Hydrogeologic Framework

By Donald S. Sweetkind, Jay R. Cederberg, Melissa D. Masbruch, and Susan G. Buto

Chapter B of

Conceptual Model of the Great Basin Carbonate and Alluvial Aquifer System

Edited by Victor M. Heilweil and Lynette E. Brooks

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
inch per day (in./d)	25.38	millimeter per day (mm/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Note: The conversion factors given above are for the entire report. Not all listed conversion factors will be in any given chapter of this report.

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Temperature in kelvin (K) may be converted to degrees Fahrenheit (°F) as follows:

°F=1.8K-459.67

Temperature in kelvin (K) may be converted to degrees Celsius (°C) as follows:

°C=K-273.15

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

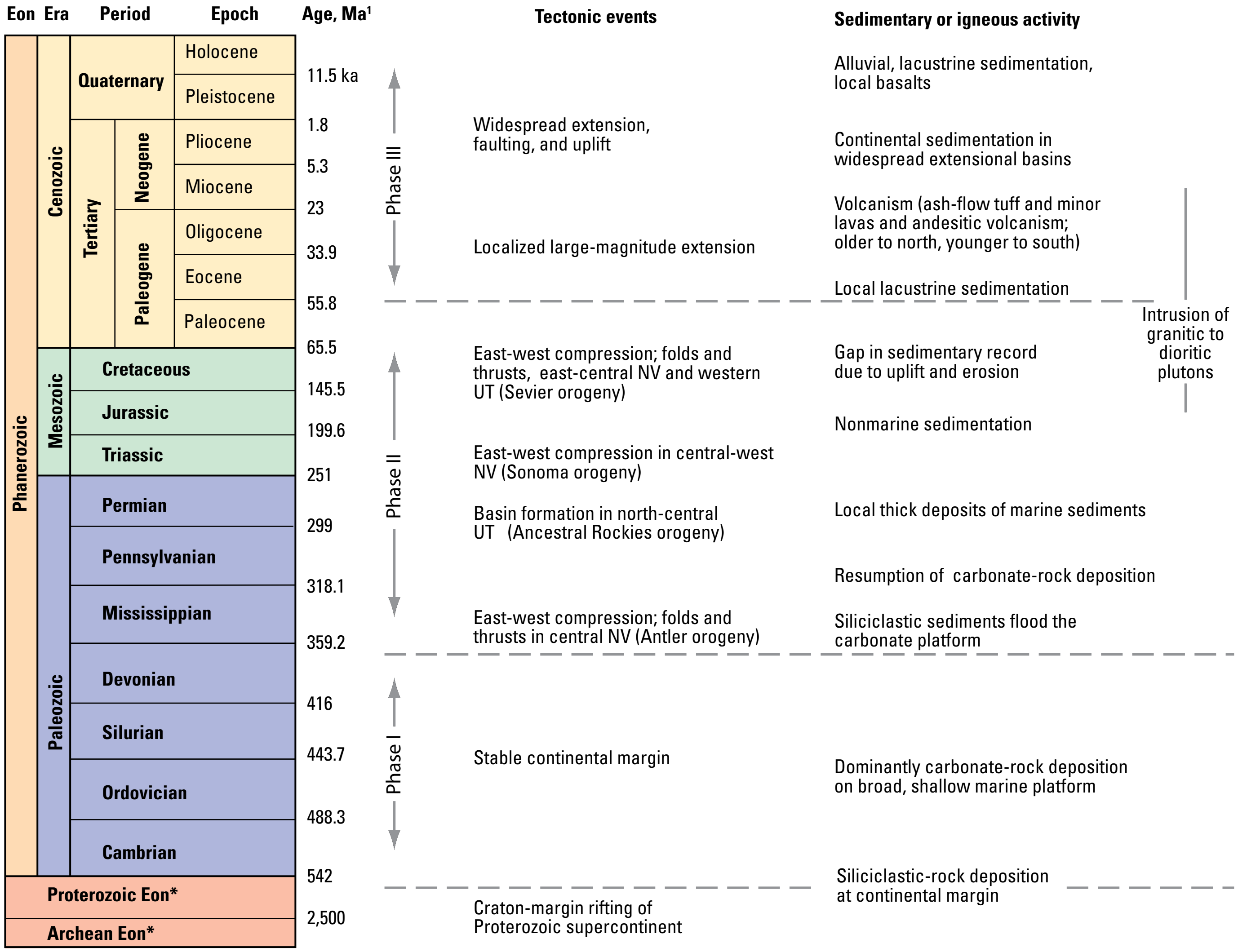
Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Chapter B: Hydrogeologic Framework

By Donald S. Sweetkind, Jay R. Cederberg, Melissa D. Masbruch, and Susan G. Buto

The geologic setting and history of the eastern Great Basin, inclusive of the Great Basin carbonate and alluvial aquifer system (GBCAAS) study area, is preserved in rocks and geologic structures that span more than a billion years (fig. B–1). This geology ranges from Late Proterozoic sedimentary rocks to widespread Quaternary alluvial deposits and active faults (Stewart and Poole, 1974; Speed and others, 1988; Dickinson, 2004; 2006). The geologic framework that has resulted from the geologic events during this protracted period profoundly affects groundwater flow. Thus, any water-resource assessment of the area must take into account the complex geologic history and consider the distribution of the diverse rock types and geologic environments.



* The Archean and Proterozoic Eons are major subdivisions of **Precambrian** time.

¹Geologic age from Gradstein and others (2004); Ma, age in millions of years, ka, thousands of years.

Figure B–1. Geologic time scale showing major geologic events in the Great Basin carbonate and alluvial aquifer system study area.

The geologic evolution of the GBCAAS study area since the end of Precambrian time may be subdivided into three general phases (Levy and Christie-Blick, 1989; Dickinson, 2006): (1) Late Proterozoic to Devonian marine sedimentation along a passive continental margin; (2) Late Devonian to Eocene compressional deformation, along with changes in sedimentation patterns related to the subduction of oceanic crust and accretion of exotic terrains along the western continental margin in western Nevada; and (3) mid- to late- Cenozoic extension, faulting, volcanism, and continental sedimentation (fig. B–1). Within the context of this three-phase evolution, numerous tectonic events and the accompanying changes in sedimentation patterns and igneous activity have occurred.

Hydrogeologic Units

The diverse sedimentary units of the GBCAAS study area are grouped into hydrogeologic units (HGUs) that are inferred to have reasonably distinct hydrologic properties due to their physical (geological and structural) characteristics. The definition of HGUs is important in conceptualizing the hydrogeologic system, construction of a geologic framework for describing the groundwater flow system, and use in numerical groundwater flow models. An HGU has considerable lateral extent and reasonably distinct physical characteristics that may be used to infer the capacity of a sediment or rock to transmit water. HGUs similar to those used in this study were first defined on the basis of geologic studies and hydrologic data for the pre-Cenozoic rocks in the vicinity of the Nevada Test Site (fig. A–1; Winograd and Thordarson, 1975). Most subsequent utilization of HGUs and groundwater flow models of the region (Laczniak and others, 1996; D’Agnese and others, 1997; Belcher, 2004) have honored these HGU subdivisions of the pre-Cenozoic sedimentary section. With modification for local stratigraphic variation and thickness changes, these units also can be used to represent the GBCAAS study area. In contrast, a variety of different approaches have been taken in subdividing the Cenozoic section into HGUs; past approaches have differed in the number of HGUs used within the GBCAAS study area and in the treatment of spatially variable material properties in the volcanic-rock units.

The consolidated pre-Cenozoic rocks, Cenozoic sediments, and igneous rocks of the GBCAAS study area are subdivided into nine HGUs: six of the units describe consolidated pre-Cenozoic rocks and the other three describe Cenozoic basin-fill and volcanic rocks (table B–1; fig. B–2). The HGUs for the GBCAAS study area include (1) a noncarbonate confining unit (NCCU) representing low-permeability Precambrian siliciclastic formations, (2) a lower carbonate aquifer unit (LCAU) representing high-permeability Cambrian through Devonian limestone and dolomite, (3) an upper siliciclastic confining unit (USCU) representing low-permeability Mississippian shale, (4) an upper carbonate aquifer unit (UCAU) representing high-permeability Pennsylvanian and Permian carbonate rocks, (5) a thrusted noncarbonate confining unit (TNCCU) representing low-permeability siliciclastic rocks incorporated in regional thrust faults, (6) a

Table B–1. Thickness and hydraulic properties of hydrogeologic units within the Great Basin carbonate and alluvial aquifer system study area.

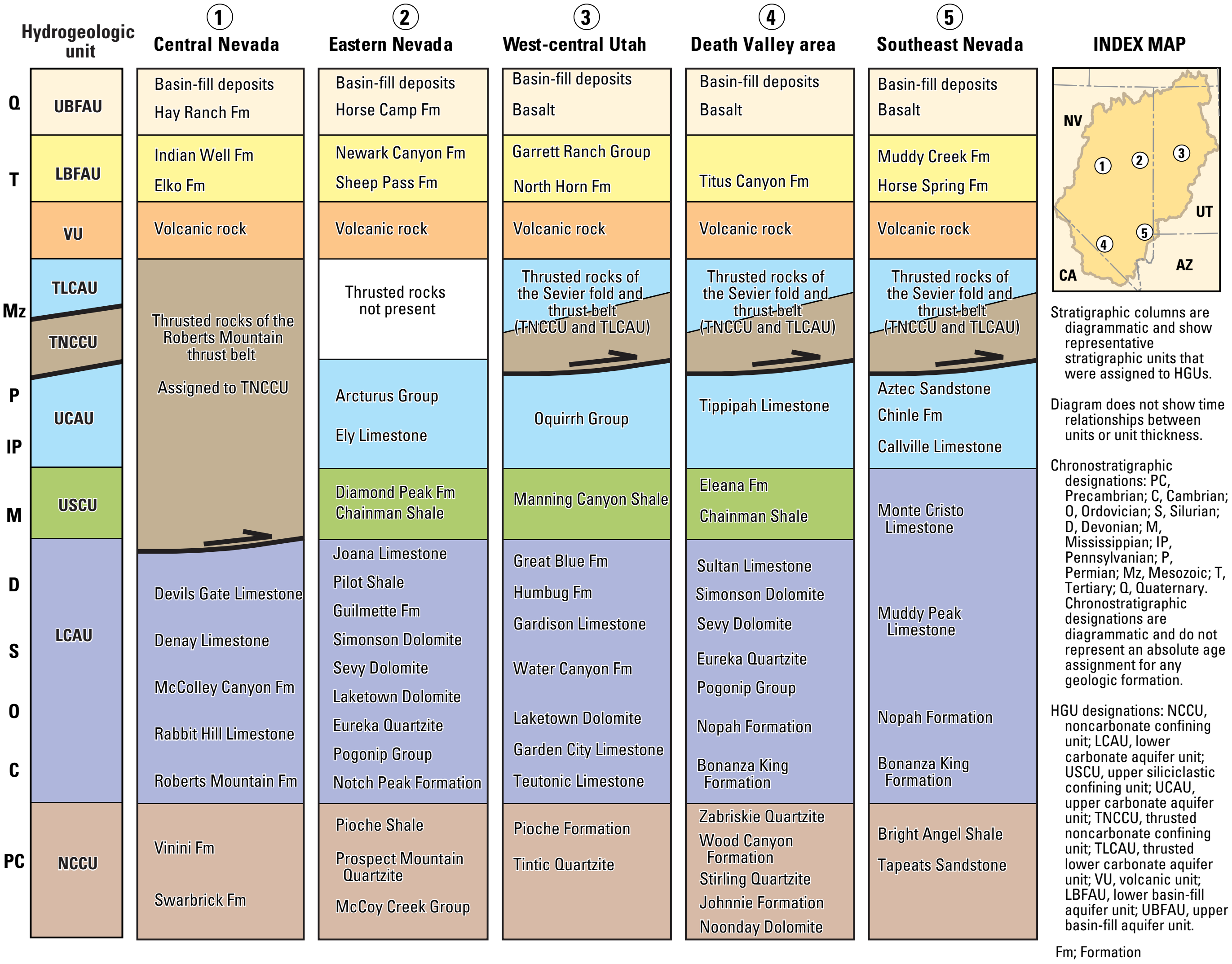
[Modified from Belcher and others, 2001; 2002. >, greater than; NC, not calculated; LBFAU, lower basin-fill aquifer unit; UBFAU, upper basin-fill aquifer unit; VU, volcanic unit; UCAU, upper carbonate aquifer unit; USCU, upper siliciclastic confining unit; LCAU, lower carbonate aquifer unit; NCCU, noncarbonate confining unit]

Major hydrogeologic unit	Hydrogeologic unit abbreviation	Maximum unit thickness (feet)	Hydraulic conductivity (feet per day)				
			Arithmetic mean	Geometric mean	Minimum	Maximum	Count
Cenozoic basin-fill aquifer sediments	LBFAU and UBFAU[1]	36,000	31	4	0.0001	431	71
Cenozoic volcanic rock	VU	3,300 (>13,000 in calderas)	20	3	0.04	179	26
Upper Paleozoic carbonate rock	UCAU	24,000	62	0.4	0.0003	1,045	28
Upper Paleozoic siliciclastic confining rock	USCU	>5,000	0.4	0.06	0.0001	3	22
Lower Paleozoic carbonate rock	LCAU[2]	16,500	169	4	0.009	2,704	45
Noncarbonate confining rock	NCCU[3]	NC	0.8	0.008	0.00000009	15	26

[1] Includes both the upper basin-fill aquifer (UBFAU) and lower basin-fill aquifer (LBFAU) hydrogeologic units.

[2] Includes the thrusted lower carbonate aquifer (TLCAU) hydrogeologic unit.

[3] Includes the thrusted noncarbonate confining rock (TNCCU) hydrogeologic unit.



Stratigraphic columns are diagrammatic and show representative stratigraphic units that were assigned to HGUs.

Diagram does not show time relationships between units or unit thickness.

Chronostratigraphic designations: PC, Precambrian; C, Cambrian; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; IP, Pennsylvanian; P, Permian; Mz, Mesozoic; T, Tertiary; Q, Quaternary. Chronostratigraphic designations are diagrammatic and do not represent an absolute age assignment for any geologic formation.

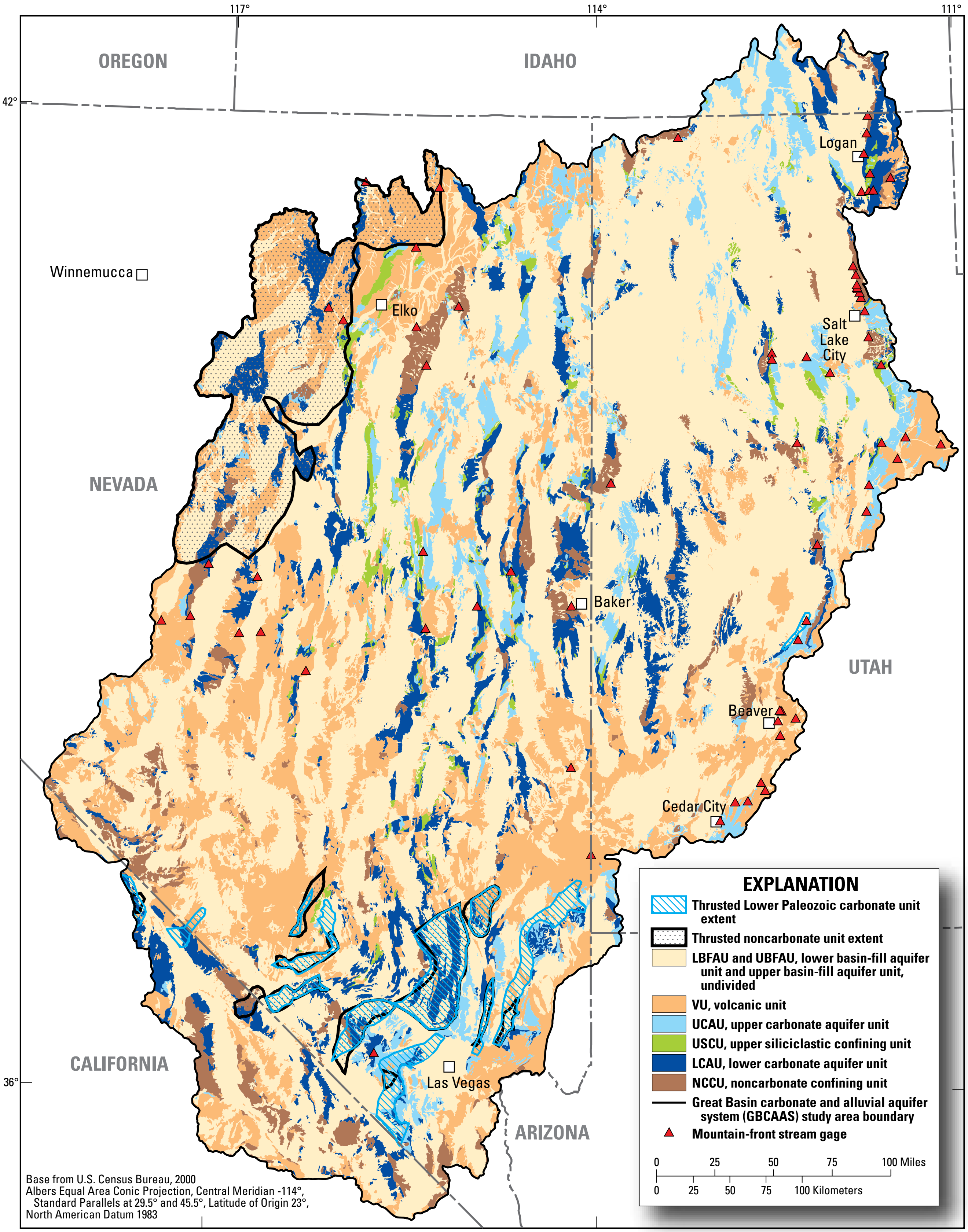
HGU designations: NCCU, noncarbonate confining unit; LCAU, lower carbonate aquifer unit; USCU, upper siliciclastic confining unit; UCAU, upper carbonate aquifer unit; TNCCU, thrusted noncarbonate confining unit; TLCAU, thrusted lower carbonate aquifer unit; VU, volcanic unit; LBFAU, lower basin-fill aquifer unit; UBFAU, upper basin-fill aquifer unit.

