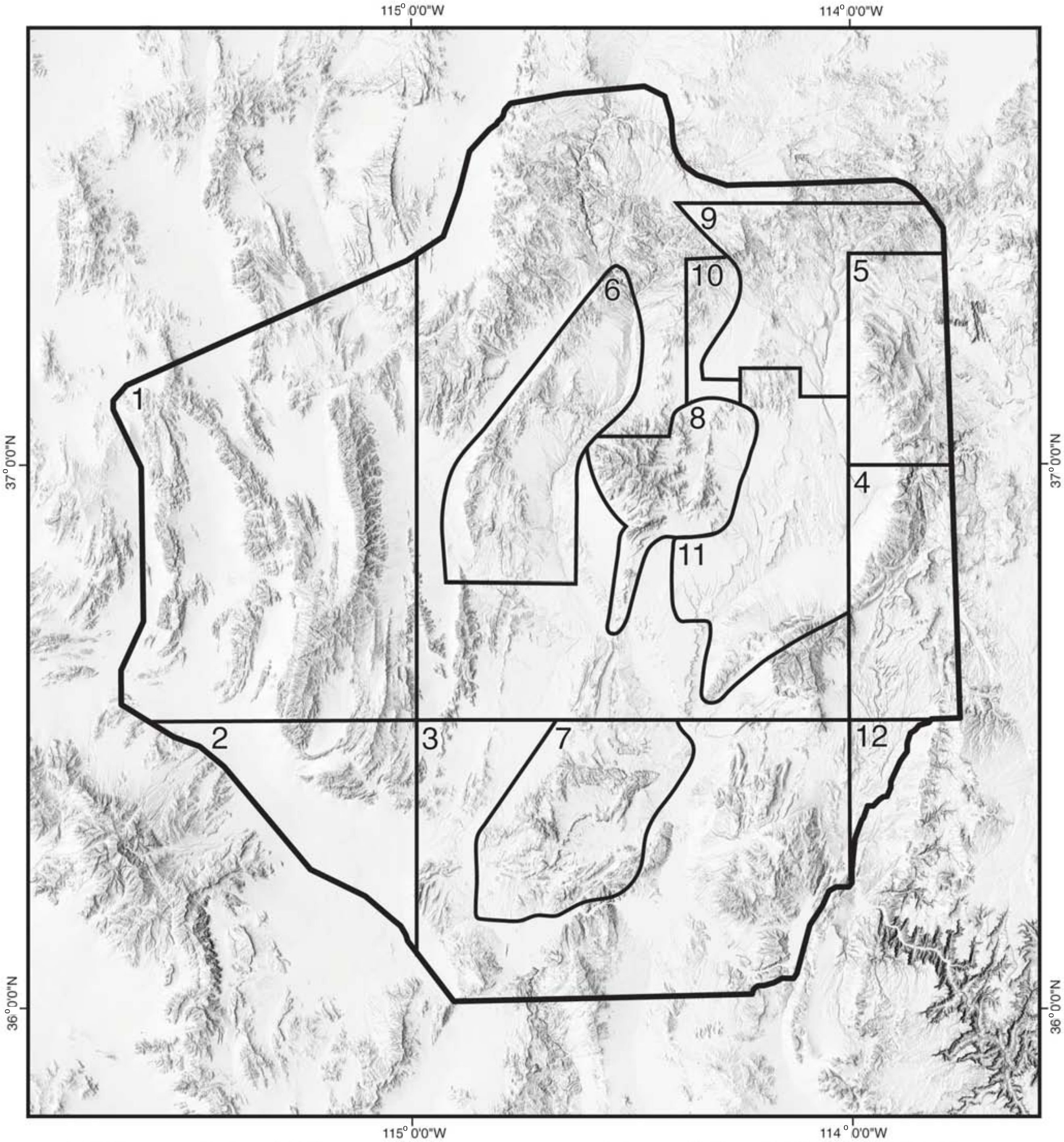
43. Littlefield (Billingsley, 1995)
44. Mountain Sheep Spring (Bohannon and others, 1991)
45. Elbow Canyon (Billingsley and Bohannon, 1995)
46. Mount Bangs (Bohannon and Lucchitta, 1991)
47. Jacobs Well and southern part of the Elbow Canyon (Bohannon, 1991)
48. Cane Springs (Lucchitta and others, 1995a)
49. Red Pockets (Bohannon, 1992b)
50. Cane Springs Southeast (Lucchitta and others, 1995b)

Lake Mead 30 x 60 Quadrangle

52. Devils Throat (Beard, 1991)
53. St. Thomas Gap (Beard, 1992)
54. Iceberg Canyon (Brady and others, 2002)
55. Hiller Mountains (Howard and others, 2003)
56. Callville Bay (Anderson, 2003)
57. Hoover Dam (Mills, 1994)
58. Boulder Beach (Smith, 1984)
59. Government Wash (Duebendorfer, 2003)
60. Frenchman Mountain (Castor and others, 2000)
61. Henderson (Bell and Smith, 1980)

Las Vegas 30 x 60 Quadrangle

62. Las Vegas NE (Matti and others, 1993)
63. Valley (Lundstrom and others, 1998)
64. Las Vegas NW (Matti and others, 1987)
65. Tule Springs Park (Bell and others, 1998)
66. Corn Creek Springs (Bell and others, 1999)



1. Workman and others (2003)
2. Page and others (2005)
3. Beard and others (in press)
4. Billingsley and Workman (1998)
5. Hintze (1986)
6. Pampeyan (1993)
7. Bohannon (1983)
8. Axen and others (1990), Skelly (1987), Olmore (1971), and Wernicke and others (1985)
9. R.E. Anderson (unpub. mapping, Clover Mountains and Bull Valley Mountains, 1990)
10. Ekren and others (1977)
11. Dixon and Katzer (2002)
12. Billingsley and Wellmeyer (2003)

Figure 3. Index to geologic mapping sources, 1:50,000 to 1:250,000-scale maps.