Fm; Formation

Figure B–2. Representative stratigraphic columns and designation of hydrogeologic units for the Great Basin carbonate and alluvial aquifer system study area.

thrusted lower carbonate aquifer unit (TLCAU) representing high-permeability limestone and dolomite incorporated in regional thrust faults, (7) a volcanic unit (VU) representing outcrop areas of volcanic rocks, (8) a lower basin-fill aquifer unit (LBFAU) representing the lower one-third of the Cenozoic basin fill, and (9) an upper basin-fill aquifer unit (UBFAU) representing the upper two-thirds of the Cenozoic basin fill. The surficial distribution of these hydrogeologic units across the study area is portrayed as a hydrogeologic map (fig. B–3).

The hydrogeologic units in the study area form three distinct aquifer systems composed of alternating more permeable and less permeable units. The three general types of aquifer materials are permeable portions of the UBFAU and LBFAU, some Cenozoic volcanic rocks within the VU—especially fractured welded tuff, and carbonate rocks of the LCAU and UCAU. Each of these units may include one or more water-bearing zones but are stratigraphically and structurally heterogeneous, resulting in a highly variable ability to store and transmit water. The aquifers within the consolidated pre-Cenozoic rocks are separated by the intervening low-permeability Mississippian shale of the USCU. Paleozoic carbonate rocks are underlain at depth by the lower permeability NCCU, which includes Cambrian and Precambrian siliciclastic formations. Volcanic rocks within the VU and the volcanic parts of LBFAU commonly display widely variable lithologic, physical, and hydraulic properties. The hydraulic properties of these deposits largely depend on the mode of eruption and cooling, the extent of primary and secondary fracturing, and the degree to which secondary alteration—such as zeolitic alteration—has affected primary permeability. Fractured rhyolite lava flows and moderately-to



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
North American Datum 1983

Figure B–3. Surficial hydrogeologic units of the Great Basin carbonate and alluvial aquifer system study area.

-densely welded ash-flow tuffs are the principal volcanic-rock aquifers. The confining units generally are nonwelded or partly welded tuff that have low fracture permeability and can be zeolitically altered in the older, deeper parts of the volcanic sections (Laczniak and others, 1996). The HGUs that correspond to the Cenozoic unconsolidated basin-fill aquifer units, LBFAU and UBFAU, include a wide variety of rock types and may have highly variable hydraulic properties. Relative differences in hydraulic properties were used to differentiate aquifers from confining or semiconfining HGUs in the study area. These evaluations primarily were based on relative differences in permeability determined from HGU material properties or on previous estimates of hydraulic conductivity—a quantitatively derived parameter that serves as a measure of permeability (Lohman, 1979; Todd, 1980).

Few aquifer tests have been completed in the study area, and, thus, estimates of hydraulic properties are sparse. Because of limited test data for the study area, estimates of hydraulic properties were compiled from aquifer tests in the Death Valley regional groundwater flow system (DVRFS) (Belcher and others, 2001; 2002). Hydraulic properties from the DVRFS area are considered to be representative of hydraulic properties over much of the GBCAAS study area because of similar rock types and HGUs (table B–1). Horizontal hydraulic conductivity (hereinafter referred to as hydraulic conductivity) values were selected from previous tabulations (Belcher and others, 2001; 2002) and grouped by HGU (table B–1).

For the study area, the hydraulic conductivity for an HGU can span three to nine orders of magnitude (Belcher and others, 2002). Statistical-probability distributions of hydraulic conductivity for specific hydrogeologic units in the DVRFS are presented in Belcher and others (2002) and generally are considered representative of the range of values in the GBCAAS study area. Carbonate and volcanic rocks are typically aquifers in the study area; in the absence of significant secondary porosity owing to fractures and dissolution, however, they are confining units. Grain size and sorting are important influences on hydraulic conductivity of the unconsolidated sediments (Belcher and others, 2001). Groundwater flow is affected by lower permeability rock units, such as consolidated siliciclastic rocks (NCCU and USCU) and low-permeability zones within the Cenozoic units. Matrix permeability, which defines the rock's primary permeability, is low for both the consolidated carbonate-rock aquifers (Winograd and Thordarson, 1975) and for the welded parts of the volcanic-rock aquifers (Blankennagel and Weir, 1973); as such, faults, shear zones, and fractures, which define the rock's secondary permeability, largely determine the water-transmitting properties of these consolidated rocks.

Each of these HGUs is stratigraphically and structurally heterogeneous, having highly variable hydraulic properties. The spatial variability of material properties is represented using a number of hydrogeologic zones for each HGU. Most zones were defined to represent geologic materials that likely have fairly uniform hydraulic properties. Properties of sediments or rocks within each HGU were derived from previously published geologic maps and reports and were used as indicators of primary and secondary permeability; examples of physical properties considered include grain size and sorting, degree of compaction, rock lithology and competency, degree of fracturing, and extent of solution caverns or karstification.

The hydrogeologic zonation presented for each HGU is intended as a geologically based starting point for further refinement of horizontal hydraulic conductivity of an HGU, perhaps by the use of groundwater flow modeling (D'Agnese and others, 1997, 2002; Belcher 2004). Many of the zones defined for each HGU do not have measurements of hydraulic conductivity from an aquifer test. In the absence of such tests, the relative differences in permeability are defined on the basis of other hydrogeologic information.

Non-Carbonate Confining Unit (NCCU)

In the GBCAAS study area, the oldest sedimentary rocks are Middle Proterozoic and Early Cambrian rocks (fig. B–2) that form a westward-thickening wedge of predominantly quartzite, siltstone, and metasedimentary rocks (Stewart, 1970; Stewart, 1972; Stewart and Poole, 1974). The NCCU includes these rocks, as well as all metamorphic and intrusive igneous rocks (Kistler, 1974; Barton, 1990; table B–1). Although only locally exposed in mountain ranges (fig. B–3), the unit is inferred to underlie most of the study area at great depth.

The permeability of the NCCU generally is low to moderate throughout the study area (Winograd and Thordarson, 1975; Plume, 1996; table B–2). Sandstones of the NCCU are often highly cemented, filling much of the original pore volume, and are overlain and underlain by a significant thickness of shale—all of which contribute to the low permeability of this HGU. Metasedimentary rocks of the NCCU that typically have schistose foliation lack a continuous fracture network. Intrusive igneous rocks act mostly as a confining unit, although small quantities of water may pass through these rocks where they are fractured or weathered; most commonly the fractures are poorly connected and these rocks generally impede groundwater flow (Winograd and Thordarson, 1975). As a result of these lithology-related controls on permeability, the NCCU has been subdivided into three hydrogeologic zones primarily on the basis of lithology (fig. B–4*A*; table B–2):

1. Siliciclastic sedimentary rocks, generally possessing a well-developed fracture network, especially along bedding planes. These rocks are Late Proterozoic to Early Cambrian in age (fig. B–1).
2. Metamorphic rocks including gneiss, schist, and slate associated with highly extended areas and metamorphic core complexes. Metamorphic rocks include Proterozoic rocks

Table B–2. Hydrogeologic zones for the noncarbonate confining unit (NCCU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Late Proterozoic siliciclastic rocks, such as the Prospect Mountain Quartzite in the northern part of the area and Wood Canyon Formation and Stirling Quartzite in the southern part of the area.	Moderate.	Generally well-developed fracture network, especially along bedding planes. Clay interbeds can inhibit connectivity; sandstones typically highly cemented.	Hintze and others (2000); Ludington and others (1996).
2	Foliated metamorphic rocks including gneiss, schist, slate associated with highly extended terranes and metamorphic core complexes.	Low.	Foliation prohibits development of well-connected fracture network, matrix is impermeable.	Raines and others (2003); Wernicke (1992).
3	Intrusive igneous rocks; inferred at depth from (a) projection of surface geology, (b) the assumption that plutons underlie calderas, and (c) published interpretation of magnetic and gravity data that portray plutons.	Low to moderate.	May support well-developed fracture networks where unit is at the surface or within 0.6 miles of the surface; deeper intrusives are probably less fractured. At depth, especially beneath calderas and volcanic centers, fracture permeability may be reduced by quartz veins filling fractures or by clay alteration along fracture walls.	Grauch (1996); Plume (1996); Glen and others (2004).

and those parts of the Paleozoic section affected by metamorphic events in Mesozoic and Tertiary time. Foliation in these rocks prohibits development of well-connected fracture networks; the rock matrix is considered impermeable. Spatial extent of metamorphic rocks was modified from maps of highly extended terrains (Wernicke, 1992; Raines and others, 2003).

3. Intrusive igneous rocks of all ages, predominantly Jurassic, Cretaceous, and Tertiary (fig. B–1). Spatial extent of intrusive igneous rocks was inferred at depth from projection of surface geology, geophysically based maps of inferred pluton extent (Grauch, 1996; Glen and others, 2004), and the assumption that plutons underlie calderas.

Lower Carbonate Aquifer Unit (LCAU)

The LCAU is a thick succession of predominantly carbonate rocks deposited throughout most of the eastern and central parts of the region during Middle Cambrian through Devonian time (fig. B–2). The LCAU represents a large volume of carbonate rock that is prominently exposed in the mountain ranges (fig. B–3), and is present beneath many of the valleys. The LCAU includes Cambrian through Devonian limestone and dolomite, with a few thin interbeds of siliciclastic rocks (fig. B–2).

In general, the carbonate rocks and calcareous shale of the LCAU form a westward-thickening carbonate-and-clastic rock section as much as 15,000 ft thick. The thickness of the unit may exceed 16,500 ft in central and southeastern Nevada, where it has been referred to as the “central carbonate corridor” (Dettinger and others, 1995). Where deposited in shallow-water continental shelf environments, such as eastern Nevada, west-central Utah, and the Death Valley area (columns 2–4, fig. B–2), carbonate rocks are thick-bedded and coarse-grained, as exemplified by units such as the Bonanza King Formation, the Notch Peak Formation, and the Laketown Dolomite. In central Nevada (column 1, fig. B–2), carbonate rocks such as the Roberts Mountain Formation were deposited in deeper water slope and deep basin environments and generally are thin-bedded and finer-grained, containing a high proportion of carbonate mud (Stewart and Poole, 1974; Poole and others, 1992; Cook and Corboy, 2004). Although thickness is not represented on figure B–2, Middle Cambrian through Devonian strata form a relatively thin (several hundreds of feet) cratonic sequence along the east side of the study area (column 5, fig. B–2; Hintze, 1988; Poole and others, 1992).

The carbonate rocks of the LCAU and UCAU form a major high-permeability, consolidated-rock aquifer system in the Great Basin (Winograd and Thordarson, 1975; Bedinger and others, 1989; Dettinger and others, 1995; Harrill and Prudic, 1998). Carbonate rocks of the LCAU and UCAU have three distinct types of permeability that influence the storage and movement of groundwater—primary or intergranular permeability; and two types of secondary permeability: fracture permeability and vug or solution permeability. Lower Paleozoic carbonate rocks in southern Nevada have relatively low primary permeability (Winograd and Thordarson, 1975). Studies of groundwater flow within the carbonate-rock province (Dettinger and others, 1995; Harrill and Prudic, 1998) and tabulations of hydraulic-property estimates for carbonate rocks (Dettinger and others, 1995; Belcher and others, 2001) emphasize the relation of faults and broad structural belts to zones of high permeability, presumably

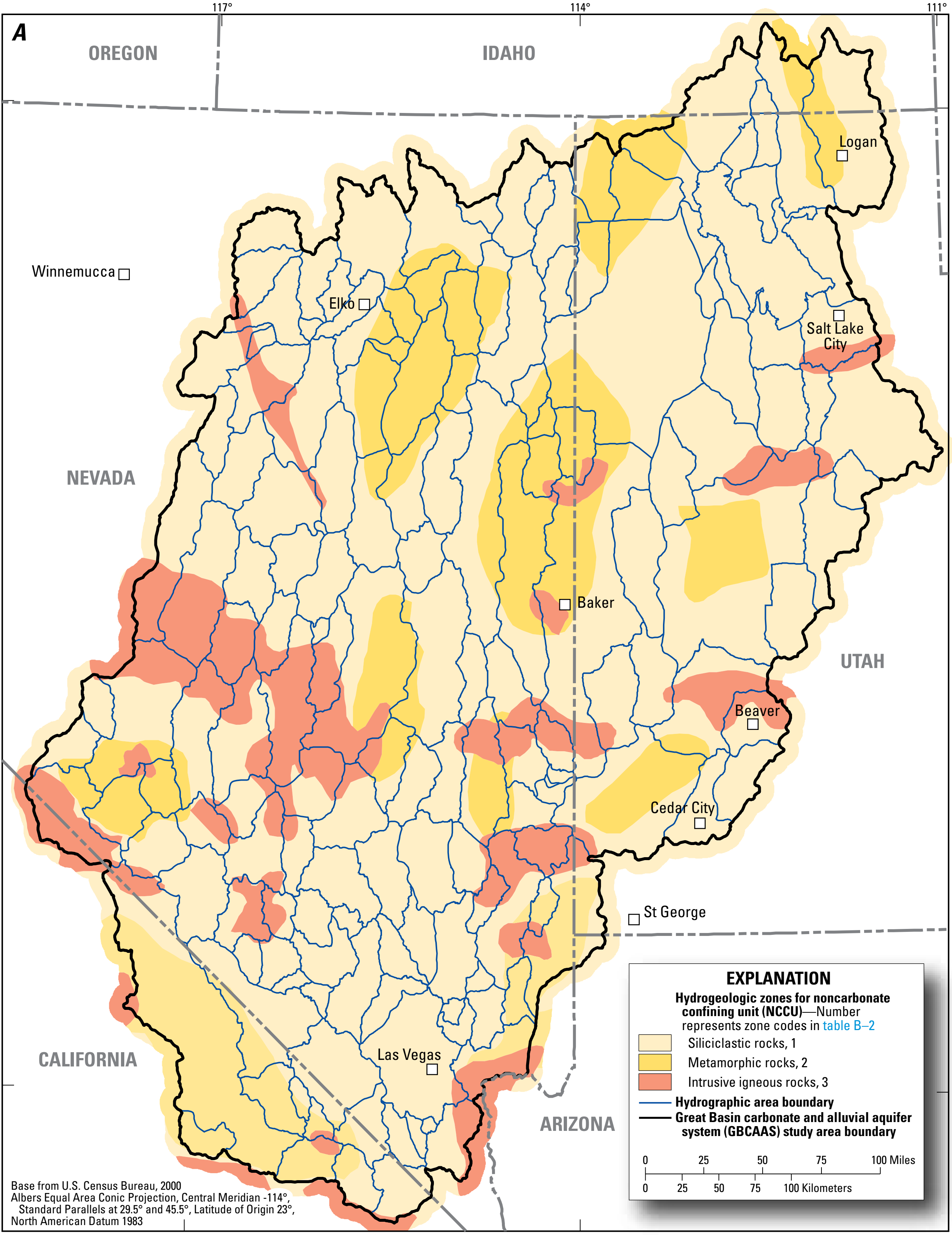


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Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: ***A***, non-carbonate confining unit (NCCU), ***B***, lower carbonate aquifer unit (LCAU), ***C***, upper carbonate aquifer unit (UCAU), ***D***, volcanic unit (VU), ***E***, lower basin-fill aquifer unit (LBFAU), and ***F***, upper basin-fill aquifer unit (UBFAU).

the result of the formation of fractures during deformation. Fracture permeability can be enhanced if vertical fractures intersect horizontal fractures, creating a well-connected network of openings through which water can move. Solution openings can create additional secondary permeability in carbonate rocks. For example, as a result of periodic declines in sea level during Paleozoic time, extensive areas of carbonate rock in east-central Nevada were exposed to subaerial weathering and subsequent erosion. These intervals of erosion are represented in the sedimentary record as unconformities (Cook and Corboy, 2004) —relatively long gaps in time when the carbonate platform was above sea level and conditions were favorable for erosion, dissolution, and development of solution caverns in the exposed carbonate rocks.

The LCAU has been subdivided into three hydrogeologic zones based on lithologic variability that potentially could affect permeability (fig. B–4*B*; table B–3). Lithology-based zones follow:

1. Carbonate rocks deposited in shallow waters. These rocks generally have high permeability as a result of coarse primary texture and frequent subaerial exposure and dissolution.
2. Shale of the Pilot basin. This zone, near the center of the GBCAAS study area, was the site of shale and other siliciclastic deposition in the Pilot basin (Poole and others, 1992) during Devonian to Mississippian time. The siliciclastic units are thin and their presence can result in a slight reduction of the overall permeability of the hydrogeologic unit.
3. Carbonate rocks deposited in deeper waters. These rocks along the western margin of the study area have lower permeability than shallow-water carbonate rocks to the east as a result of the dominance of carbonate mud within the rocks, thin bedding, and higher proportion of shale interbeds.

Upper Siliciclastic Confining Unit (USCU)

The USCU comprises Mississippian mudstone, siltstone, sandstone, and conglomerate that overlie the Lower Paleozoic carbonate rocks. Rocks in the USCU were formed as siliciclastic sediments that were shed eastward from a highland created by the Antler orogeny (fig. B–1), west of the study area. Sediments were deposited in a northeast-to-southwest-trending basin (Poole and Sandberg, 1977; Poole and others, 1992) and include an easterly thinning wedge of coarse clastic detritus, the Diamond Peak Formation (grading eastward into relatively low permeability argillites and shales), and the Chainman Shale (columns 2 and 4, fig. B–2). Siliciclastic rocks of similar age in western Utah include the Manning Canyon Shale (column 3, fig. B–2). This succession of sedimentary rocks is distributed widely across the study area and, where not thinned structurally, generally ranges in thickness from 2,500 ft to greater than 5,000 ft (Hose and others, 1976). The effects of the Antler orogeny did not extend to the southeastern part of the GBCAAS study area, and deposition of shelf-type carbonate rocks, such as the Monte Cristo Limestone, continued during Mississippian time (column 5, fig. B–2).

The shaly siliciclastic rocks of the USCU are fine grained and have low primary porosity and permeability (table B–1). Because of its low susceptibility to dissolution or fracturing, the USCU also lacks significant secondary permeability. The shaly rocks of the USCU yield in a ductile manner when deformed, and deformation does not result in significant fracture

Table B–3. Hydrogeologic zones for the lower carbonate aquifer unit (LCAU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Carbonate rocks deposited in shallow waters.	High.	Generally high permeability as a result of coarse primary texture and frequent subaerial exposure and dissolution.	Dettinger and others (1995); Plume (1996); Cook and Corboy (2004).
2	Shale and siliciclastic rocks of the Pilot basin.	Moderate to high.	Low-permeability shale and other higher permeability siliciclastic deposition in the Pilot basin during Devonian to Mississippian time. Unit is thin but may reduce LCAU permeability where repeated by faulting.	Poole and others (1992).
3	Carbonate rocks deposited in deeper waters.	Moderate.	Lower permeability than shallow-water carbonate rocks to the east as a result of the dominance of carbonate mud within the rocks, thin bedding, and higher proportion of shale interbeds.	Cook and Corboy (2004).

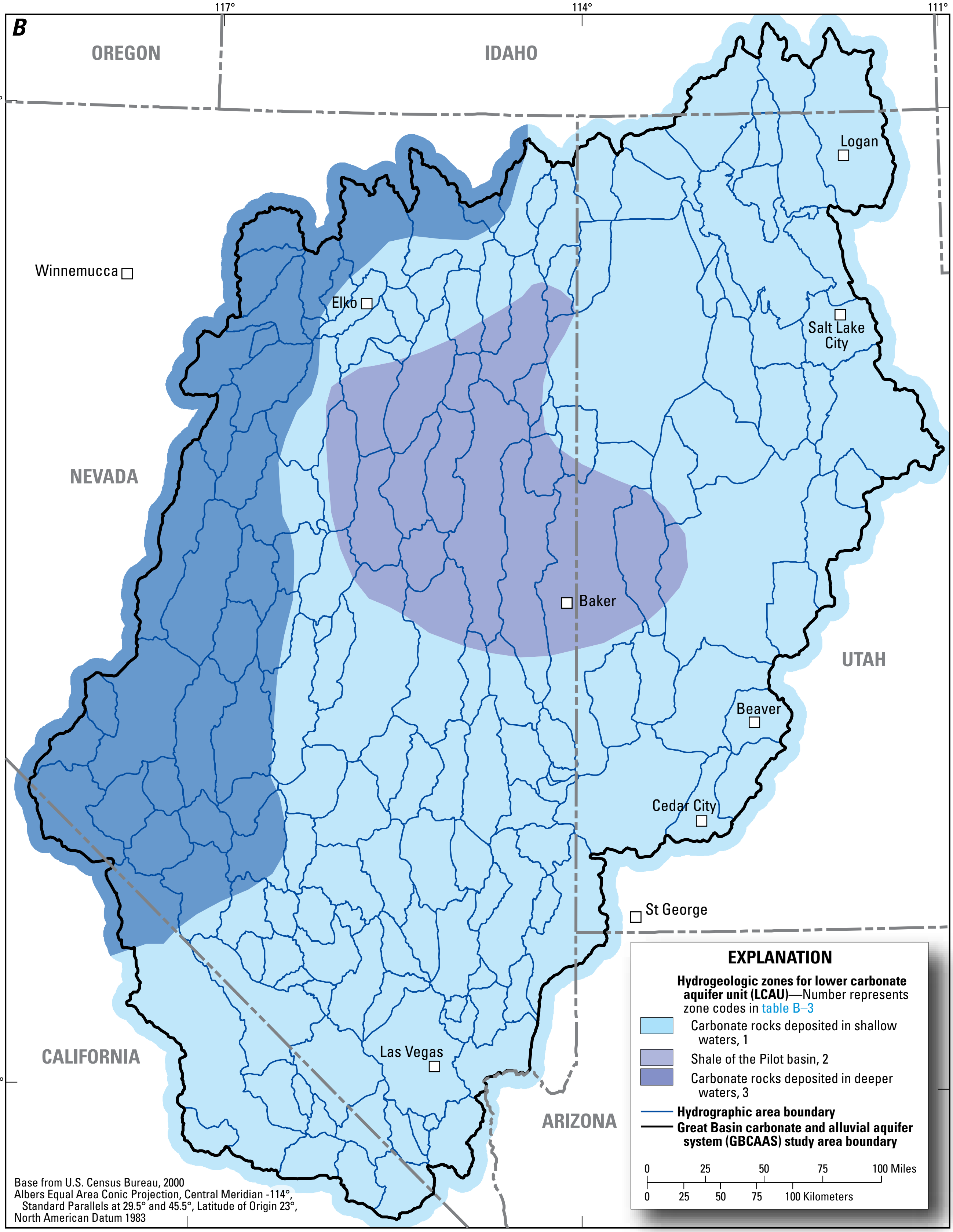


Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: *B*, lower carbonate aquifer unit (LCAU).—Continued openings through which water can flow. In southern Nevada, steep hydraulic gradients at the Nevada Test Site are attributed to the low permeability of the Mississippian siliciclastic rocks (Winograd and Thordarson, 1975; D'Agnese and others, 1997). The low porosity of the Chainman Shale in the study area has been documented (Plume, 1996) from data from oil and gas exploration wells.

Upper Carbonate Aquifer Unit (UCAU)

The UCAU primarily comprises thick, widespread Pennsylvanian and Permian rocks that overlie the Mississippian rocks of the USCU (table B–1); this unit generally represents the resumption of deposition of shallow-water marine carbonate sediments on the continental shelf (fig. B–1; Miller and others, 1992). The UCAU dominates outcrops in mountain ranges and at interbasin divides in the eastern parts of the study area (fig. B–3). In eastern Nevada, the unit is as much as 10,000 ft thick and includes the Ely Limestone, Arcturus Group limestone and silty limestone (Hose and others, 1976) (column 2, fig. B–2). In southern Nevada, the unit includes carbonate rocks such as the Tippipah Limestone (column 4, fig. B–2). In west-central Utah, the UCAU includes as much as 24,000 ft of Oquirrh Group marine limestone and sandstones that were deposited in localized basins in Utah as a result of the Ancestral Rocky Mountains orogenic event (fig. B–1; Burchfiel and others, 1992).

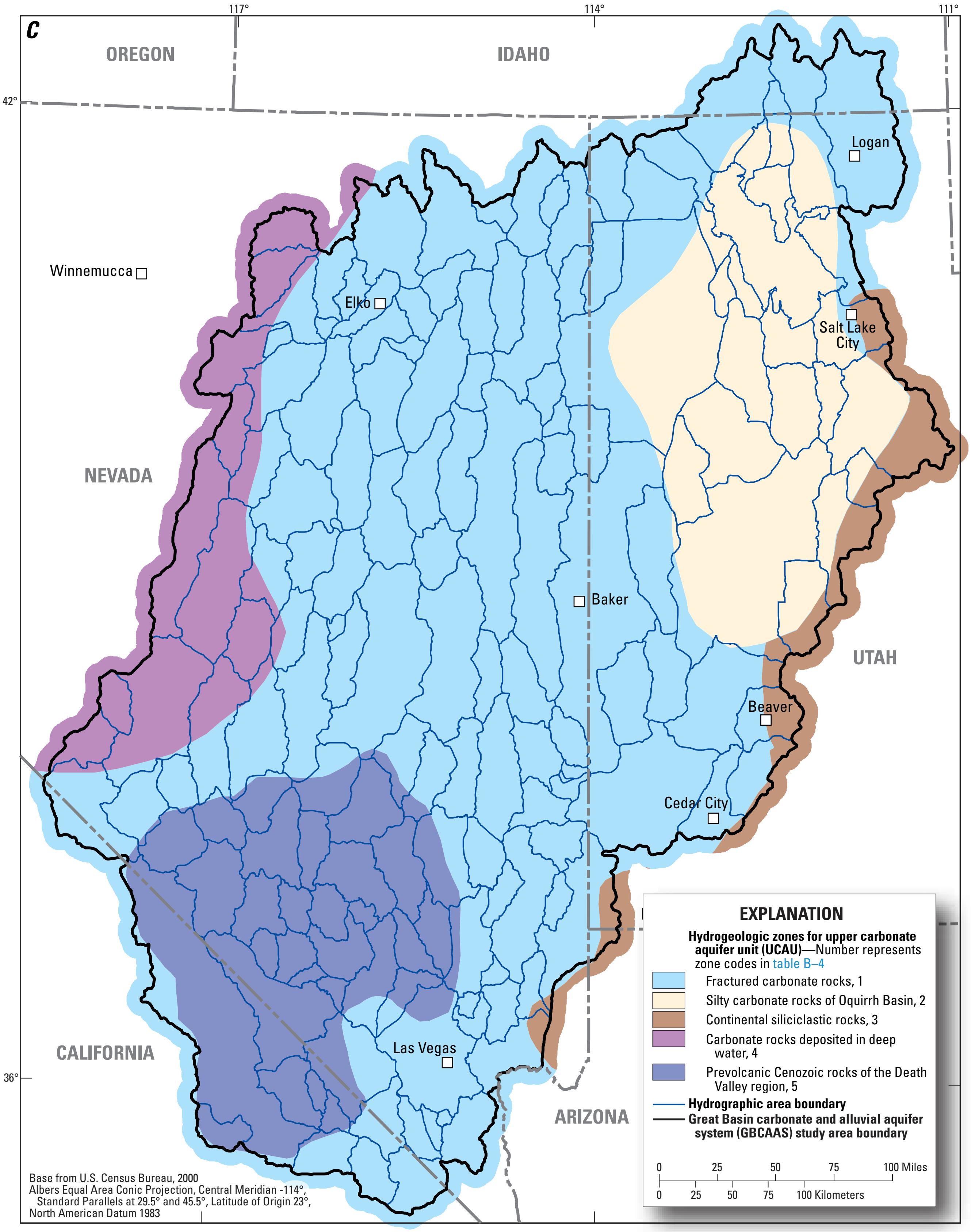
From the Late Triassic to Paleocene (early Tertiary) time, the entire width of the eastern Great Basin was compressed in a general west-to-east direction during the Sevier orogeny (fig. B–1). Uplift related to this tectonic event resulted in erosion or nondeposition of sediments in much of the study area; Mesozoic sedimentary rocks are either thin or entirely missing in most of the study area, except for in the extreme southeast (Stewart, 1980). To simplify the hydrogeologic map compilation and 3D-framework construction, outcrops of Mesozoic sedimentary rocks along the southeastern edge of the study area, such as the Chinle Formation and the Aztec Sandstone (column 5, fig. B–2), are also included in UCAU, as are local outcrops of prevolcanic Cenozoic sedimentary rocks in the Death Valley region.

The UCAU generally has high permeability throughout the study area (Winograd and Thordarson, 1975; Plume, 1996). The unit has similar secondary fracture and solution permeability to the LCAU (Winograd and Thordarson, 1975). Given the heterogeneous nature of this unit and the broad age span of the included rocks, the UCAU has been subdivided into five hydrogeologic zones on the basis of lithology and geologic age (fig. B–4*C*; table B–4):

1. Fractured carbonate rocks of Pennsylvanian-Permian age deposited in shallow water that occur throughout most of the study area (Miller and others, 1992).

Table B–4. Hydrogeologic zones for the upper carbonate aquifer unit (UCAU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Fractured carbonate rocks of Pennsylvanian-Permian age that were deposited in shallow water and occur throughout most of the study area. Predominantly limestone; Ely limestone and Arcturus Formation in central Nevada.	High.	Generally well-developed fracture network, in thick upper Paleozoic carbonate rocks.	Hintze and others (2000); Ludington and others (1996); Miller and others (1992).
2	Very thick silty carbonate rocks deposited in the Oquirrh Basin during Pennsylvanian time.	Moderate to high.	Generally well-developed fracture network, in thick upper Paleozoic carbonate rocks. Generally more silty than the shallow-water carbonates of zone 1, may somewhat reduce permeability.	Miller and others (1992); Hintze and others (2000).
3	Continental siliciclastic rocks and other Upper Paleozoic and Mesozoic rocks of the Colorado Plateau that occur along the eastern boundary of the study area.	Moderate.	Section is much thinner than in zones 1 and 2 and contains Triassic siliciclastic rocks, such as Chinle and Moenkopi Formations, that are shaly.	Hintze (1988); Ludington and others (1996).
4	Carbonate rocks deposited in deep water, generally thin-bedded, shaly Pennsylvanian-Permian rocks; exposed along western side of study area.	Low to moderate.	Thin bedded, shaly carbonate rocks deposited as turbidites. Thin bedding and fine-grained interbeds may preclude development of good fracture network and reduce overall permeability.	Miller and others (1992); Poole and others (1992).
5	Prevolcanic Cenozoic rocks of the Death Valley region.	Low to moderate.	Zone created for compatibility with the Death Valley three-dimensional hydrogeologic framework.	Faunt and others (2004).