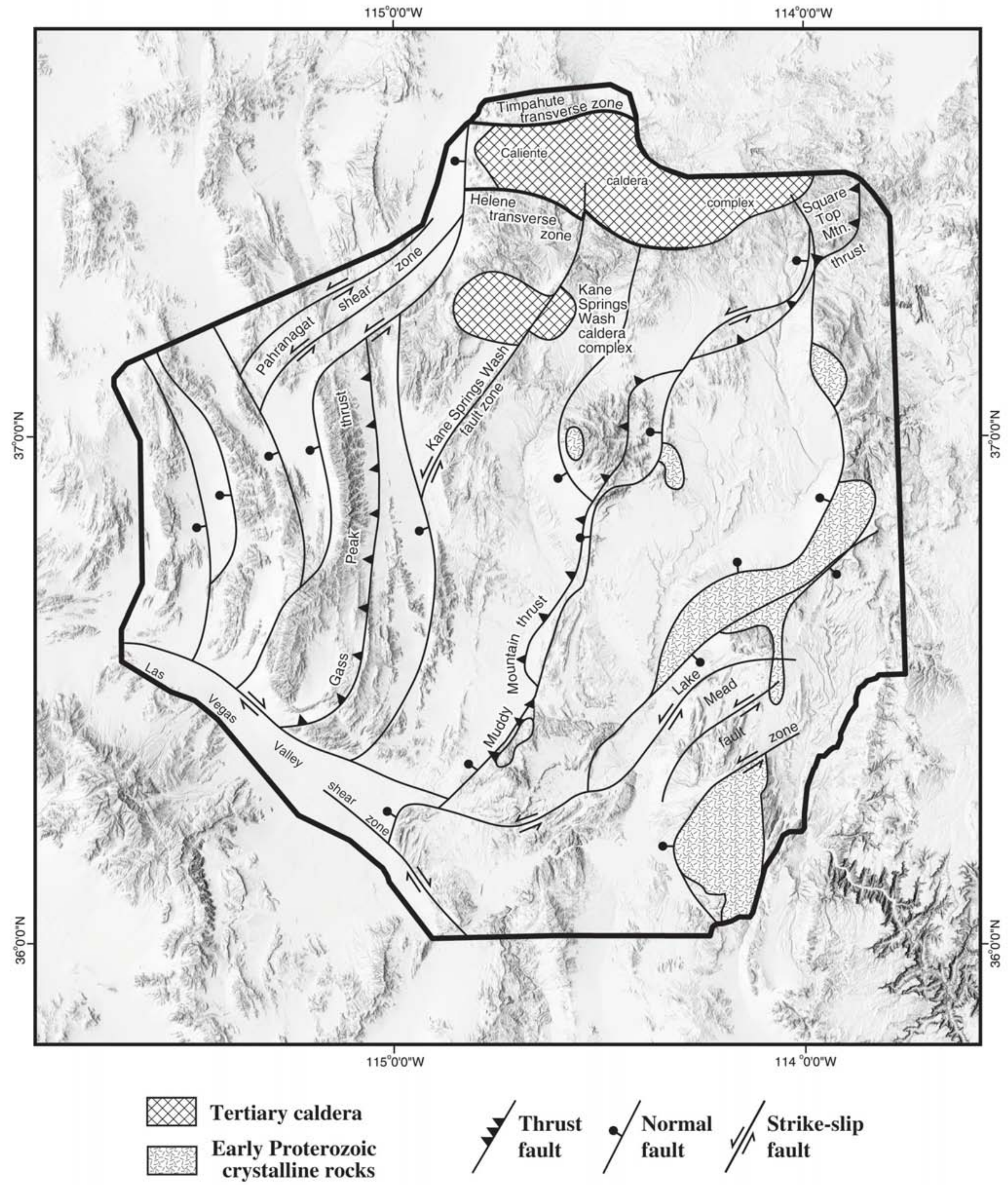


Figure 4. Generalized map of the principal structural features in the map area.

Late Proterozoic sedimentary rocks are exposed in the Desert and Sheep Ranges and northern Delamar Mountains. These are mostly clastic rocks and consist of quartzite, conglomerate, sandstone, siltstone, and shale, but they contain subordinate amounts of limestone and dolostone. The Late Proterozoic sedimentary rocks are well-cemented, contain few or no pore spaces, and have low permeability. They were deposited in shallow marine waters along a passive continental margin of what is now western North America (Stewart, 1976; Stewart and Poole, 1972). Late Proterozoic rocks are interpreted to represent initial deposits of the Cordilleran miogeocline (Stewart and Poole, 1972; Stewart, 1972, 1976).

Like the Late Proterozoic sedimentary rocks, Lower Cambrian rocks are also predominantly well-cemented, clastic units containing mainly quartzite, conglomerate, siltstone, and shale. Together, the Lower Cambrian and Late Proterozoic sedimentary rocks in the western part of the map area form a confining unit. In the Desert Range, these rocks attain their maximum thickness in the map area and may form a potential barrier to westward groundwater flow. In the Death Valley groundwater flow system, these same rocks are referred to as the lower clastic aquitard (Winograd and Thordarson, 1975), or the lower clastic confining unit (Belcher and others, 2002). Late Proterozoic clastic units pinch out in the eastern part of the map area and are absent in the Mormon, Virgin, and Beaver Dam Mountains. Here, the lower clastic confining rocks include the Lower Cambrian Tapeats Sandstone and the Lower and Middle Cambrian Bright Angel Shale that have a combined thickness ranging from 125 to 445 m.

Middle Cambrian through Lower Permian rocks are widely distributed in the map area and record a significant shift in deposition to predominantly carbonate sedimentation, from mostly clastic sedimentation in pre-Bonanza King Late Proterozoic and Cambrian units. The carbonate rocks are predominantly limestone and dolostone and form the regional aquifer in the map area (Dettinger and others, 1995). The Middle and Upper Cambrian Bonanza King Formation (and equivalent Highland Peak and Muav Formations) forms the basal part of the regional carbonate aquifer in the White River and Colorado flow systems, and in the Death Valley groundwater flow system (Winograd and Thordarson, 1975; Laczniak and others, 1996; Belcher and others, 2002; D'Agnese and others, 2002). Groundwater flow through the carbonate rocks is mostly through fractures and faults. Because the rocks are soluble in groundwater, dissolution features are also important in the development of secondary porosity and permeability. Zones of high transmissivity in the carbonate rock aquifer are indicated by large spring discharge (36,000 ac-ft/yr [44 hm^3/yr] at Muddy River Springs) in areas of low potentiometric gradient, and by water wells exhibiting extremely high hydraulic conductivity (900 ft^2/d [84 m^2/d] at MX-5 in Coyote Spring Valley) (Dettinger and others, 1995).

Middle Cambrian through Lower Permian rocks are dominantly carbonate rocks with the exception of several units that have greater proportions of clastic material: these units include the Upper Cambrian Dunderberg Shale Member of the Nopah Formation, Middle Ordovician Eureka Quartzite, Upper Mississippian Chainman Shale, Upper Mississippian Indian Springs Formation, and the Lower Permian redbeds. These clastic units are generally not thick enough to form regional confining units in the map area, but they may act as confining units locally within the region, especially the Lower Permian redbeds which have a maximum thickness of 600 m.

The upper part of the carbonate aquifer in the map area includes the Bird Spring Formation and partly equivalent Callville Limestone. Lower Permian redbeds overlie these formations and represent a shift from dominantly carbonate marine to mostly continental and marginal marine sedimentation. Continental sedimentation predominated through the Mesozoic and into the lower Tertiary.

Late Proterozoic-Paleozoic facies belts

Late Proterozoic-Paleozoic rocks in the map area can be broadly subdivided into western, central, and eastern facies belts (see correlation of map units). Rocks in the western belt include Late Proterozoic through Devonian units deposited as part of the Cordilleran miogeocline in offshore carbonate shelf and intertidal depositional settings, and an overlying Mississippian to Permian sequence deposited mostly in a carbonate platform depositional setting. Units of the western belt are exposed as far east as the Las Vegas Range, Arrow Canyon Range, Meadow Valley Mountains, and Delamar Mountains (fig. 1).

The eastern facies belt includes cratonic platform rocks of the Colorado Plateau region exposed in the Beaver Dam and Virgin Mountains, and in the Lake Mead area including Frenchman Mountain. The rocks are mostly shallow marine sediments deposited in near-shore, intertidal, and continental settings. The facies belt is characterized by a large magnitude unconformity separating Middle Devonian from Upper Cambrian rocks (see correlation of map units). Rock units in the belt also include significant amounts of evaporite deposits, especially in the Permian formations. The central facies belt includes rocks that are transitional between the eastern and western belts; these rocks are exposed in the Muddy Mountains, Mormon Mountains, and Tule Springs Hills (fig. 1).