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
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Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: *C*, upper carbonate aquifer unit (UCAU).—Continued

2. Silty carbonate rocks deposited in the Oquirrh Basin during Pennsylvanian time. These rocks generally are more silty than the shallow-water carbonates of zone 1, resulting in potentially lower permeability (Hintze, 1988).
3. Continental siliciclastic rocks and other Upper Paleozoic and Mesozoic rocks of the Colorado Plateau that occur along the eastern boundary of the study area.
4. Carbonate rocks of Pennsylvanian-Permian age deposited in deep water and that are generally thin-bedded, shaly, and exposed along the western side of study area.
5. Prevolcanic Cenozoic rocks of the Death Valley region. This zone was created to maintain consistency with the Death Valley three-dimensional hydrogeologic framework (Faunt and others, 2004).

Thrusted Non-Carbonate Confining Unit (TNCCU) and Thrusted Lower Carbonate Aquifer Unit (TLCAU)

Major thrust faults of the Roberts Mountain thrust belt and the Sevier fold-and-thrust belt (fig. B–5) resulted from the Antler and Sevier orogenies, respectively (fig. B–1). These thrust faults have stratigraphic offsets of several thousands of feet and horizontal displacements of several miles (Armstrong, 1968; Burchfiel and others, 1992; Allmendinger, 1992; DeCelles, 2004), resulting in stratigraphic repetition of HGUs. Because the HGUs must be represented as grids in the 3D-hydrogeologic framework, they cannot have multiple altitudes at a single location, as would be the case for repeated units. The repeated stratigraphy in thrusted areas was therefore treated as two additional HGUs, the TNCCU and the TLCAU. The TNCCU includes all Late Proterozoic siliciclastic rocks that are repeated by thrust faults within the Sevier fold-and-thrust belt (fig. B–5). For simplicity, the TNCCU also includes all thrusted rocks of the Roberts Mountain belt (fig. B–5), regardless of age or lithology. The TLCAU unit includes all thrusted Paleozoic rocks of the LCAU, USCU, and UCAU HGUs that lie within the Sevier fold-and-thrust belt (fig. B–5).To simplify construction of the 3D-hydrogeologic framework, thrusted rocks from three HGUs were assigned to the single thrusted HGU, TLCAU, regardless of age or lithology. This simplification is justified because most of the thrusted units are carbonate rocks. Not all thrusts within the study area are delineated as separate units; thrusted areas were selected for their size, offset, and potential hydrologic importance in juxtaposing carbonate and noncarbonate units. As such, relatively minor thrust repetition within the central Nevada thrust belt (fig. B–5) was not included.

A variety of potential changes to rock permeability are possible as a result of thrust faulting. Rocks involved in regional thrusting may be more highly fractured as a result of compressive deformation and transport as thrust sheets. Thrust faults often have sufficient offset to juxtapose higher permeability shallow-water facies against lower-permeability rocks deposited in deeper waters; such juxtaposition of different HGUs is considered the most important hydrologic effect of thrust faults.

Volcanic Unit (VU)

The VU includes large volumes of middle Tertiary (Eocene to middle Miocene) volcanic rocks that include welded and nonwelded tuff of rhyolite-to-andesite composition deposited during caldera-forming eruptions, as well as basalt, andesite, and rhyolite lava flows (McKee, 1971; Cross and Pilger, 1978; McKee and Noble, 1986; Best and others, 1989). Ash-flow tuffs erupted from multiple calderas as part of a general southward and westward sweep of volcanism across the study area in Oligocene and Miocene time (Best and others, 1989; McKee, 1996; Dickinson, 2002). The aggregate thickness of these eruptive deposits can exceed 3,000 ft; volcanic accumulations within the calderas can be up to 10,000 ft thick (Best and others, 1989; Sweetkind and du Bray, 2008). With the exception of Eocene andesitic volcanism to the north of Elko, Nevada, in the northwestern part of the study area (Ludington and others, 1996), the VU is relatively minor in the northern one-third of the study area (fig. B–3). As volcanism swept from north to south, eruption of many of the ash-flow tuffs in the central part of the study area occurred relatively early in the extensional history of the area (Best and Christiansen, 1991). As a consequence, regionally distributed ash-flow tuffs in the central part of the study area are preserved deep in the stratigraphy of the downfaulted basins and are often covered by thick intervals of younger sedimentary deposits. Continued sedimentation in the southern part of the study area resulted in the accumulation of considerable local thickness of sedimentary rocks that predate volcanic activity. In the southern parts of the study area, volcanic rocks are relatively young, occur high in the section, and form extensive outcrops.

Fractured Cenozoic volcanic rocks near the major volcanic fields are locally thick enough to be important subregional aquifers that interact with regional groundwater flow through the underlying Paleozoic carbonate rocks (Dettinger, 1989; Harrill and others, 1988). Volcanic-rock units commonly display widely variable lithology and degree of welding, both vertically and horizontally. The hydraulic properties of these deposits (table B–1) primarily depend on the mode of eruption and cooling, the extent of primary and secondary fracturing, and the degree to which secondary alteration (crystallization of volcanic glass and zeolitic alteration) has affected primary permeability. Fractured rhyolite-lava flows and moderately-to-densely welded ash-flow tuffs are the principal volcanic-rock aquifers. Rhyolite-lava flows and thick intracaldera welded tuff are relatively restricted to local areas areally, whereas outflow welded-tuff sheets are more regionally distributed and may provide lateral continuity for water to move through the regional flow system. Local confining units are generally formed by nonwelded or partly welded tuff that has low fracture permeability and can be zeolitically altered in the

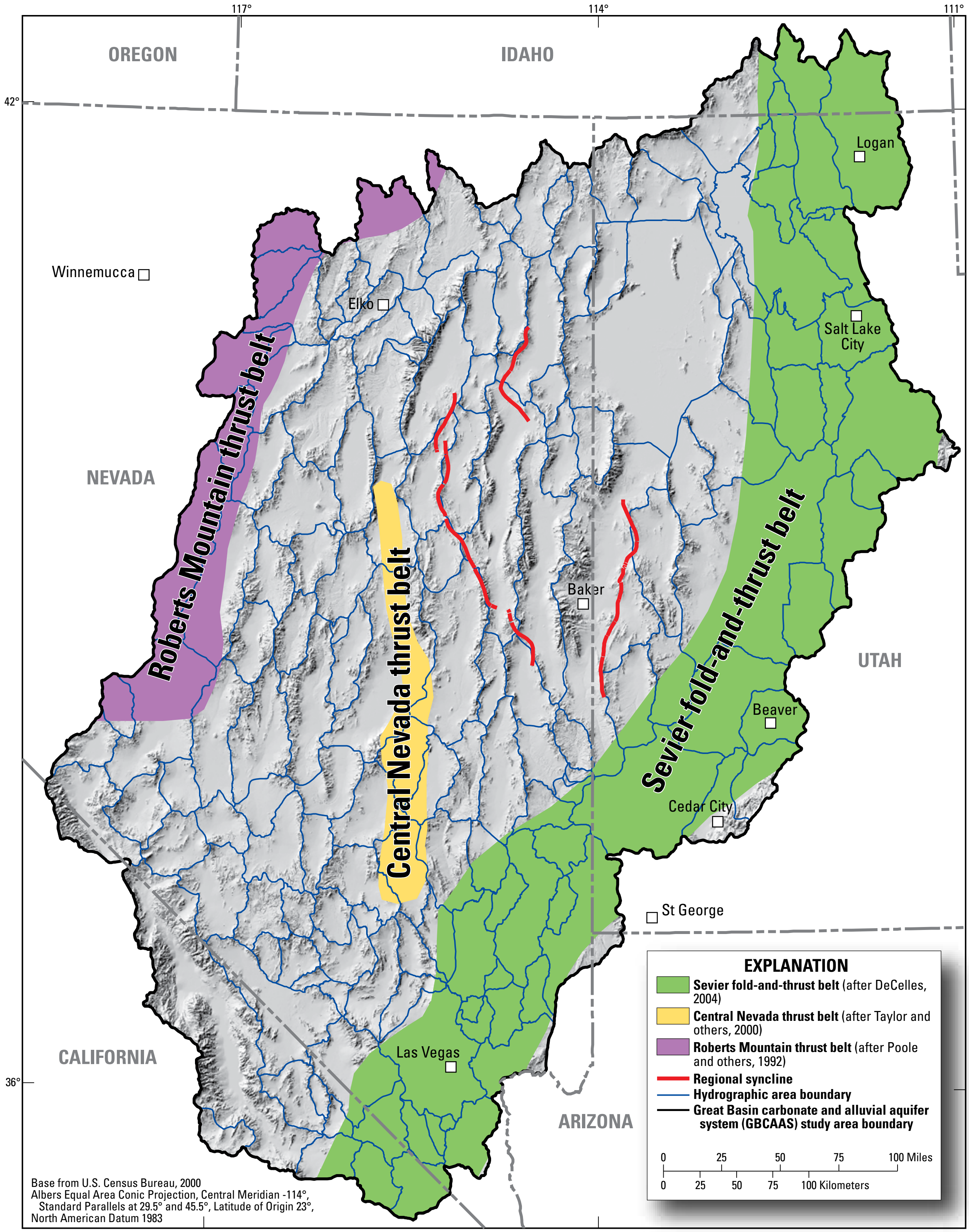


Figure B–5. Major Mesozoic structural belts of the Great Basin carbonate and alluvial aquifer system study area.

older, deeper parts of the volcanic sections (Laczniak and others, 1996). The hydraulic properties of volcanic rocks in the vicinity of the Nevada Test Site (fig. B–4*D*) were described by Blankennagel and Weir (1973) and Belcher and others (2001); these concepts likely apply throughout the GBCAAS study area.

The VU has been subdivided into seven hydrogeologic zones based on lithology and volcanic rock properties (fig. B–4*D*; table B–5). Because of the methodology used to construct the 3D-hydrogeologic framework, these zones primarily apply to surficial outcrops of VU; volcanic rock units buried within the basin fill are treated as part of the LBFAU. The zones of the VU are:

1. Welded ash-flow tuff. Generally in thick sequences and assumed to have a well-developed fracture network.
2. Local lava flows. Areas of rhyolite to andesite lava flows that form localized accumulations, not widespread sheets. These rocks can be highly fractured, but fracture pattern typically is disorganized and fractures are short.
3. Prevolcanic basins. Areas where significant amounts of sedimentary rocks may underlie outcrops of volcanic rocks.
4. Shallow basalt. Areas of outcropping or near-surface basalt flows. This zone was created to allow thin surficial basalt flows to stack correctly in the 3D framework.
5. Mesozoic and Cenozoic sedimentary rocks. Generally along the Wasatch Front and Colorado Plateau Basin and Range transition. This zone was created as a result of combination of some Mesozoic and Cenozoic sediments with VU.
6. Heterogeneous rocks in California. Includes tuff, rhyolite to basalt lava flows, and interbedded sedimentary rocks.
7. Intracaldera ash-flow tuff and other rocks related to caldera collapse.

Lower Basin-Fill Aquifer Unit (LBFAU)

Formations that fill Cenozoic basins were grouped into one of two HGUs based on the thickness of the basin-fill deposits: the LBFAU that comprises the deepest one-third of the basin fill and the UBFAU that comprises the shallowest two-thirds of the basin fill. The LBFAU consists of a wide variety of rock types, including volcanic rocks buried within the basin fill near the main volcanic centers, along with consolidated older Cenozoic basin-fill rocks that underlie the more recent basin-fill deposits (table B–6). The volcanic rocks include regionally distributed welded ash-flow tuffs and more local lava-flow deposits. The consolidated older Cenozoic basin-fill rocks are comprised of fluvial and lacustrine limestone, sandstone, siltstone, and local conglomerate, often with significant volcanic detritus. Permeability of the sedimentary part of the basin fill is affected by the original depositional environment, proximity to volcanic centers during sediment deposition, and depth of burial.

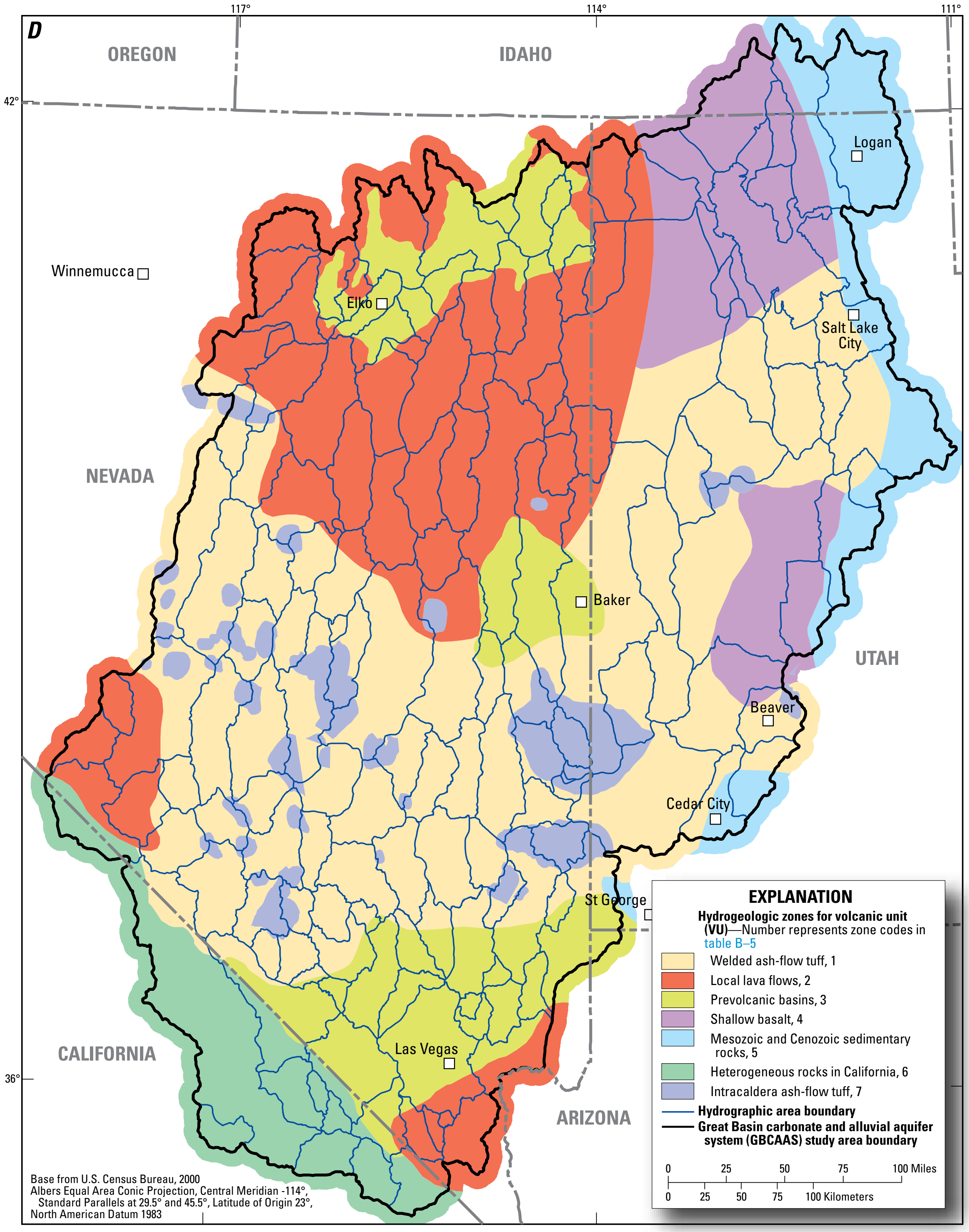
The lower unit (LBFAU) has been subdivided into five hydrogeologic zones based on lithology and volcanic rock properties (fig. B–4*E*; table B–6):

1. Welded ash-flow tuff. Thick sequences that fill the bottoms of Cenozoic basins within and surrounding volcanic fields; the spatial extent of buried volcanic rocks was guided by Cenozoic volcanic rocks (Best and others, 1989; Sweetkind and du Bray, 2008) and regional aeromagnetic maps (Raines and others, 2003; Glen and others, 2004).
2. Intracaldera ash-flow tuff and other rocks, where calderas extend from mountain ranges into intervening valleys.
3. Local lava flows. Areas of more localized lava flows, generally andesite or rhyolite, filling the bottoms of Cenozoic basins within and surrounding volcanic centers.
4. Prevolcanic Cenozoic sedimentary rocks. Generally lakebed and other fine-grained deposits (Fouch, 1979; Fouch and others, 1979), but can include some sandy or coarse-grained material.
5. Coarse-grained basin fill. Inferred to be early-to-mid Cenozoic sands and gravels, and may be intercalated with volcanic rocks or contain significant ash or volcanic detritus.

Upper Basin-Fill Aquifer Unit (UBFAU)

Modern Basin and Range topography began forming in Neogene time, resulting from extension along high-angle faults (fig. B–1). At this time, unconsolidated sediments began filling the broad, intermontane basins. Sedimentation in this period was largely postvolcanic, except for local basalts. Modern drainages were established during this period; low base levels along the Colorado River and Death Valley forced headward erosion along tributary drainages, resulting in downcutting and exposure of older sediments within the basins. In Pleistocene time, pluvial climates led to the creation of widespread shallow lakes throughout the region (Reheis, 1999). The drier Holocene climate led to the drying of these lakes and the abandonment or reduction in flow of numerous springs. This has resulted in the exposure of paleo-spring discharge deposits, common in many valleys in the southern part of the study area (Quade and others, 1995).

The UBFAU comprises the shallowest two-thirds of the basin fill and includes a wide variety of Quaternary and Tertiary basin-fill sediments younger than the VU and LBFAU (table B–1). Neogene sediments were deposited in lacustrine, fluvial, and alluvial environments and include unconsolidated alluvium and colluvium, along with local deposits of fresh water limestone, tuffaceous sandstone and siltstone, laminated clays, and water-lain tuffs and ash. Quaternary and Tertiary basalts, also included with this unit, are thin but locally cover significant areas. The distribution of Quaternary units and their hydrologic significance has been mapped in detail for Nevada (Maurer and others, 2004), but similar types of maps are lacking for other states in the GBCAAS study area. Unfortunately, the mapping by Maurer and others (2004) lacks



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
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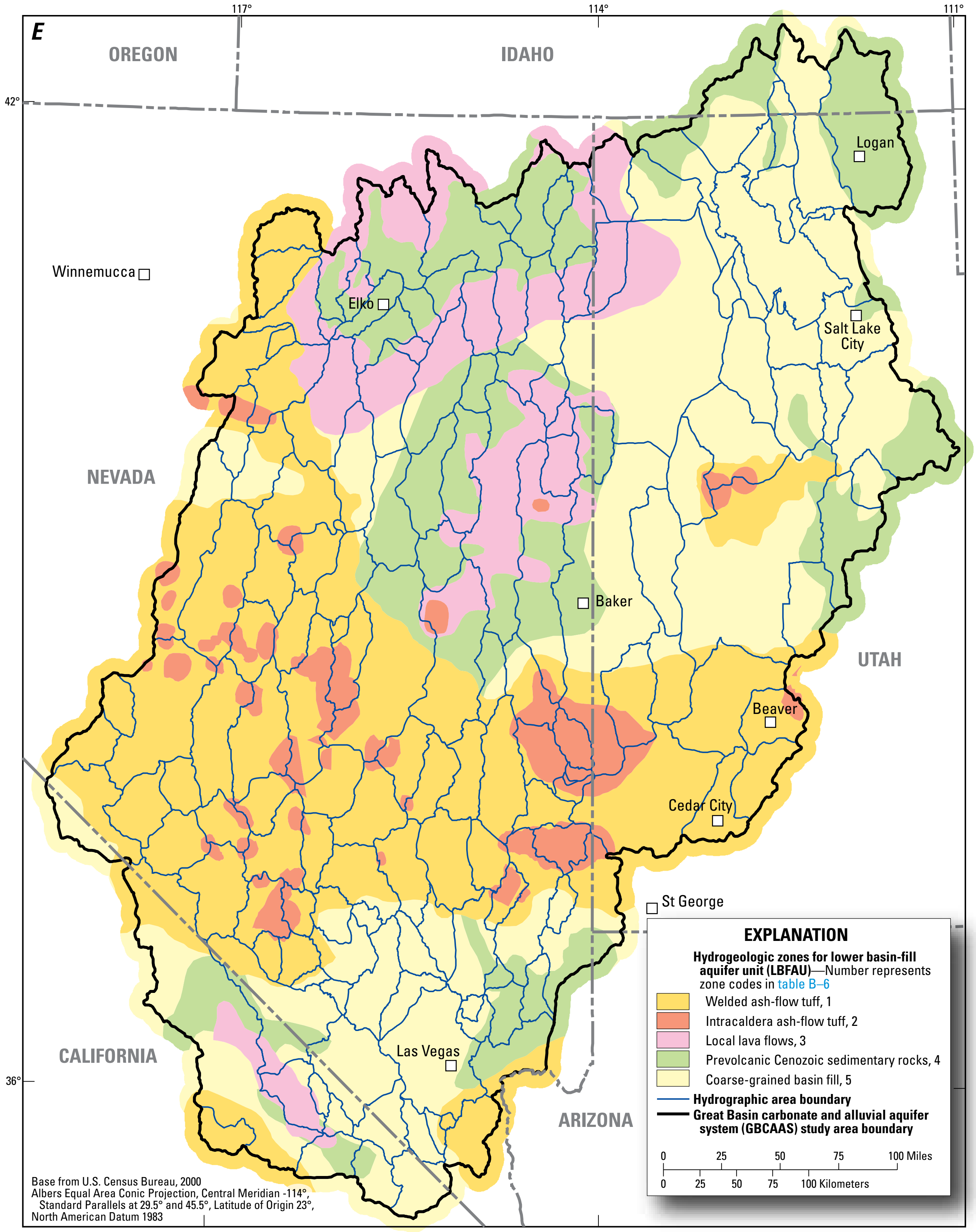
Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: *D*, volcanic unit (VU).—Continued

Table B–5. Hydrogeologic zones for the volcanic unit (VU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Welded ash-flow tuff; generally in thick sequences.	High.	Generally well-developed fracture network in sequences of welded ash-flow tuff. Permeability may be reduced somewhat inside calderas due to lithologic heterogeneity.	Laczniak and others (1996); Blankennagel and Weir (1973); Belcher and others (2001).
2	Local lava flows; areas of rhyolite to andesite lava flows that form localized accumulations, not widespread sheets.	Moderate to high.	Can be highly fractured, but fracture pattern is typically disorganized and fractures are short.	Laczniak and others (1996); Blankennagel and Weir (1973); Belcher and others (2001).
3	Prevolcanic basins; areas where significant amounts of sedimentary rocks may underlie outcrops of volcanic rocks.	Moderate.	Section consists of early Cenozoic lake beds and generally fine-grained deposits; can include some sandy or coarse-grained material. Zone created to account for areas where prevolcanic sedimentary rocks were combined with VU in the 3D hydrogeologic framework.	Hintze (1988); Ludington and others (1996).
4	Shallow basalt; areas of outcropping or near-surface basalt flows.	Moderate.	Zone was created to allow thin surficial basalt flows and underlying basin-fill sediments to stack correctly in the three-dimensional framework.	Hintze (1988); Ludington and others (1996).
5	Mesozoic and Cenozoic sedimentary rocks; generally along the Wasatch Front and Colorado Plateau-Basin and Range transition.	Low to moderate.	Zone created to revise hydrogeologic unit attribution from hydrogeologic map; several polygons of Mesozoic and Cenozoic sediments were included in VU.	Hintze (1988); Ludington and others (1996).
6	Heterogeneous rocks in California; includes tuff, rhyolite to basalt lava flows, and interbedded sedimentary rocks.	Low to moderate.	Zone created to revise hydrogeologic unit attribution that was inconsistent with Nevada and Utah hydrogeologic maps. Heterogeneous mixture of lithologies may tend to reduce overall permeability.	Hintze (1988); Ludington and others (1996).
7	Intracaldera ash-flow tuff and other rocks related to caldera collapse.	Moderate, variable.	Permeability of volcanic rocks may be reduced inside calderas due to extreme lithologic diversity and lack of organized fracture networks. Intracaldera volcanic rocks are thick sequences of highly heterogeneous volcanic rocks (including welded and nonwelded tuff, lava flows, volcanic breccias, and nonvolcanic megabreccia deposits) that are bounded by the caldera structures. This unit overlies intrusive rocks of the noncarbonate confining unit (NCCU) inferred to be present at depth with calderas; unit has potential to be hydrothermally altered.	Laczniak and others (1996); Blankennagel and Weir (1973); Belcher and others (2001).



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
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Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: *E*, lower basin-fill aquifer unit (LBFAU).—Continued

Table B–6. Hydrogeologic zones for the lower basin-fill aquifer unit (LBFAU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Welded ash-flow tuff; thick sequences that fill the bottoms of Cenozoic basins within and surrounding volcanic fields.	High.	Generally well-developed fracture network, in sequences of welded ash-flow tuff. Permeability may be reduced somewhat inside calderas due to lithologic heterogeneity.	Best and others (1989); Sweetkind and du Bray (2008); Raines and others (2003); Glen and others (2004).
2	Intracaldera ash-flow tuff and other rocks, where calderas extend from mountain ranges into intervening valleys.	Moderate, variable.	Permeability of volcanic rocks may be reduced inside calderas due to extreme lithologic diversity and lack of organized fracture networks. Intracaldera volcanic rocks are thick sequences of highly heterogeneous volcanic rocks (including welded and nonwelded tuff, lava flows, volcanic breccias, and nonvolcanic megabreccia deposits) that are bounded by the caldera structures. This unit overlies intrusive rocks of the noncarbonate confining unit (NCCU) inferred to be present at depth with calderas; unit has potential to be hydrothermally altered.	Best and others (1989); Sweetkind and du Bray (2008); Raines and others (2003); Glen and others (2004).
3	Local lava flows; areas of more localized lava flows, generally andesite or rhyolite, that fill the bottoms of Cenozoic basins within and surrounding volcanic centers.	Moderate to high.	Rhyolite to andesite lava flows form localized accumulations, not widespread sheets. Can be highly fractured, but fracture pattern is typically disorganized and fractures are short.	Best and others (1989); Sweetkind and du Bray (2008); Raines and others (2003); Glen and others (2004).
4	Prevolcanic Cenozoic sedimentary rocks; generally lake-bed and other fine-grained deposits, but can include some sandy or coarse-grained material. Includes the Sheep Pass, Horse Spring, Muddy Creek, and Elko Formations.	Moderate.	Section consists of early Cenozoic lake beds and generally fine-grained deposits; can include some sandy or coarse-grained material. Thin bedding and generally fine grain size reduce permeability.	Fouch (1979); Fouch and others (1979); Hintze (1988); Ludington and others (1996).
5	Generally coarse-grained basin fill.	Moderate.	Inferred to be early-to-mid Cenozoic sands and gravels; deep burial and cementation may reduce permeability.	Fouch (1979); Fouch and others (1979); Hintze (1988); Ludington and others (1996); Plume (1996).

a thickness component that would allow the mapped units to be used as an HGU within a geologic framework.

The UBFAU comprises gravel, sand, silt, clay, and fresh-water limestone and, thus, is expected to have a large range of permeability. Sediments of the UBFAU are not commonly cemented, but are semiconsolidated at depth. Where these deposits are coarse grained and well sorted, they are permeable and form local aquifers, particularly the alluvial fan and stream channel deposits (Belcher and others, 2001). However, in some areas, this unit contains intercalated, less permeable, finer grained sediments, or volcanic ash.

The UBFAU has been subdivided into four hydrogeologic zones based on lithology (fig. B–4*F*; table B–7):

1. Near-surface basalt flows. This zone was created to allow thin surficial basalt flows to stack correctly in the 3D framework.
2. Prevolcanic and synvolcanic sediments that are thick enough to be present within the shallowest two-thirds of the basin fill. Prevolcanic sections consist of early Cenozoic lake beds and generally fine-grained deposits. Zeolitic alteration of ash in synvolcanic sections that

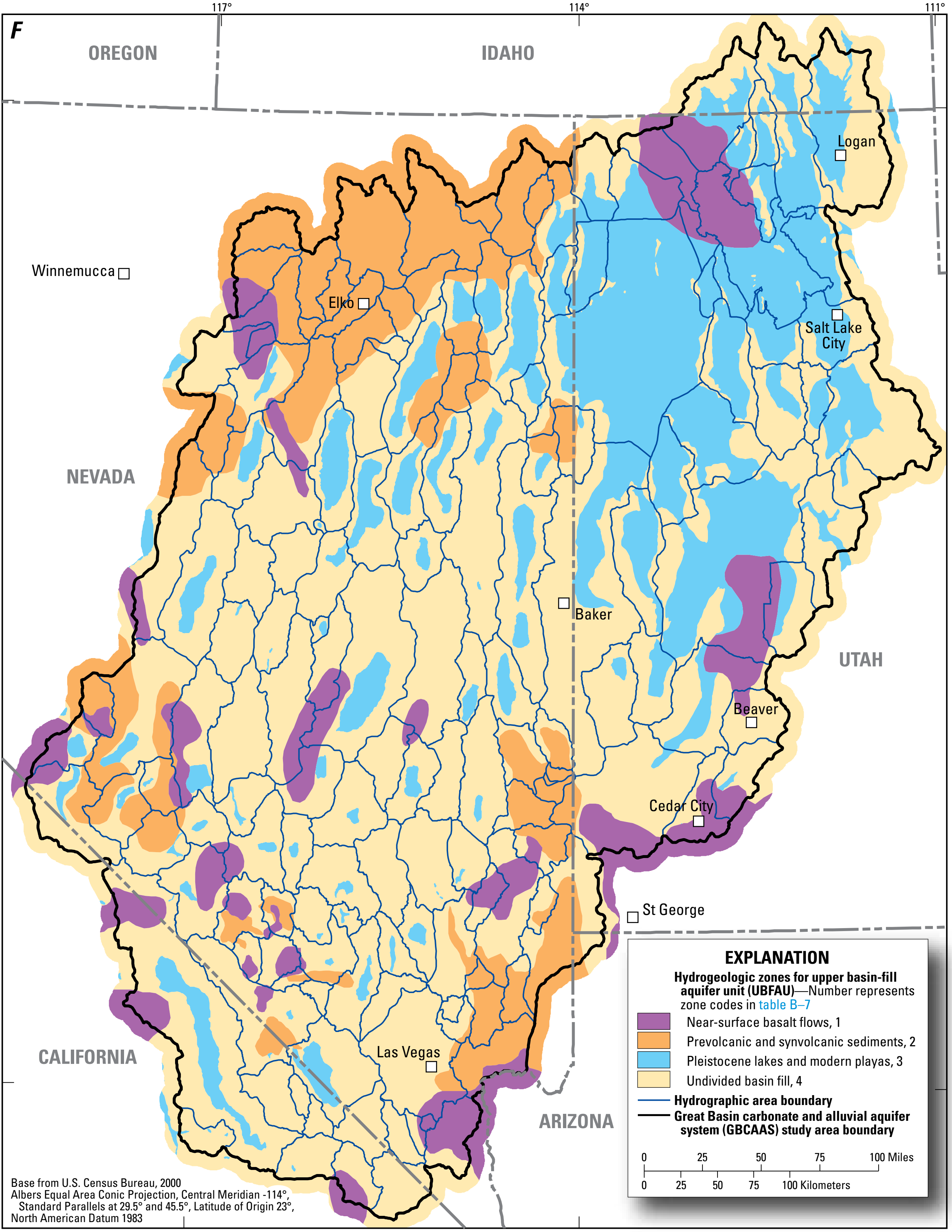


Figure B–4. Zones within some of the hydrogeologic units in the Great Basin carbonate and alluvial aquifer system study area: *F*, upper basin-fill aquifer unit (UBFAU).—Continued

Table B–7. Hydrogeologic zones for the upper basin-fill aquifer unit (UBFAU).

Zone code	Dominant lithology	Relative permeability	Permeability characteristics	Reference
1	Near-surface basalt flows.	Moderate.	Basalts are mostly thin flows either overlying or within coarse-grained basin fill. Basalts can have high fracture permeability and permeable zones at contacts between flows. Local alteration may reduce permeability.	Hintze (1988); Ludington and others (1996).
2	Prevolcanic and synvolcanic sediments that are thick enough to be present within the shallowest two-thirds of the basin fill.	Moderate-low.	Section consists of early Cenozoic lake beds and generally fine-grained deposits; synvolcanic basins that contain significant amount of volcanic ash may have lowered permeability due to zeolitic alteration of ash.	Fouch (1979); Fouch and others (1979); Hintze (1988); Ludington and others (1996).
3	Areas of Pleistocene lakes and modern playas consisting of fine-grained surficial sediments.	Moderate to low.	Fine-grained surficial units; considerable uncertainty as to how deep these units exist in the subsurface.	Hintze (1988); Ludington and others (1996); Reheis (1999).
4	Undivided basin fill.	Moderate.	Inferred to be late Cenozoic alluvial sands and gravels.	Hintze (1988); Ludington and others (1996); Plume (1996).

contain significant amounts of volcanic ash may lower permeability.