Thickness of Middle Cambrian to Lower Permian carbonate rocks, which define the regional aquifer, decrease dramatically across the belts from west to east over a distance of about 100 km—from about 4 to 6 km thick in the western belt to less than 2 km thick in the eastern belt. The carbonate rocks average about 2.5 km thick in the central belt. The thinning resulted from erosion of individual units along major unconformities and stratigraphic thinning of individual units toward the craton, but the large thickness variation across the belts is primarily due to southeast-vergent Mesozoic thrusting (see section on Structural Geology below).

Mesozoic Rocks

Mesozoic rocks are predominantly continental clastic units consisting of conglomerate, sandstone, siltstone, mudstone, shale, gypsum, but they also include minor limestone and dolostone. These rocks were deposited in fluvial, lacustrine, eolian, and marginal marine environments, and include Triassic, Jurassic, and Cretaceous units that are about 3 to 4 km thick (Bohannon, 1983). These rocks have low permeability compared with the Paleozoic carbonate rocks because of their high proportion of clastic material. They are generally considered confining units, but they may be permeable where highly fractured. Units containing large amounts of shale and mudstone, such as in the Triassic formations, generally have low permeability. The Jurassic Navajo Sandstone in the Utah part of the map area is an aquifer (Heilweil and others, 2002), but in other parts of southern Nevada, such as in Las Vegas Valley, the Aztec Sandstone has low permeability. This example illustrates the variability in hydrologic properties of the Mesozoic rocks in the map area. The distribution of Mesozoic rocks is limited to the eastern half of the map area, although some units extend into the Basin and Range province and westward into the Jurassic arc terrane of southeastern California (Marzolf, 1990). East-vergent thrusting related to the Sevier orogeny affected the map area from Early Cretaceous into early Tertiary time (see structure section below).

Tertiary Rocks

Tertiary rocks in the map area belong to three sequences based on age. The oldest is the basal Tertiary unit of fluvial and lacustrine origin, partly derived from erosion of highlands resulting from Sevier deformation to the west. The best-known unit is the Eocene and Oligocene Claron Formation (Anderson and Rowley, 1975) that makes up the colorful rocks of Bryce Canyon National Park, but these rocks are confined to the northeastern part of the map area.

The second sequence consists of voluminous calc-alkaline volcanic rocks of rhyolite to andesite composition, as well as their source plutons. Most of these igneous rocks were deposited between about 35 to 20 Ma, but in the northern Colorado River extensional corridor near and south of Lake Mead, calc-alkaline magmatism began at about 20 Ma and continued until about 12 Ma (Faulds and others, 2001). Many volcanic rocks are ash-flow tuffs erupted from calderas, but stratovolcanoes were locally present. Ash-flow tuffs are potential aquifers where broken by faults. The largest caldera in the map area is the east-elongated (80 km east-west versus 35 km north-south) Caliente caldera complex (at least 24 Ma to 13.5 Ma, representing eruptions of calc-alkaline rocks, then bimodal rocks) in the northeastern part of the area (fig. 4). The caldera is broken by numerous north-striking fault zones that may provide important conduits for north-south groundwater flow in the region.

The third sequence of Tertiary rocks evolved during the major episode of east-west basin-range extension. North of Lake Mead, this extension took place from about 20 Ma to present (e.g., Rowley and Dixon, 2001). Over most of the map area, volcanic rocks of bimodal composition (high-silica rhyolite and basalt) and of generally low volume intertongue with basin-fill deposits. In the northern Colorado River extensional corridor, however, major extension followed and accompanied later calc-alkaline volcanism, whereas basalts generally accompanied only the waning stages of extension (Faulds and others, 2001). The basin-fill deposits are mostly fluvial sediments deposited in grabens that resulted from the basin-range faults. In some places, as in the Virgin Valley, the basin-fill sediments are at least 8 km thick (Langenheim and others, 2000, 2001a); they constitute the dominant aquifer in the Virgin Valley basin (Dixon and Katzer, 2002; Johnson and others, 2002). Langenheim and others (2001c) reported Tertiary basin-fill deposits in the California Wash basin (fig. 1) to be from 2 to 3 km thick based on seismic reflection and gravity data. The geometry of basins in the map area is generally complex, and geophysical investigations have demonstrated that many of the basins, such as Virgin Valley, Las Vegas Valley, and Meadow Valley Wash, consist of a series of sub basins (Langenheim and others, 2000, 2001a, b).

During basin-range extension, the map area was broken by mostly north-striking normal faults. Northeast-striking left lateral faults, northwest-striking right-lateral faults, and low angle normal (detachment) faults occur locally. In addition, the map area includes a series of east-striking transverse faults, which started to form in the late Mesozoic and early Tertiary (Ekren and others, 1976; Brothers and others, 1996; Rowley, 1998; Rowley and Dixon, 2001) and continued to deform the area.

STRUCTURAL GEOLOGY

Major thrust faults in the map area include the Muddy Mountain thrust in the Muddy Mountains and its equivalent thrusts that extend northward to the Beaver Dam Mountains (Square Top Mountain thrust), and the Gass Peak thrust in the eastern Sheep Range (fig. 4). The faults strike north to northeast and are part of the Sevier orogenic belt (Armstrong, 1968; Fleck, 1970). The Muddy Mountains thrust is the frontal thrust of the Sevier orogenic belt in southern Nevada. The thrust is reported to be late Albian to Cenomanian(?) in age (Bohannon, 1983; Carpenter and Carpenter, 1994; Fleck and Carr, 1990).

The thrust faults partly control the thickness of the Paleozoic carbonate aquifer from west to east across the map area. The Gass Peak thrust transported thick western facies rocks about 30 km eastward (Guth, 1980, 1981) above thin transitional central facies rocks. The Muddy Mountain thrust juxtaposes transition rocks above even thinner eastern facies cratonic platform rocks. Therefore, a large thickness variation exists in the Paleozoic rocks from west to east (from 6 km to less than 2 km) across the map area, because the rocks were telescoped into a narrower zone by Mesozoic thrusting.

The control of groundwater flow by thrust faults in the map area is poorly understood. Burbey (1997) suggested that Late Proterozoic-Lower Cambrian clastic confining units in the upper plate of the Gass Peak thrust may restrict eastward groundwater flow from the Sheep Range and areas to the west. The Muddy Mountain thrust in the Muddy Mountains juxtaposes Paleozoic carbonate rocks in the upper plate against less permeable Mesozoic rocks in the lower plate; such relationships suggest that the thrust acts as a flow barrier. Although the thrust may act as a barrier in localized zones along strike, we believe that overprinting of the thrust by Tertiary normal faults (California Wash fault zone; Langenheim and others, 2002) provides linkage between rocks in the upper and lower plates allowing for some component of groundwater flow across the thrust. This example may apply to other pre-Tertiary thrust faults in the map area, especially where the thrusts are highly modified by younger Tertiary extensional faults.

During Sevier thrusting and following its termination in the Paleocene, erosion of highlands created by these thrusts contributed clastic material that was shed largely to the east. The early Tertiary was a time of deep dissection of these highlands, with deposition of the resulting detritus in the northeastern part of the area and in areas farther east.

East-striking transverse fault zones began to form in the late Mesozoic and transected the Great Basin (Ekren and others, 1976; Rowley, 1998; Rowley and Dixon, 2001). Like transform zones in the ocean basins, they allowed the bounding crustal blocks to deform in different ways and at different rates. The transverse zones also partly controlled emplacement of plutons and caldera complexes, beginning with the start of calc-alkaline magmatism at about 35 Ma. The most notable of these zones in the map area is the Timpahute transverse zone (fig. 4), which defined the northern side of the Caliente caldera complex. Another zone, the Helene transverse zone (fig. 4), controlled not only the southern side of the Caliente caldera complex but also gold mineralization in Delamar and other mining districts on the southern side of the caldera complex. The Caliente caldera complex is elongated east-west because it was extended in that direction by north-striking normal faults and synchronous intracaldera eruptions were focused by bounding transverse faults.