3. Areas of Pleistocene lakes and modern playas consisting of fine-grained surficial sediments. There is considerable uncertainty as to how deep these units extend in the subsurface.
4. Undivided basin fill. Areas of generally coarse-grained Late Cenozoic alluvial and colluvial sands and gravels.

Structural Geology

The structural geologic setting of the GBCAAS study area is complex, exhibiting several ages and styles of deformation. The study area is affected by two general phases of deformation: Late Devonian to Eocene compressional deformation characterized by regional folding and overthrusting, and a subsequent phase of Neogene extension characterized by regional-scale normal and strike-slip faulting (fig. B–1). Locally, Miocene calderas are an important structural element. HGUs are commonly disrupted by large-magnitude offset thrust, strike-slip, and normal faults, and locally affected by caldera formation, resulting in a complex distribution of rocks. Faults and caldera boundaries juxtapose HGUs with contrasting hydraulic properties and may divert groundwater flow paths and disrupt regional groundwater flow. Chapter C describes how these geologic controls affect groundwater flow.

Compressional Deformation

The oldest deformation of hydrologic significance in the GBCAAS study area was the Late Devonian to Late Mississippian east-west compression of the Antler orogeny (Poole and Sandberg, 1977; Speed and Sleep, 1982; Burchfiel and others, 1992; Poole and others, 1992; fig. B–1). This deformational event created the Roberts Mountain thrust belt, a stack of thrust sheets as much as 8,000 ft. thick along the northwestern margin of the study area (fig. B–5). The thrusts transported lower-permeability siliciclastic rocks (deposited in deeper water), all assigned to TNCCU, eastward onto the carbonate platform (fig. B–2). Although carbonate rocks extend some distance westward beneath the thrust sheet, in general, the eastern boundary of this thrust system forms the general western edge of the carbonate-rock section. Other compressive orogenic events occurred in western Nevada (Crafford, 2008) in Late Paleozoic time (fig. B–1), but had relatively little effect on the distribution of rocks in the study area.

The Paleozoic rocks throughout the region were affected by east-west compression related to the Sevier orogeny from Late Triassic to Paleocene time (fig. B–1). This deformational event resulted in the north-to-northeast-trending Sevier fold-and-thrust belt (fig. B–5) that extends along the eastern flank of the GBCAAS study area from near Las Vegas, Nevada, to southern Idaho (Armstrong, 1968; Allmendinger, 1992; Burchfiel and others, 1992; DeCelles, 2004). A second, smaller fold-and-thrust belt, the Central Nevada thrust belt (Speed, 1983; Taylor and others, 2000), is present as a generally north-south belt in east-central Nevada. These thrusts are discontinuous and more localized than the frontal thrusts of the Sevier thrust belt, but they can locally disrupt the continuity of the Paleozoic carbonate-rock section.

Associated with the Mesozoic regional thrusting are regional folds (fig. B–5). Regional synclines or downfolds have broadly sinuous but generally north-trending fold axes. These thrust-related synclines preserve Triassic rocks in their core and maintain a chiefly uninterrupted section of Paleozoic carbonate-rock section.

Cenozoic Extensional and Strike-Slip Deformation

Cenozoic deformation of the region is characterized by a variety of structural patterns that overlap in space and time and include (1) local extreme extension along detachment faults associated with the development of metamorphic core complexes and the development of greatly extended zones, (2) development of discrete strike-slip faults and transtensional basins within the Walker Lane belt (fig. B–6), (3) linear structural belts striking northwest-southeast or east-west that may represent reactivation of older crustal structures, (4) Basin and Range extension along steeply dipping faults, and (5) Cenozoic volcanism that preceded and was contemporaneous with regional extension, creating huge caldera complexes and depositing voluminous material into evolving basins.

A regional episode of extension occurred in Eocene-Oligocene time (fig. B–1) prior to the formation of much of the present Basin and Range physiography (Zoback and others, 1981). Large-magnitude extension occurred in localized highly deformed and extended areas (fig. B–6), creating metamorphic core complexes (Coney, 1980; Armstrong, 1982; Wernicke, 1992). These zones feature gentle-to-moderate dipping, large-offset extensional detachment faults that typically separate broadly domed, ductilely deformed metamorphic rocks of the NCCU in their lower plates from overlying unmetamorphosed rocks and brittlely deformed rocks of various HGUs that commonly are highly extended and tilted along a myriad of normal faults (Hamilton, 1998; Wernicke, 1992).

By Early Miocene time, the northwest-trending Walker Lane belt (fig. B–6) was established along the southwestern part of the GBCAAS study area (Stewart, 1988; Hardyman and Oldow, 1991; Stewart, 1998; Stewart and Crowell, 1992). The Walker Lane belt is a complex structural zone dominated by large right-lateral faults with northwest orientations, and it contains discontinuous east-northeast-trending left-lateral strike-slip faults and local normal faults (Stewart, 1988; Stewart and Crowell, 1992). Some of these faults are significant in that they are oriented transverse to the inferred direction of regional groundwater flow. The Walker Lane belt also includes the detachment faults and metamorphic core complexes near Death Valley that have accommodated large-magnitude northwest-directed horizontal extension (fig. B–6). These features are separated by major strike-slip faults that likely evolved coevally and are the result of northwest-directed extension (Wright, 1989).

Long, linear structures with northwest-southeast and east-west orientations (fig. B–6) have been proposed as being long-duration, crustal-scale features because of a variety of geologic, geophysical, and isotopic evidence. Mineral belts defined by the northwest-striking Carlin (Hofstra and Cline, 2000; Wallace and others, 2004; Cline and others, 2005; Emsbo and others, 2006) and Battle Mountain-Eureka trends (Crafford and Grauch, 2002) likely represent reactivated structural conduits of large-scale crustal geologic features; the Northern Nevada rift (Zoback and Thompson, 1978; Zoback and others., 1994; fig. B–6) may have similar origins. The existence of generally east-west-striking transverse zones (fig. B–6) in the central part of the study area has been proposed on the basis of changes in regional patterns of stratal dip direction (Stewart, 1998) and on alignments of plutons and volcanic vents, geophysical anomalies, and mineral deposits (Ekren and others, 1976; Rowley, 1998). These zones are not well expressed in surficial outcrops and the influence of such zones on modern groundwater flow patterns is largely unknown. Many zones are oriented, however, at a high angle to the valley axes of current basins and ranges and, as a result, may influence the rate or direction of groundwater flow parallel to valley axes.

In addition to the hydrologic effects of individual faults, rock deformation affecting broader areas may influence regional groundwater flow. Such subregional deformation might include widespread brecciation and fracturing, either of which could strongly influence the hydraulic conductivity of bedrock. Greatly extended regions (fig. B–7) are characterized by carbonate-rock aquifers that are disrupted by faulting and structural thinning (Dettinger and Schaefer, 1996; Wernicke, 1992). In contrast, less extended regions (fig. B–7) may be highly permeable as a result of preservation of primary texture and secondary dissolution features within relatively undeformed rock (Dettinger and others, 1995; Dettinger and Schaefer, 1996; Plume, 1996; Cook and Corboy, 2004). Zones of active seismicity (fig. B–7; Rogers and others, 1987; Bjarnason and Pechmann, 1989; Bennett and others, 1999) may be of special interest from a hydrologic standpoint. Active fault zones would be expected to have enhanced permeability in the rupture zone and enhanced fluid flow in fractured rock (Faunt, 1997; Potter and others, 2002). Certain areas within the Walker Lane and adjacent to the Las Vegas Valley shear zone have the potential for enhanced permeability as a result of rock deformation affecting broad areas not specifically associated with a single fault (fig. B–7; Carr, 1984; Potter and others, 2002). Such subregional deformation might include widespread brecciation and fracturing.

The southward sweep of volcanism across the eastern Great Basin during Oligocene through Miocene time (McKee, 1971; Cross and Pilger, 1978; McKee and Noble, 1986; Best and others, 1989) resulted in caldera-forming eruptions from several volcanic centers (fig. B–8). Calderas are structurally

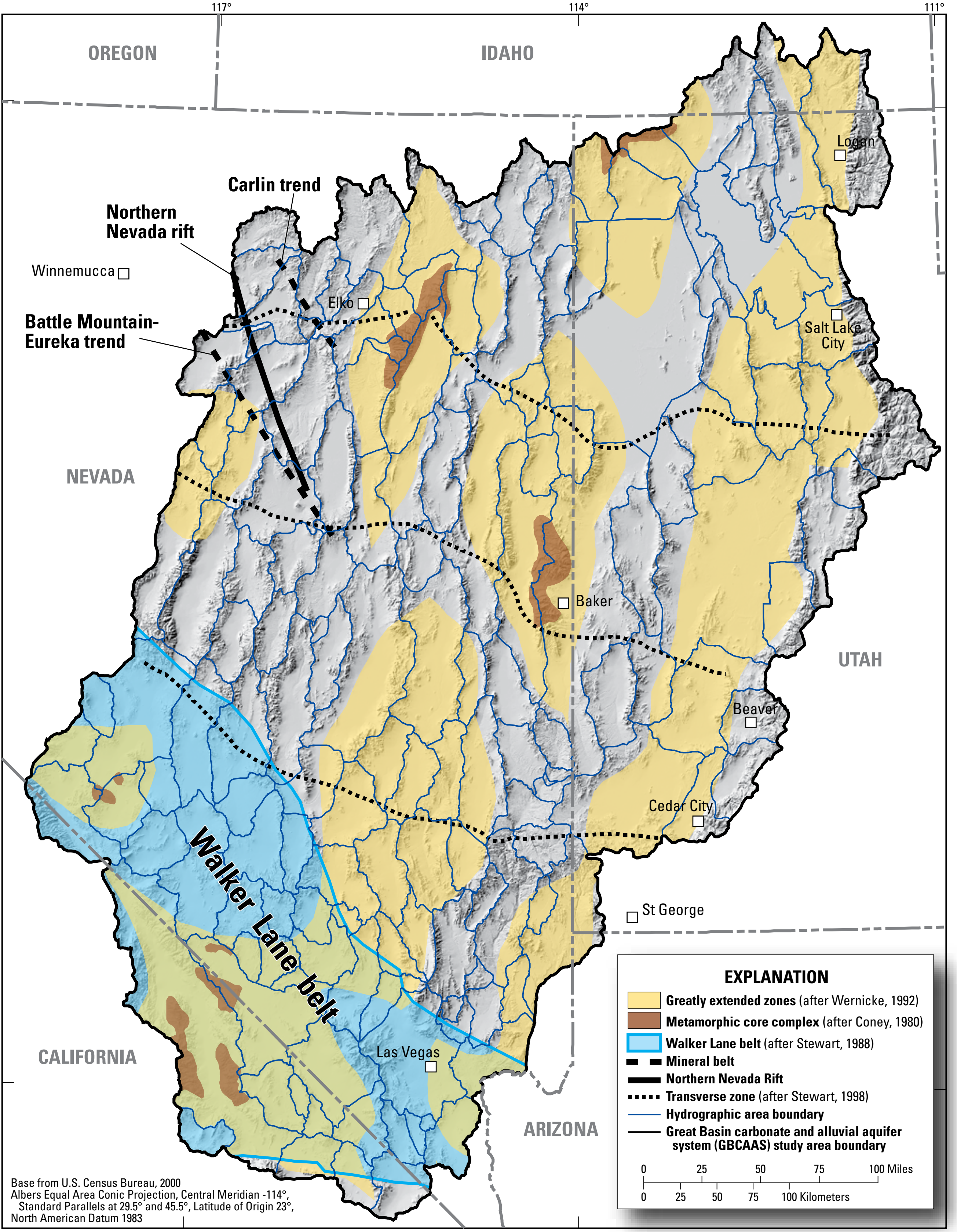
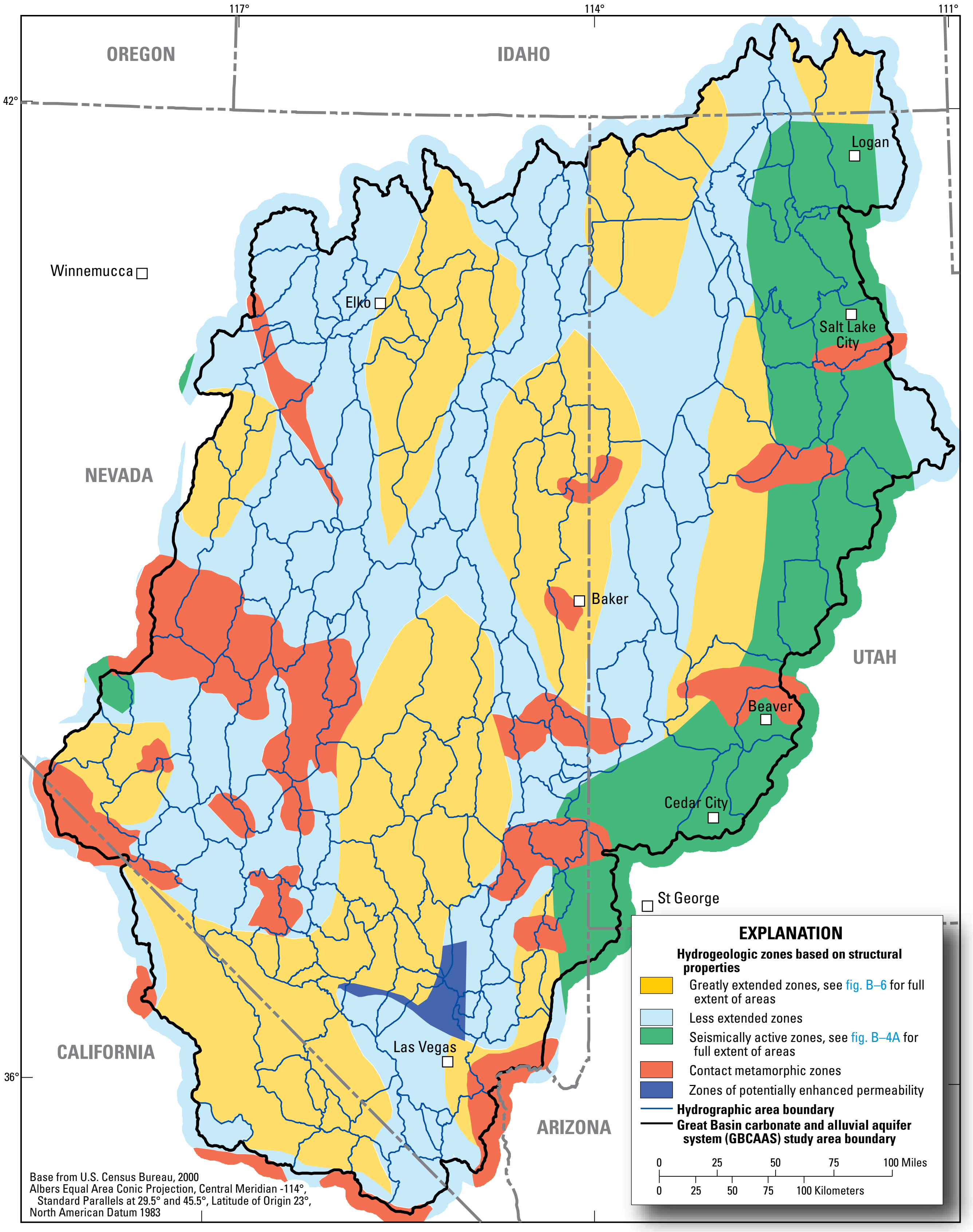


Figure B–6. Cenozoic tectonic provinces and structural belts of the Great Basin carbonate and alluvial aquifer system study area.



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
North American Datum 1983

Figure B–7. Structural areas of potential hydrologic significance within the Great Basin carbonate and alluvial aquifer system study area.

complex depressions that can be as sizeable as 75 mi in diameter and are often bounded by structural and topographic margins (Smith and Bailey, 1968; Lipman, 1984). Subcaldera intrusions and other bodies of intrusive rocks within the study area (Grauch, 1996; Plume, 1996; Glen and others, 2004) can feature contact metamorphic zones around plutons (fig. B–7), especially in carbonate rock. Contact metamorphism may reduce carbonate-rock permeability through mineral growth and deposition in available pore space and recrystallization of rock matrix.