In the northern part of the map area, east-west extension took place during calc-alkaline magmatism. Extension was accompanied by north-directed lateral compression, resulting in north-northeast- and north-northwest-striking strike-slip and oblique-slip faults (Rowley and Dixon, 2001). The oblique left-lateral, north-northeast-striking Kane Springs Wash fault zone (fig. 4) likely began to form during the time of calc-alkaline magmatism, as did the many unnamed right-lateral, northwest-striking faults in the northeastern part of the mapped area.

At about 20 Ma, with increased east-west extension, bimodal magmatism began in the Great Basin in the northern part of the map area (Rowley and Dixon, 2001). To the south, calc-alkaline intermediate magmatism began about 20 Ma and continued to about 12 Ma (Faulds and others, 2001). Locally before 10 Ma, basin-range faulting blocked out north-trending ranges and intervening basins. These faults, which define the Desert, Sheep, Arrow Canyon, and Delamar Ranges, are especially prominent in the western part of the map area. Locally, during east-west extension, east-northeast-striking faults formed, including the Pahranagat shear zone (fig. 4). The east-northeast-striking fault zones accommodate left-lateral oblique-slip movement and merge laterally with north-striking basin-range faults. The northwest-striking Las Vegas Valley shear zone (fig. 4) is a large magnitude right-lateral strike-slip transverse fault zone (Rowley, 1998) with about 50 km lateral offset. Major movement on the shear zone is constrained between 14 and 8.5 Ma (Duebendorfer and Black, 1992). The shear zone truncates the southern Las Vegas, Sheep, Desert, and Pintwater Ranges in the area and extends for nearly 150 km from the Lake Mead area to Mercury, Nevada.

DESCRIPTION OF MAP UNITS

Surficial Units

Relative age assignments for surficial deposits are estimated chiefly on the basis of their height above present streams, degree of post-depositional modification of original surface morphology, and degree of soil development—especially the morphology and thickness of calcium-carbonate-enriched horizons.

Qa **Channel alluvium (Holocene)** Unconsolidated silt, sand, and gravel in active channels and flood plains of rivers and streams. As thick as 10 m.

Qay **Young alluvium (Holocene to latest Pleistocene)** Unconsolidated fine- to coarse-grained gravel and sand and less common silt and clay deposited in alluvial fans and piedmont slopes. Deposits exhibit minor to no dissection. From 1 to 20 m thick.

Qayf **Young fine-grained alluvium (Holocene to late Pleistocene)** Unconsolidated silt, sand, and minor pebble gravel. Deposits form low relief surfaces and exhibit little or no dissection. Exposed in axial parts of valleys in distal portions of alluvial fans and adjacent to playa deposits (Qp). As thick as 10 m.

Qp **Playa deposits (Holocene to late Pleistocene)** Clay, silt, sand, and minor secondary carbonate and evaporite minerals. Playa surfaces are smooth and flat. As thick as 10 m.

Qe **Eolian deposits (Holocene)** Unconsolidated to slightly consolidated silt and sand deposited as dunes, sand ramps, and sand sheets. Deposits include buried paleosols. As thick as 10 m.

Qsa **Spring-apron deposits (Holocene to middle Pleistocene)** Mostly consolidated limestone and travertine deposited near fault-controlled springs. Limestone and travertine deposits contain organic debris (root casts and other plant material) and form spring mounds and aprons. Deposits exposed at southern end of Meadow Valley Mountains and California Wash areas, Nevada, and Virgin Valley area of Utah and Nevada. Generally less than 10 m thick.

Qds **Modern and past groundwater discharge deposits (Holocene to late Pleistocene)** Mostly unconsolidated to consolidated mud, silt, and sand, that locally form small bluffs in the axial parts of major basins. These sediments locally contain organic zones (black mats) and fossils such as fresh-water mollusks and late Pleistocene bone fragments of mammoth, horse, camel, and bison (Quade and others, 1995, 1998). Thickness 1 to 10 m.

Qayo **Intermediate alluvium (late to middle Pleistocene)** Partially consolidated sand and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes. Deposit surfaces have low to moderate relief and dissection and may stand as high as 10 m above active channels. From 0 to 10 m thick.

Qao **Old alluvium (middle to early Pleistocene)** Partly consolidated silt, sand, and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes. Deposits have well-developed calcareous soils and are moderately to highly dissected. From 0 to 30 m thick.

QTa **Oldest alluvium (early Pleistocene to Pliocene)** Consolidated sand and medium- to coarse-grained gravel deposited in alluvial fans and piedmont slopes; includes well developed soil horizons. Deposit surfaces form ballena topography and are highly dissected. Unit mostly exposed in the proximal parts of major drainages flowing into the Colorado River, including Beaver Dam and Meadow Valley Washes. Unit may be 100 m thick or greater.

QTls **Landslide and megabreccia deposits (Pleistocene to Miocene?)** Unit includes highly brecciated rock-avalanche deposits and kilometer-size coherent landslide blocks. Base of unit may be bound by shear slip surface. Unit is composed mostly of Paleozoic bedrock units exposed along mountain range margins, as along the west side of the Sheep Range and west flank of the Beaver Dam Mountains. Maximum thickness about 100 m.

QTc **Calcrete (Pleistocene and Pliocene)** Well consolidated caliche containing embedded pebbles, cobbles, boulders, sand and silt. Caliche beds contain laminar and thin bedded to massive carbonate nodules and pisolites. Deposit surfaces have low relief and represent soil and/or groundwater deposition. Unit best exposed at Mormon Mesa (Machette, 1985). Unit is 1 to 20 m thick.

Bedrock Units

Within much of the Tertiary section, we have followed the mapping strategy of Ekren and others (1977), in which sedimentary and volcanic units are subdivided based upon rock type and age range. The age range follows five main stages in the evolution of this part of the Basin and Range province. Unit 1 consists of sedimentary rocks that predate the oldest Tertiary volcanic units in the area. Unit 2 consists of the oldest Tertiary volcanic rocks of calc-alkaline composition, about 32 to 26 Ma; no sedimentary rocks are associated with this age range. Unit 3 consists of younger calc-alkaline volcanic rocks and related sedimentary rocks ranging in age from 26 to 18 Ma. Unit 4 consists of the older bimodal sequence (locally calc-alkaline) of volcanic rocks and related sedimentary rocks, associated in most areas with the early phases of major regional basin-range extension and ranging in age from 17 to 11 Ma. Unit 5 consists of the younger bimodal sequence of volcanic rocks and related sedimentary rocks associated with both the main episode of regional extension and waning extension, and ranges in age from about 11 to 2 Ma; volcanic rocks of this age are included within the older basaltic flows (Tb). Within the pre-Tertiary regional sedimentary section, some regional sedimentary units are separated geographically, into Proterozoic-Paleozoic facies belts, even though they may be partly or entirely correlative (see correlation of map units). This is because facies changes prevent exact correlations between areas and thus different names have been applied to rocks of the same age.

Qb **Younger basaltic lava flows (Pleistocene)** Exposed only in the northeastern Beaver Dam Mountains. Resistant, dark-gray and black, mostly crystal-poor olivine basalt lava flows and cinder cones. Maximum thickness of individual flow sequences about 100 m.

Tb **Older basaltic lava flows (Pliocene and Miocene)** Resistant, dark-gray and black, mostly crystal-poor olivine basalt lava flows and cinder cones. Includes flows in and near Kane Springs Valley of about 8.0 to 5.6 Ma (Scott and others, 1995b), and in the Lake Mead area of about 11 to 4.4 Ma (Faulds and others, 2001). Maximum thickness of individual flow sequences about 200 m.

Ts5 **Sedimentary rocks, unit 5 (Pliocene and Miocene)** The primary unit is the Muddy Creek Formation (11 to 5 Ma). Muddy Creek Formation is soft to moderately consolidated, tan, gray, and pink, fluvial and lacustrine, tuffaceous sandstone, mudstone, gypsum, halite, and conglomerate that fills fault-block basins. Other named and unnamed units of the same general age fill many other basins: these include the Panaca Formation in the Panaca basin (Rowley and Shroba, 1991), and several unnamed units in northern Kane Spring Valley. The unit also includes age-equivalent basin-fill deposits in the Lake Mead area consisting of conglomerate, sandstone, siltstone, mudstone, limestone, and gypsum. Maximum thickness at least 1,000 m, but may be 3,000 m or more in deeper basins.

Ts4 **Sedimentary rocks, unit 4 (Miocene and Oligocene)** Moderately to well consolidated, mostly gray and tan, fluvial and lacustrine, locally tuffaceous sandstone, tuff, conglomerate, limestone, siltstone, mudstone, and gypsum that fill the lower parts of fault-block basins. The primary unit is the Horse Spring Formation (20 to 12 Ma; Bohannon, 1984). Also included is the red sandstone unit (12 to 11 Ma) that unconformably overlies the Horse Spring Formation (Bohannon, 1984). Total maximum thickness of the Horse Spring at least 2,600 m in Muddy Mountains (Bohannon, 1984), but may be 3,000 m or more in deeper basins.

Ts1 **Sedimentary rocks, unit 1 (Oligocene and Eocene)** Moderately to well consolidated, white, pink, red, and tan, fluvial and lacustrine limestone, sandstone, mudstone, and conglomerate that pinch out westward. Includes the Claron Formation (Oligocene and Eocene) in the northeast part of the map area; roughly correlative rocks extend as far west as the Dodge Spring Quadrangle (Anderson and Hintze, 1993), although they are only 70 m thick at that locality. Unit also includes age-equivalent basin-fill conglomerate and tuff as much as 100 m thick in the Pintwater Range area (Guth, 1980). Maximum thickness about 500 m.

Tt4 **Ash-flow tuffs and interbedded airfall tuffs, unit 4 (Miocene)** Poorly to densely welded, crystal-poor, bimodal high-silica rhyolite and peralkaline ash-flow tuff and related airfall tuffs; gray, red, tan, and brown. Includes Ox Valley Tuff (13.5 Ma), tuff of Etna (14.0 Ma), tuff of Rainbow Canyon (15.6 Ma), tuff of Acklin Canyon (17.1 Ma), and tuff of Dow Mountain (17.4 Ma), derived from the Caliente caldera complex (Rowley and others, 1995; Snee and Rowley, 2000). Also includes 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), derived from the Kane Springs Wash caldera complex (Scott and others, 1995a, b). Maximum thickness of outflow sheets generally less than 200 m, but intracaldera tuffs at least 500 m thick.

Tt3 **Ash-flow tuffs and interbedded airfall tuffs, unit 3 (Miocene and Oligocene)** Poorly to densely welded, crystal-poor and crystal-rich, calc-alkaline, low-silica rhyolite and dacite ash-flow tuff and related airfall tuffs; gray, brown, tan, and pink. 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 (Rowley and others, 1995; Snee and Rowley, 2000); the Harmony Hills Tuff (22.0 Ma), probably derived from the eastern Bull Valley Mountains (Williams, 1967; Anderson and Rowley, 1975); the Leach Canyon Formation (23.8 Ma), probably derived from the Caliente caldera complex (Williams, 1967; Anderson and Rowley, 1975); and the Pahranagat Formation (22.6 Ma) and Shingle Pass Tuff (26.4 Ma), derived from the central Nevada caldera complex (Best and others, 1993) 50 km north of the map area. Thickness of individual outflow sheets generally less than 300–450 m, but thickness of intracaldera tuffs at least 1,000 m.

Tt2 **Ash-flow tuffs and interbedded airfall tuffs, unit 2 (Oligocene)** Moderately to densely welded, crystal-poor and crystal-rich, calc-alkaline, low-silica rhyolite, dacite, and trachydacite ash-flow tuff and related airfall tuffs; gray, brown, reddish-brown, and pink. Includes the Isom Formation (about 27 Ma), probably derived from the Indian Peak caldera complex (Best and others, 1993) 20 km north of the map area; the Monotony Tuff (27.3 Ma), derived from the central Nevada caldera complex (Best and others, 1993); and the Needles Range Group (32 to 28 Ma), derived from the Indian Peak caldera complex (Best and others, 1989). Thickness of individual outflow sheets generally less than 500 m.

Tr4 **Rhyolite lava flows, unit 4 (Miocene)** High-silica rhyolite. Includes thick sequences in the Caliente caldera complex, some related to emplacement of the Ox Valley Tuff. Maximum thickness about 300 m.

Tr3 **Rhyolite lava flows, unit 3 (Miocene and Oligocene)** Low-silica rhyolite. Includes an east-striking string of domes and dikes along the south side of the Caliente caldera complex that have the same age as the Hiko Tuff. Maximum thickness about 300 m.

Ta4 **Intermediate-composition lava flows, unit 4 (Miocene)** Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia; red, reddish-brown, brown, and gray. Andesite of the Hamblin-Cleopatra volcano (14.2 to 11.5 Ma) in the southern Lake Mead area (Anderson, 1973). Maximum thickness about 300 m.

Ta3 **Intermediate-composition lava flows, unit 3 (Miocene and Oligocene)** Andesitic and locally dacitic lava flows, flow breccia, and mudflow breccia; red, reddish-brown, brown, and gray. In the northeast part of the map area, includes the crystal-rich andesite of Maple Ridge underlying the Racer Canyon Tuff, and the andesite of Little Creek that lies between the Harmony Hills Tuff and the Condor Canyon Formation (Blank, 1959, 1993; Rowley and others, in press). Includes thick stratovolcano deposits, derived from an adjacent pluton, between the Caliente and Kane Springs Wash caldera complexes. Maximum thickness about 1,000 m.

Tg **Granitic intrusive rocks (Miocene)** Granite or other silicic intrusive rock; gray, tan, and locally pink. On the north side of the Kane Spring Wash caldera complex, includes the trachyte stock of Sawmill Spring (14.4 Ma), which postdates volcanic units from the complex. On the west side of the Kane Springs Wash caldera complex, includes the stock of Jumbo Wash, which predates volcanic units from the complex, but is probably less than 15.6 Ma (Scott and others, 1995b).

Tai **Intermediate-composition intrusive rocks (Miocene and Oligocene)** Gray quartz monzonite, granodiorite, diorite, and other intermediate-composition intrusive rocks. In the Lake Mead area, includes diorite and granodiorite source plutons for the Hamblin-Cleopatra volcano and the volcanic rocks of the Black Mountains. In the south Clover Mountains and southwest Bull Valley Mountains, includes 22 to 20 Ma quartz monzonite porphyry plutons of the northeast-striking Iron Axis, such as the Mineral Mountain pluton (Hacker and others, 2002; Rowley and others, in press); includes small dioritic breccia pipes and a nearby large, although fault-fragmented, diorite and granodiorite pluton that was the source of an andesitic stratovolcano complex along the south side of the Caliente caldera complex. Includes the 25-Ma Cobalt Canyon stock of quartz monzonite at the northern edge of the map area (Rowley and others, 1994).