The present Basin and Range physiography across much of the GBCAAS study area generally is the result of Late Eocene through Holocene extension that created steeply dipping, range-bounding faults (fig. B–8) and intervening downfaulted basins (Zoback and others, 1981; Stewart, 1998). These faults produced elongated mountain ranges and controlled subsidence in the intervening Neogene basins. Moderately dipping, listric-to-planar extensional faults, with as much as 10,000 ft of displacement, separate basins from mountain ranges on one, or in some cases, both sides (Dohrenwend and others, 1996). Regional gravity investigations and models have played a critical role in defining major basin-bounding and intrabasin faults, delineating the thickness of Cenozoic geologic units, and inferring the subsurface 3D geometry of pre-Cenozoic rocks (fig. B–8; Saltus and Jachens, 1995; Blakely and Ponce, 2001; Watt and Ponce, 2007). Many of the basins have a characteristic half-graben structure with a dominant range-front fault on one side of the basin; this fault accommodates much of the extensional deformation and subsidence, producing a tilted, asymmetric basin (Stewart, 1998). Less commonly, basins have major faults bounding both sides of the basin, resulting in a symmetric graben located along the basin axis. A number of basins contain several subbasins that are separated by buried, structurally controlled intrabasin highs (fig. B–8).

Three-Dimensional Hydrogeologic Framework

A 3D-hydrogeologic framework was constructed from a variety of information sources, including geologic maps, cross-section data, drill-hole data, geophysical models representing the thickness of Cenozoic basin fill, and stratigraphic surfaces created for other 3D-hydrogeologic frameworks (Appendix 1). The 3D framework was constructed by standard subsurface mapping methods of creating structure contour and thickness maps for each of the HGUs; grids representing the top and base of each unit were then stacked in stratigraphic sequence. The 3D stacking was guided by rules that controlled stratigraphic onlap, truncation of units, and minimum thickness.

The 3D-hydrogeologic framework and component gridded surfaces were evaluated for accuracy by visual inspection and by mathematical manipulations. The extent and thickness of the HGUs were reviewed and compared to published geologic interpretations; in many cases, grids were reinterpreted to create more consistent isopach trends. For consistency, the elevations of HGUs were compared to a digital elevation model (DEM) and to each other. The 3D digital solid of the framework was clipped to the topographic surface by intersecting the solid volume with a DEM. The resulting upper surface of the 3D-hydrogeologic framework closely resembles the surficial hydrogeologic map (fig. B–3), and lends confidence to the subsurface interpretation. Vertical cross sections sampled from the digital 3D framework model along the trace of previously published geologic sections were compared to the published sections.

Geometric relations of the HGUs in the 3D-hydrogeologic framework were visualized by creating vertical slices through the 3D solid volume in several parts of the GBCAAS study area to portray cross-sectional views. Cross sections (figs. B–9 and B–10) were chosen to portray important hydrogeologic features. Several factors complicate the visual inspection of the vertical slices from the 3D-hydrogeologic framework, including (1) graphic artifacts related to the grid spacing (see Appendix 1); (2) abrupt truncation of HGUs as a result of gridding rules; and (3) the representation of faults as abrupt changes in unit elevation and thickness, rather than as discrete features. Although faults are shown on the vertical sections on figure B–10 as a visual aid, they are not modeled in the 3D solid as discrete digital surfaces.

Section *A–A′* (figs. B–9 and B–10*A*) in the northeast part of the GBCAAS study area portrays relatively thick subsurface sections of hydrogeologic units LCAU and USCU that are not readily apparent from exposures in isolated mountain blocks at the surface. The east-west section *C-C′* (figs. B–9 and B–10*A*) from east (near Salt Lake City, Utah) to west (near Elko, Nevada) portrays the following features: (1) uplifted NCCU in the Wasatch Range at the east end of the section, and in the Stansbury Mountains to the west of Tooele Valley; (2) an interpreted section of thick LCAU and UCAU beneath the Great Salt Lake Desert, including fault-bounded mountain blocks of predominantly UCAU between Goshute Valley and Ruby Valley; (3) uplifted NCCU in the Ruby Mountains, to the west of Ruby Valley; and (4) thrusted rocks of the Roberts Mountain thrust belt (fig. B–5), assigned to TNCCU that overlie LCAU near Pine Valley. Farther to the south, in section *D–D′* (figs. B–9 and B–10*A*), the NCCU generally is elevated where the section crosses more highly extended zones of the study area (fig. B–6). The Paleozoic carbonate section is preserved within the Butte syncline beneath Jakes Valley, and the Confusion Range syncline between Snake Valley and Tule Valley. Section *E–E′* in the western part of the study area (figs. B–9 and B–10*B*), portrays a thick, continuous section of LCAU that is mantled by LBFAU; surface exposures are predominantly volcanic rocks of the VU (fig. B–3). Section *F–F′* (figs. B–9 and B–10*B*), through the Indian Peak caldera complex, portrays the absence of carbonate rock within the caldera complex where granitic rocks of the NCCU are interpreted to be present in the subsurface. Thick LCAU is interpreted to exist to the west of the caldera complex beneath

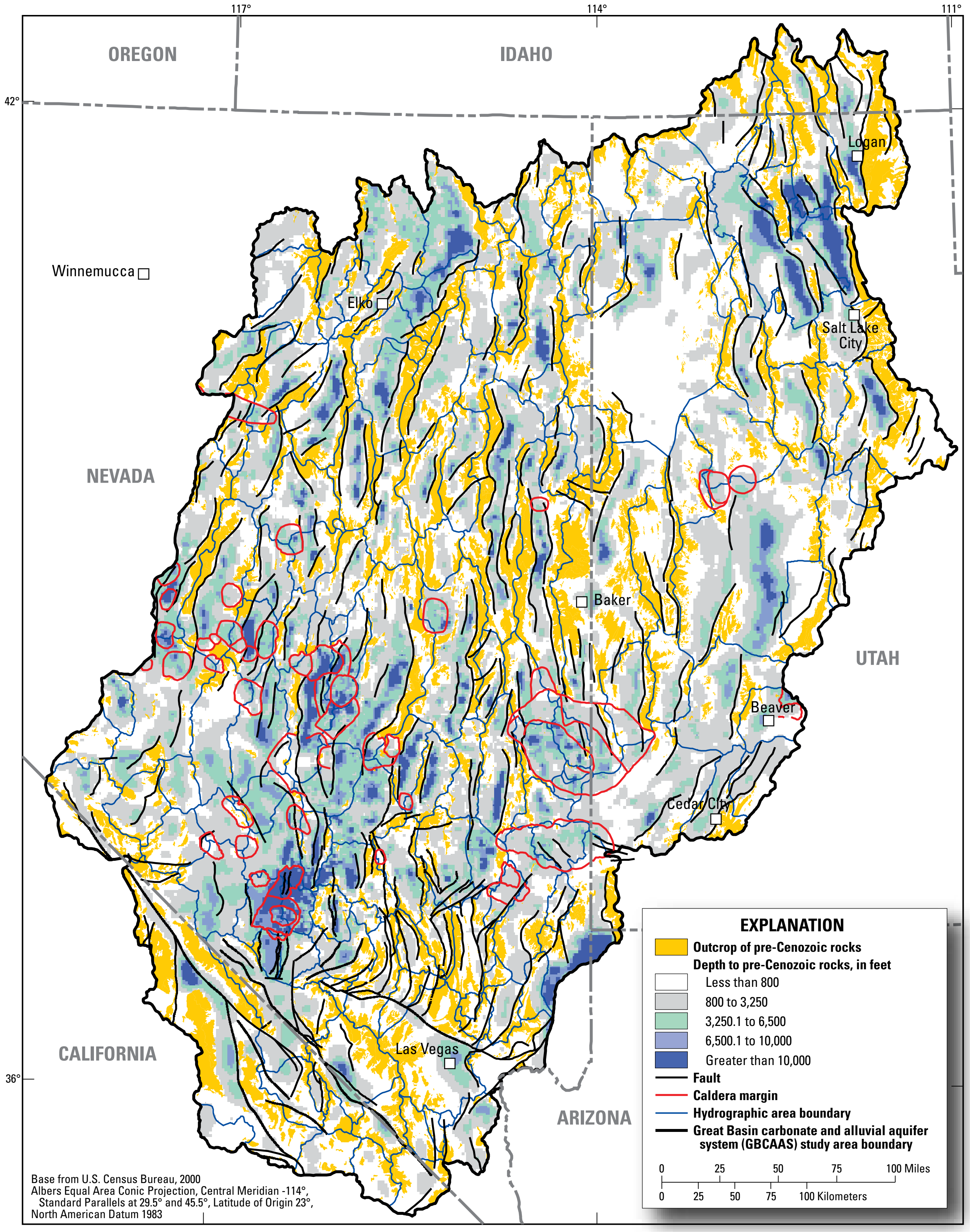
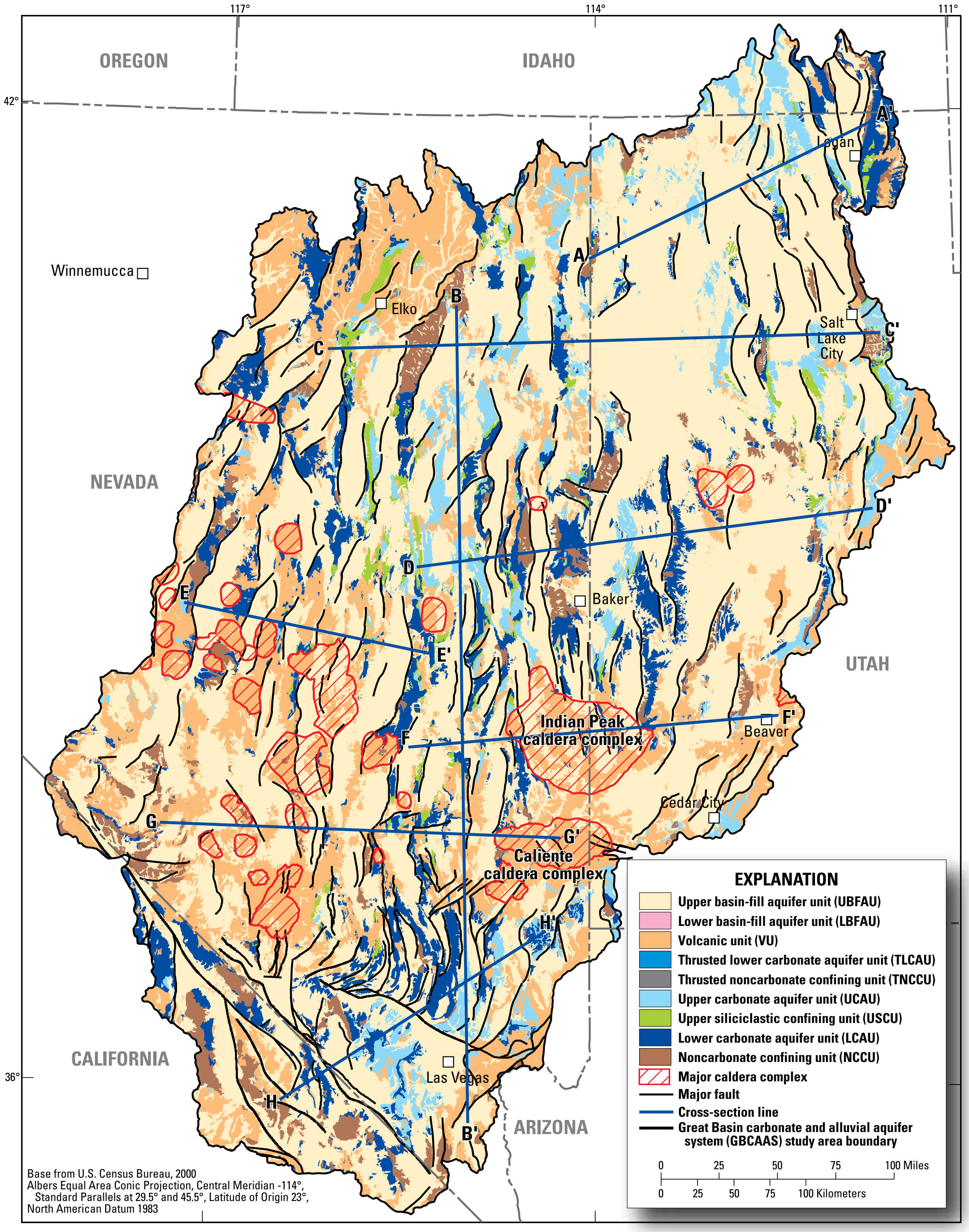


Figure B–8. Exposure of pre-Cenozoic rocks, depth to pre-Cenozoic rocks, and location of major fault zones and calderas in the Great Basin carbonate and alluvial aquifer system study area.



Base from U.S. Census Bureau, 2000
Albers Equal Area Conic Projection, Central Meridian -114°,
Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
North American Datum 1983

Figure B–9. Locations of cross sections representing the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area.

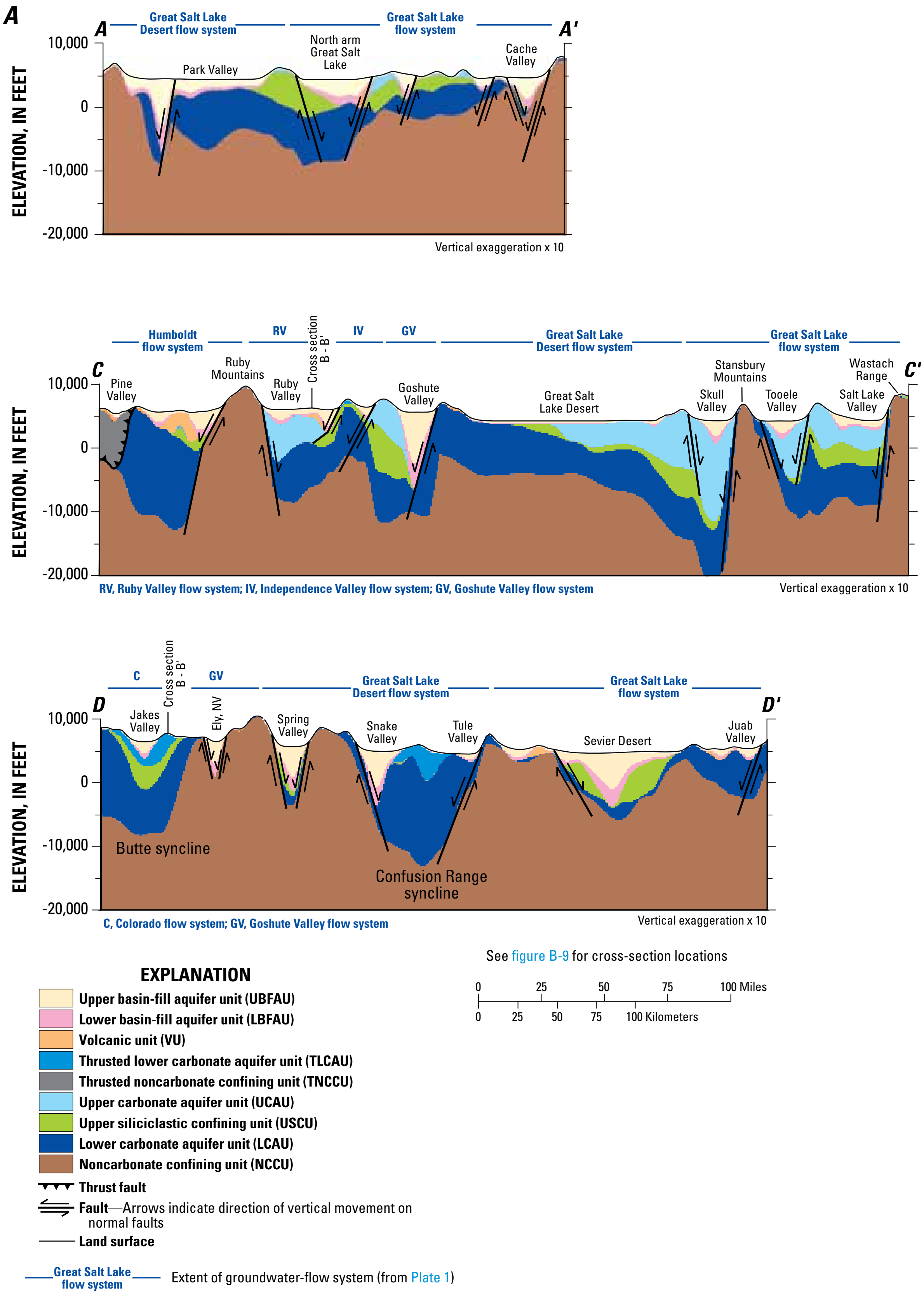
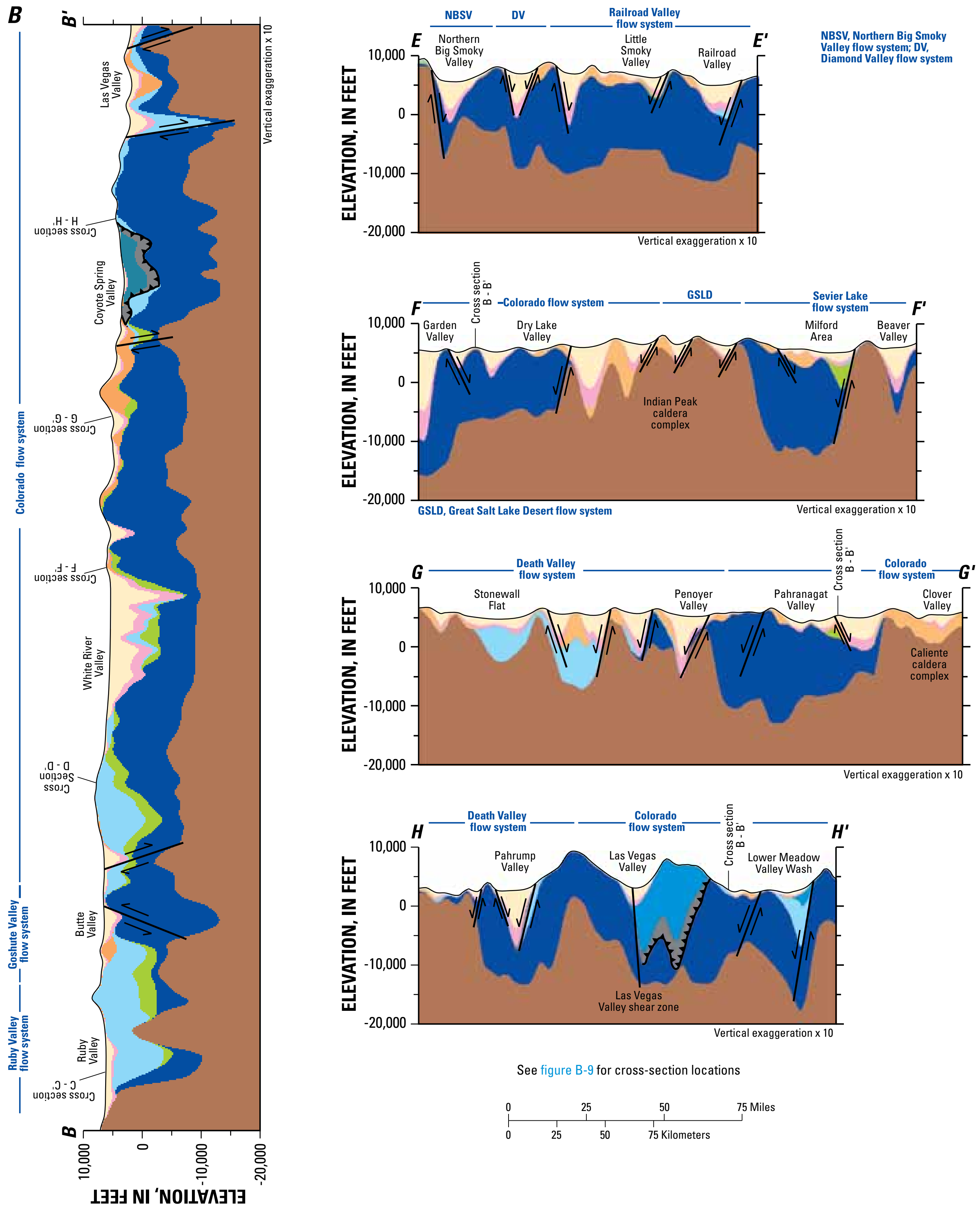