TKg **Grapevine Wash Formation (Tertiary? and Cretaceous?)** Mostly tan conglomerate and sandstone derived from erosion of Sevier thrust sheets. Exposed northwest of Gunlock, Utah, where its maximum thickness is about 600 m.

Kmg **Granite of Walker Wash (Upper Cretaceous)** Muscovite-biotite granite exposed in Walker Wash of the Lake Mead area; intrudes Early Proterozoic gneiss.

Ku **Cretaceous rocks, undivided (Upper and Lower Cretaceous)** Sevier-age synorogenic deposits, including the Baseline Sandstone and Willow Tank Formation, and the Iron Springs Formation and Cedar Mountain Formation. The Baseline Sandstone consists of red, white, and brown sandstone and conglomerate. The Willow Tank Formation consists of conglomerate, sandstone, siltstone, and mudstone; also includes tuff beds with a K-Ar date of about 98 Ma (Fleck, 1970). The Baseline Sandstone and Willow Tank Formation, which overlie Jurassic sandstone along an angular unconformity, are exposed mostly in the Muddy Mountains and are from 1,000 to more than 1,600 m thick. In the northeast part of the map area, unit consists of the Iron Springs Formation, which is tan mudstone, shale, sandstone, and conglomerate about 1,000 m thick. The Iron Springs Formation is underlain by a 7-m-thick bentonite bed which has a fission-track date of 101.7 Ma; beneath the bentonite bed is the Cedar Mountain Formation which is gray conglomerate about 20 m thick (Biek, 2003; Hintze and others, 1994).

Jct **Carmel and Temple Cap Formations, undivided (Middle Jurassic)** The Carmel Formation consists of red and gray siltstone, limestone, dolostone, and mudstone about 160 m thick and containing a tuff bed dated at 165 Ma (Hintze and others, 1994). The underlying Temple Cap Formation consists of red mudstone, sandstone, and gypsum as much as 150 m thick.

Jam **Aztec Sandstone, Navajo Sandstone, Kayenta Formation, and Moenave Formation, undivided (Lower Jurassic)** Includes the Aztec Sandstone in most of southern Nevada (Basin and Range province), and the correlative Navajo Sandstone in southwest Utah and northwest Arizona (Colorado Plateau province). Unit also includes the Kayenta and Moenave formations which underlie both the Aztec Sandstone and Navajo Sandstone. Aztec, Navajo, and Kayenta Formations are red, yellow, and light gray, fine-grained, cliff-forming, cross-bedded quartzose sandstone; the Moenave Formation consists of resistant red siltstone, shale, and sandstone. Gradational contact between map unit and underlying Triassic rocks. Aztec is from 850 to 1,200 m thick in the Muddy and Virgin Mountains and about 200 m thick at Frenchman Mountain; Navajo is 600–700 m thick; combined thickness of Kayenta and Moenave Formations ranges from 170 to 800 m.

Ȼu **Triassic rocks, undivided (Triassic)** Includes Chinle and Moenkopi Formations. The Chinle Formation (Upper Triassic) consists of the Petrified

Forest and Shinarump Members; the Petrified Forest Member is variegated red, purple, gray, and yellow, bentonitic mudstone, siltstone, and sandstone. The underlying Shinarump Member is orange, brown and gray, massive-bedded, trough-crossbedded conglomeratic sandstone and conglomerate; includes some petrified wood fragments. The Chinle Formation unconformably overlies the Moenkopi Formation (Middle? and Lower Triassic) which consists, from top to base, of the upper red member, Shnabkaib Member, Virgin Limestone Member, lower red member, and Timpoweap Member. The upper red member is red sandstone, siltstone, mudstone, conglomerate, and gypsum. The Shnabkaib Member is white, light gray, and pink to red slope-forming dolostone, mudstone, siltstone, sandstone, and gypsum. The Virgin Limestone Member is thin bedded to laminated limestone and dolostone, and gypsiferous siltstone and mudstone. The Timpoweap Member is gray, sandy limestone and gypsiferous siltstone, yellow and red conglomeratic sandstone, and gray to brown conglomerate. Moenkopi Formation unconformably overlies the Kaibab Limestone. Map unit is about 1,000 m thick.

Pkt **Kaibab and Toroweap Formations undivided (Lower Permian)** The Kaibab Formation consists of the Harrisburg and Fossil Mountain Members. The Harrisburg Member consists of gray and yellow cherty dolostone and limestone, and red and gray siltstone, sandstone, and gypsum. The Fossil Mountain Member is yellowish-gray sandy and cherty limestone. The Toroweap Formation consists of the Woods Ranch, Brady Canyon, and Seligman Members. The Woods Ranch Member is gray, orange, and red siltstone, sandstone, gypsum, and minor dolostone and limestone. The Brady Canyon Member is gray cherty limestone and dolostone. The Seligman Member is gray and red sandy limestone, dolostone, gypsiferous sandstone, siltstone, and minor shale. The Toroweap Formation unconformably overlies the Lower Permian redbeds unit. Combined, the Kaibab and Toroweap Formations are about 300 to 550 m thick.

Pr **Lower Permian redbeds** Red and tan cross-bedded sandstone, siltstone, and sandy shale. Unit defined by Longwell and others (1965) and correlated with parts of the Queantoweap and Esplanade Sandstones and the Hermit Formation. Unit is 400 to 600 m thick.

PIPc **Callville Limestone and related rocks (Lower Permian and Pennsylvanian)** Mapped in the Virgin and Beaver Dam Mountains. Map unit partly equivalent to the Bird Spring Formation. The Callville Limestone (Pennsylvanian) consists of gray fossiliferous limestone and dolostone. Also includes layers and nodules of brown chert; brown sandstone beds common in upper half. Map unit includes the Pakoon Dolostone (Lower Permian). The Pakoon is light-gray dolostone with minor limestone, sandstone, and gypsum. Unit is from 460 to 880 m thick.

PMb **Bird Spring Formation and related rocks (Lower Permian to Upper Mississippian)** Gray and yellowish-gray bioclastic limestone, dolostone, siltstone, silty limestone, brown sandstone, and gray and red shale. Forms stair-step ledges. Contains abundant discontinuous layers and nodules of gray to brown-weathering chert; chert makes up more than 50 percent of rock volume in some beds. Upper part is mostly gray cherty bioclastic limestone and brown sandstone of Leonardian age (Page and others, 2005). Middle part is a distinctive red, silty limestone marker unit (Page, 1992, 1993, and 1998); marker unit contains submarine debris flow conglomerate and turbidite beds and represents a slope to basin sequence in contrast to the carbonate shelf sequence that typifies most of the Bird Spring Formation in the region. The basal 20 to 60 m of the map unit in west and south-central parts of map area consists of the Upper Mississippian Indian Springs Formation of Webster and Lane (1967) and Webster (1969). The Indian Springs Formation is yellowish-gray bioclastic limestone, black to red shale, and tan sandstone. The map unit attains a maximum thickness in the Las Vegas Range area, where it is about 2,500 m thick; top of unit not exposed in most of map area.

Msc **Scotty Wash Quartzite and Chainman Shale (Upper Mississippian)** Mapped in northern Meadow Valley Mountains near the margin of Kane Springs Wash. Scotty Wash Quartzite is tan, red and brown crossbedded quartzite. The Chainman Shale is black, olive-gray, and brown, fissile shale, red siltstone, and gray limestone. The siltstone is exposed mostly in the lower part of the unit and is interbedded with thin, crinoidal limestone. Map unit is partly correlative with Indian Springs Formation of Webster and Lane (1967). Unit is 200 to 320 m thick.

Mm **Monte Cristo Group of Langenheim and others (1962) (Upper and Lower Mississippian)** Carbonate platform rocks consisting of Yellowpine, Bullion, Anchor, and Dawn Limestones. The Yellowpine Limestone is gray limestone containing sparse nodules of gray to brown chert. The Bullion Limestone is gray encrinitic limestone and some beds of brown chert. The Anchor Limestone is gray limestone and brown chert. The Dawn Limestone is gray bioclastic, oolitic limestone and brown chert. The Monte Cristo Group is about 300 m thick in the Muddy Mountains and Tule Springs Hills, 280 m thick in the Mormon Mountains, 460 m thick in the southern Meadow Valley Mountains, and about 500 m thick in the Arrow Canyon and south Las Vegas Ranges.

Mr **Redwall Limestone (Upper and Lower Mississippian)** Consists of the Horseshoe Mesa, Mooney Falls, Thunder Springs, and Whitmore Wash Members. Unit is mostly equivalent to the Monte Cristo Group of Langenheim and others (1962) but is thinner and represents cratonic platform sequence of the Colorado Plateau province. Members of the Redwall are correlative and lithologically similar to the Yellowpine, Bullion, Anchor, and Dawn Limestones of the Monte Cristo Group, respectively. The Horseshoe Mesa Member consists of cliff-forming limestone containing nodules and layers of chert. The Mooney Falls Member is cliff-forming bioclastic limestone. The Thunder Springs Member consists of bioclastic limestone and chert. The Whitmore Wash Member is gray, bioclastic limestone and dolostone. Mapped in the Virgin and Beaver Dam Mountains and Lake Mead area. The Redwall Limestone is about 200 to 260 m thick.

MDu **Lower Mississippian to Middle Devonian rocks, undivided** In western part of the map area unit consists of the Upper and Middle Devonian Guilmette Formation and either the overlying Lower Mississippian and Upper Devonian Crystal Pass Limestone (in the Arrow Canyon Range and south Meadow Valley Mountains) or the Lower Mississippian and Upper Devonian Pilot Shale and Lower Mississippian Joana Limestone (in the north Meadow Valley Mountains, Delamar Mountains, and Sheep Range). The Crystal Pass Limestone is micritic limestone containing sparse gastropods and intraclasts and is about 60 to 70 m thick. The Joana Limestone is gray, cherty, bioclastic limestone about 250 m thick. The Pilot Shale is gray and red platy limestone and is about 215 m thick in the Meadow Valley Mountains. The Guilmette Formation is gray burrow-mottled dolostone and limestone and minor dolomitic quartzite. The Guilmette Formation is 440 to 480 m thick. In eastern part of map area (Muddy Mountains, Tule Springs Hills, and Mormon Mountains), map unit includes Sultan Limestone of Hewett (1931). The Sultan Limestone is mostly equivalent to, but thinner than the Guilmette Formation, and includes the Crystal Pass, Valentine, and Ironside Members. The Valentine and Ironside Members consist of dark-gray limestone and light-gray dolostone. The Sultan is 200 to 400 m thick in the map area.

Dtb **Temple Butte Formation (Upper and Middle? Devonian)** Gray dolostone with subordinate beds of purple and gray siltstone and sandstone. Unit represents a cratonic platform sequence of the Colorado Plateau province and is partly equivalent to the Sultan Limestone and Guilmette Formation but is restricted to a Devonian age. Also partly equivalent to the Muddy Peak Limestone of Longwell (1921). Unit mapped in the Virgin and Beaver Dam Mountains and the Lake Mead area. Unit is 150 to 220 m thick in the Beaver Dam Mountains and 60 to 120 m thick in the Virgin Mountains.

DSu **Middle Devonian to Silurian rocks, undivided** Miogeoclinal sequence exposed in western part of map area, includes rocks equivalent to parts of the Middle Devonian Simonson Dolomite, the Lower Devonian Sevy Dolomite, and the Silurian Laketown Dolomite. The Simonson Dolomite consists of light to dark gray dolostone, 250 m thick in the Sheep Range and southern Delamar Mountains, 170 m thick in the Meadow Valley Mountains, and 100 m thick in the Arrow Canyon Range. The Sevy Dolomite consists of gray, aphanic dolostone to dolomudstone that includes cherty argillaceous unit of Johnson and others (1989) at top. The Sevy Dolomite is 235 m thick in the southern Delamar Mountains, and 100 to 150 m thick in the Meadow Valley Mountains and Arrow Canyon Range. The Laketown Dolomite displays a tri-part character that is widely recognized in the Great Basin: upper dark, middle light, and lower dark dolostone parts; the upper dark dolostone is medium dark gray, fossiliferous dolostone. The middle part is light-gray, fossiliferous dolostone. The lower part is medium-gray, vuggy and burrowed dolostone containing some layers and nodules of brown chert. The Laketown Dolomite is Early Silurian age based on conodonts collected in the Sheep Range (Page and others, 2005). The Laketown Dolomite is about 300 m thick in the Sheep Range and southern Delamar Mountains, 150 m thick in the Meadow Valley Mountains, about 160 m thick in the Lime Mountain area, and about 100 m thick in the Arrow Canyon Range. In the latter two areas, typical tri-part character is absent and the rocks are mostly light-gray dolostone.

SOu **Silurian and Ordovician rocks, undivided** Unit mapped only in Mormon Mountains and Tule Springs Hills and includes rocks equivalent to parts of the Silurian Laketown Dolomite, Upper Ordovician Ely Springs Dolomite, Middle Ordovician Eureka Quartzite, and Middle and Lower Ordovician Pogonip Group. Unit is about 260 m thick in the Mormon Mountains and 730 m thick in Tule Springs Hills.

Oes **Ely Springs Dolomite (Upper Ordovician)** In the western part of map area, uppermost part of unit is composed of light-olive-gray, burrow-mottled, finely saccharoidal dolostone to dolomudstone. Middle and lower parts of the formation consist of medium-dark-gray dolostone containing planar laminations and some scattered chert. In the Arrow Canyon Range, basal beds include pale-red shale and siltstone. Unit unconformably overlies Eureka Quartzite. Unit is from 120 to 140 m thick in the western part of the map area, and 100 m thick in the Tule Springs Hills and Mormon Mountains, and is absent in the Virgin, Beaver Dam, and Muddy Mountains, as well as at Frenchman Mountain and in the Lake Mead area.

Oep **Eureka Quartzite (Middle Ordovician) and Pogonip Group (Middle Ordovician to Upper Cambrian), undivided** Unit mapped in the Meadow Valley Mountains (460 m thick), southern Delamar Mountains (610 m thick), and the Arrow Canyon Range (650 m thick). Rocks are lithologically similar to, but thinner than those described for the Eureka Quartzite (Oe) and Pogonip Group (O€p) below.