Figure B–10. Cross sections representing the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area. ***A***, Sections *A–A′*, *C–C′*, and *D–D′*; ***B***, Sections *B–B′*, *E–E′*, *F–F′*, *G–G′*, and *H–H′*.



See figure B-9 for cross-section locations

Figure B–10. Cross sections representing the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area. ***B***, Sections *B–B′*, *E–E′*, *F–F′*, *G–G′*, and *H–H′*.—Continued

Dry Lake Valley, and to the east beneath the Milford Area and Beaver Valley. The east-west section *G*–*G*′ (figs. B–9 and B–10*B*) farther to the south portrays relatively little carbonate rock in the western part of the study area, with thick LCAU present along the main corridor of the Colorado groundwater flow system beneath Pahranagat Valley. The east end of section *G*–*G*′ portrays relations within the Caliente caldera complex where VU overlies subcaldera intrusions of NCCU. The southernmost section, *H*–*H*′ (figs. B–9 and B–10*B*) represents TLCAU of the Sevier fold-and-thrust belt overlying thick LCAU. The abrupt termination of the thrust sheet beneath Las Vegas Valley results from truncation against the Las Vegas Valley shear zone, a major strike-slip fault of the Walker Lane belt. In contrast to the generally disrupted nature of the LCAU as shown on east-west sections, section *B*–*B*′ (figs. B–9 and B–10*B*), the lone north-south section, highlights the overall continuity of Paleozoic carbonate rocks when the cross section is parallel to the predominant north-south fault strike associated with Basin and Range extension and between mountain ranges. UCAU dominates section *B*–*B*′ at the north end, whereas LCAU is predominant farther to the south. The TLCAU of the Sevier fold-and-thrust belt is apparent beneath Coyote Spring Valley on this section.

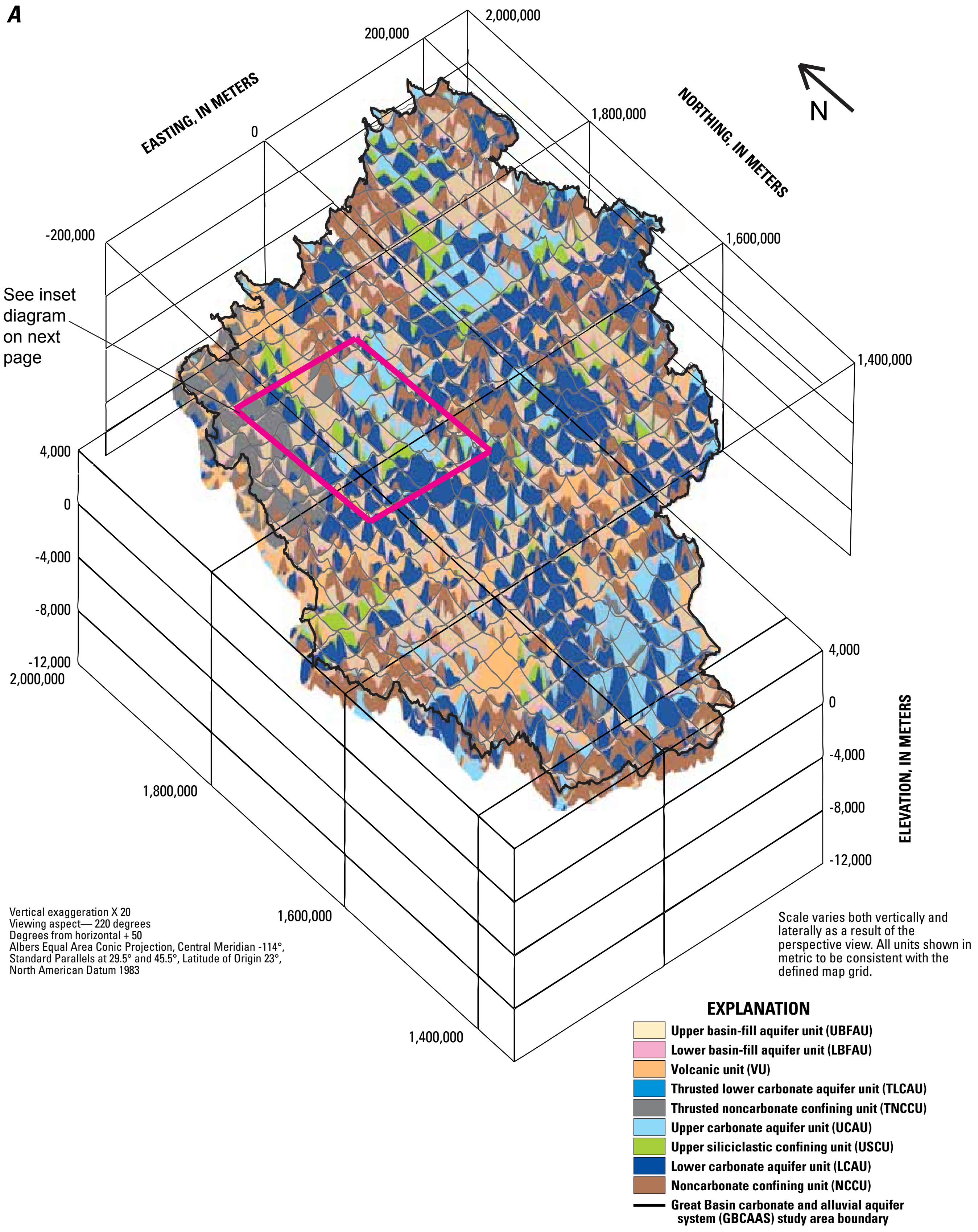
Perspective views of multiple vertical sections that cut through the solid-volume 3D-hydrogeologic framework model (fig. B–11*A*) emphasize the overall continuity of key HGUs between adjacent cross sections. Thrusted rocks (TNCCU) related to the Sevier fold-and-thrust belt are visible on several sections near the south end of the study area (fig. B–11*A*). Caldera complexes appear as tracts of thick volcanic rock (VU) underlain by NCCU. The Roberts Mountain thrust belt (TNCCU) is apparent along the northwest edge of the study area (fig. B–11*B*).

Summary

The GBCAAS study area contains numerous stratigraphic units that have been subjected to a variety of structural disruptions. The complex stratigraphy has been simplified to nine HGUs that differ in their ability to store and transmit water. HGU designations were based on lithologic, stratigraphic, and structural characteristics. Igneous, metamorphic, and siliciclastic rocks of the NCCU and Paleozoic siliciclastic rocks of the USCU typically form the least permeable HGUs within the consolidated, pre-Cenozoic rocks. Paleozoic carbonate rocks of the LCAU and the UCAU typically form the most permeable HGUs within the pre-Cenozoic consolidated rocks. Fractured Cenozoic volcanic rocks of the VU and permeable Cenozoic basin fill of the UBFAU and LBFAU are important local aquifers that interact with the underlying Paleozoic carbonate-rock aquifers. Most of these HGUs have been subdivided into a series of hydrogeologic zones that relate to differences in lithologic character or structural setting. These geologically defined zones provide a geologic basis for future refinement of horizontal hydraulic conductivity within each HGU.

Many of the HGUs are disrupted by large-magnitude offset thrust, strike-slip, and normal faults and calderas. Structural disruption has juxtaposed diverse rock types, ages, and deformational structures, creating variable and complex subsurface conditions. A 3D-hydrogeologic framework was constructed to represent the regional hydrogeology in digital form. The framework was constructed using numerous data sets including digital elevation, geologic and structural geologic maps, stratigraphic data from boreholes, cross sections, and gridded data from previously constructed geologic framework and geophysical models. The framework incorporates the spatial extent and thickness of each HGU and the geometry of major structures.

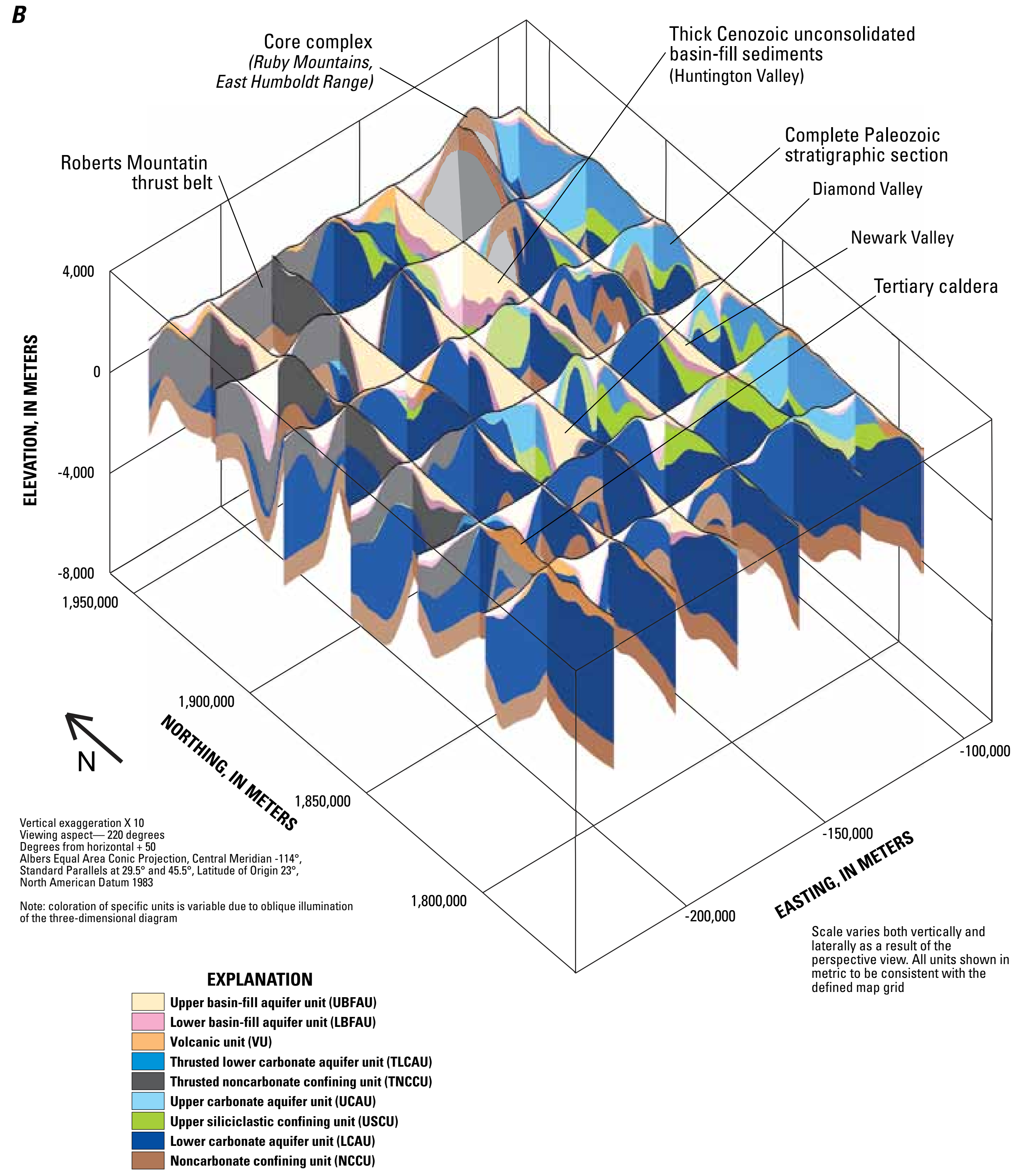
The 3D framework is useful for depicting the extent of the consolidated carbonate-rock aquifers LCAU and UCAU throughout the eastern and central parts of the GBCAAS study area. The carbonate-rock HGUs are segmented in a general east-west direction by numerous north-striking, Basin and Range faults that juxtapose carbonate rocks against other HGUs. In a north-south direction, parallel to the strike of these faults, these carbonate-rock HGUs are much more continuous. The 3D framework accurately represents areas where carbonate-rock HGUs have been thinned or disrupted as a result of large-magnitude extension and interrupted by regional thrust faults. Calderas represent a significant local impediment to any regional flow through carbonate rock HGUs because the aquifers have been removed locally as a consequence of caldera collapse, volcanism, and igneous intrusion. Thick sequences of young basin fill are present in all basins in the study area and constitute the shallow aquifer.



Vertical exaggeration X 20
Viewing aspect— 220 degrees
Degrees from horizontal + 50
Albers Equal Area Conic Projection, Central Meridian -114°, Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°, North American Datum 1983

Scale varies both vertically and laterally as a result of the perspective view. All units shown in metric to be consistent with the defined map grid.

Figure B–11. Fence diagrams representing the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area. ***A***, the entire modeled hydrogeologic framework and ***B***, an inset portion of central Nevada.



Vertical exaggeration X 10
Viewing aspect— 220 degrees
Degrees from horizontal + 50
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Standard Parallels at 29.5° and 45.5°, Latitude of Origin 23°,
North American Datum 1983

Note: coloration of specific units is variable due to oblique illumination of the three-dimensional diagram

Scale varies both vertically and laterally as a result of the perspective view. All units shown in metric to be consistent with the defined map grid

Figure B–11. Fence diagrams representing the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area. ***B***, an inset portion of central Nevada.—Continued

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