Oe **Eureka Quartzite (Middle Ordovician)** Light- to moderate-brown and white to light-brown, fine to medium grained quartzite, friable sandstone, and minor sandy carbonate beds. Contains tabular-planar crossbeds and *skolithus* burrows. Map unit is 50 to 120 m thick in the Sheep and Desert Ranges, 40 to 50 m thick in the southern Delamar Mountains and Arrow Canyon Range, 10 m thick in the Dry Lake Range, and 3 to 8 m thick in the Mormon Mountains and Tule Springs Hills. Unit is absent in cratonic platform (Frenchman Mountain, Lake Mead area, and the Muddy, Virgin, and Beaver Dam Mountains).

Op **Pogonip Group (Lower Ordovician)** Unit exposed only in the Muddy Mountains and consists of cherty gray dolostone equivalent to Lower Ordovician part of the Pogonip Group; these rocks were called the Monocline Valley Formation by Longwell and Mound (1967) and Bohannon (1983). Map unit is 220 m thick. Ordovician rocks are absent in cratonic platform (Frenchman Mountain, Lake Mead area, and Virgin and Beaver Dam Mountains).

O€p **Pogonip Group (Middle Ordovician to Upper Cambrian)** Miogeoclinal section of the Pogonip Group exposed in western part of map area. Consists of the Antelope Valley and Goodwin Limestones. The Antelope Valley Limestone consists of gray to orange and yellowish-gray bioclastic and arenaceous limestone and dolostone. Beds are burrow-mottled and have abundant ooids, oncoids, and intraclasts, and contain scattered brown chert nodules and layers. Lower part of unit is equivalent to the Goodwin Limestone which consists of orange and gray limestone and abundant brown chert layers, intraclasts, and ooids. Samples from the lower beds of the Goodwin Limestone in the Sheep Range and in ranges to the west have produced Late Cambrian conodonts (Page and others, 2005). Pogonip Group is 600 to 900 m thick.

€nb **Nopah (Upper Cambrian) and Bonanza King (Upper and Middle Cambrian) Formations, undivided** Mapped only in the Mormon Mountains and Tule Springs Hills.

€n **Nopah Formation (Upper Cambrian)** Light- to dark-gray burrow-mottled dolostone, minor gray to orange silty limestone, and scattered chert layers and nodules. Alternating light and dark gray beds form several distinctive color bands. At base of unit, includes the Dunderberg Shale Member, which consists of brown silty limestone and siltstone and olive green shale. Map unit is 300 to 380 m thick in the Sheep Range, 560 m in the southern Delamar Mountains, about 400 m thick in the Meadow Valley Mountains, 115 m thick in the Mormon Mountains, about 200 m thick in the Tule Springs Hills and Muddy Mountains, and 400 m thick in the Beaver Dam Mountains.

€bk **Bonanza King Formation (Upper and Middle Cambrian)** Light- to dark-gray and olive-gray dolostone and subordinate light-brown to orange, silty dolostone. Partly equivalent to the Highland Peak Formation as used by Tschanz and Pampeyan (1970) in Lincoln County, and to the Muav Formation of the Colorado Plateau province. Unit is 900 m thick in the Sheep Range, 700 m thick in the Meadow Valley Mountains, 770 m thick in the Mormon Mountains and Tule Springs Hills, and 1,800 m thick in the Desert Range.

€hp **Highland Peak Formation (Upper and Middle Cambrian)** Light- and dark-gray limestone and dolostone. Unit is restricted to Delamar Mountains in the northern part of the map; well exposed in the Pioche mining district where it was first named (Westgate and Knopf, 1932) and described (Merriam, 1964). Unit has a maximum thickness of 1,500 m.

Ꞓm **Muav Limestone (Middle Cambrian)** Light to dark gray and brown limestone, dolostone, and mudstone. Cratonic platform facies exposed in the eastern part of the map area (Beaver Dam and Virgin Mountains, Lake Mead area, and Frenchman Mountain). Unit as much as 410 m thick in the northern Virgin Mountains.

Ꞓc **Carrara Formation (Middle and Lower Cambrian)** Gray, yellow, and red limestone, siltstone, sandstone, and shale. Exposed in the western part of the map area. About 300 m thick in the Desert Range area, and about 265 m thick in the Sheep Range.

Ꞓcp **Chisholm Shale and Lyndon Limestone (Middle Cambrian) and Pioche Shale (Middle and Lower Cambrian), undivided** Unit exposed only in the Delamar Mountains in northern part of map area. Chisholm Shale is brown shale (Walcott, 1916; Westgate and Knopf, 1932) about 35 m thick. The Lyndon Limestone is gray limestone and sandstone (Westgate and Knopf, 1932) about 50 m thick. The Pioche Shale is green shale (Walcott, 1908) as much as 275 m thick.

Ꞓbt **Bright Angel Shale (Middle and Lower Cambrian) and Tapeats Sandstone (Lower Cambrian), undivided** Cratonic platform facies mapped in the Mormon Mountains, Tule Springs Hills, Frenchman Mountain, Lake Mead area, and Virgin and Beaver Dam Mountains. The Bright Angel Shale is greenish gray and gray micaceous siltstone, sandstone, quartzite, and minor limestone and dolostone. Equivalent to the Pioche Shale, Lyndon Limestone, and Chisolm Shale defined in the Pioche, Nevada area, and to the Carrara Formation in the western part of the map area. The Bright Angel Shale is about 140 m thick in the Mormon Mountains, 80 to 100 m thick in the Beaver Dam and Virgin Mountains, and 180 m thick at Frenchman Mountain. The Tapeats Sandstone is orange quartzite, conglomerate, and sandstone. Equivalent in part to the Prospect Mountain Quartzite as used in parts of Lincoln and Clark County, Nevada (Tschanz and Pampeyan, 1970; Longwell and others, 1965). About 145 m thick in the Mormon Mountains, 365 m thick in the Beaver Dam Mountains, 80 m thick in the Virgin Mountains, and 50 m thick at Frenchman Mountain.

ꞒZw **Wood Canyon Formation (Lower Cambrian and Late Proterozoic)** Brown quartzite, sandstone, siltstone, shale, and sandy shale. Lower contact with the Stirling Quartzite is transitional. Unit is about 600 to 700 m thick in the Desert Range, and an incomplete section in the Sheep Range is about 450 m thick. Unit is exposed in the northern part of the map area in Delamar Mountains, and is as much as 480 m thick (Stewart, 1984).

Zs **Stirling Quartzite (Late Proterozoic)** Purple, pink, maroon, gray, and white conglomeratic quartzite, quartzite, and sandstone, and minor beds of sandy shale and siltstone. Lower contact with the Johnnie Formation is transitional. Unit is 945 m thick in the Desert Range, but only the uppermost 100 m is exposed in Las Vegas Range (Maldonado and Schmidt, 1991). In the north part of the map area (Delamar Mountains), upper contact is transitional with the Wood Canyon Formation, and formation is as much as 600 m thick, with the base not exposed (Stewart, 1984).

Zj **Johnnie Formation (Late Proterozoic)** Brown, gray, and green quartzite, sandstone, siltstone, and dolostone. Upper part contains greater proportion of shale compared to lower part and several brown to tan oolitic dolostone beds. Lower part is predominantly fine-grained quartzite and thin beds of shale. Unit is about 1,580 m thick in the Desert Range.

Xu **Early Proterozoic crystalline rocks** Gneiss, schist, and granite exposed at Frenchman Mountain, Lake Mead area, Virgin Mountains, Beaver Dam Mountains, and Mormon Mountains. Rocks are dated at 1.7 Ga (Quigley and others, 2002).

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