Appendix 1: Three-Dimensional Hydrogeologic Framework

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

Appendix 1 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.

Appendix 1: Three-Dimensional Hydrogeologic Framework

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

A three-dimensional (3D) hydrogeologic framework was constructed to represent the regional hydrogeologic units (HGUs) and major structures in the Great Basin carbonate and alluvial aquifer system (GBCAAS) study area. A generalized conceptual model of geology, structure, and faulting, incorporating hydrogeologic properties of the HGUs was used to develop a computer generated hydrogeologic framework. The digital 3D-hydrogeologic framework is the physical skeleton that will form the foundation of the groundwater flow model of the study area being developed concurrently (2011).

The 3D-hydrogeologic framework, consisting of nine HGUs with distinct hydraulic properties, was constructed by extracting and combining information from a variety of datasets. The top altitudes of the HGU surfaces were modeled from the input data using a 2.59 km^2 (1 mi^2) grid cell size. The modeled HGU surfaces were constrained by two regional datasets: (1) the National Elevation Dataset Digital Elevation Model (NED DEM) surface (U.S. Geological Survey EROS Data Center, 1999) and (2) the depth-to-basement surface (depth to pre-Cenozoic rocks) (see section "Depth-to-Basement Surface"). The HGU surfaces were combined and stacked together, resulting in the 3D-hydrogeologic framework for the GBCAAS study area. Major fault zones and caldera margins were incorporated to define regional trends and structural controls on the hydrogeology. A detailed description of structural controls and HGU designations within the GBCAAS study area is given in the "Hydrogeologic Units" section of Chapter B.

Interpolation of spatial data points into grids representing the HGU surfaces was processed using Rockware Rockworks14® software. Further modification and interpretation of the gridded HGU surfaces was completed using Environmental Science Research Institute ARC/INFO® geographic information system (GIS) software.

Input Data

Construction of the 3D-hydrogeologic framework utilized data from multiple sources to define the top surface and extent of each HGU. Input data sources include topographic data, geologic maps, borehole logs, previously published geologic cross sections, and digital geophysical models.

Topographic Data

Digital elevation data for the study area consist of seamless 1:24,000-scale National Elevation Data (NED) digital elevation models (DEM) (U.S. Geological Survey EROS Data Center, 1999). Data are in Albers projection North American Datum 1983 with a grid cell spacing of about 30 m.

Geologic Maps

Data from digital state geologic maps of Arizona, California, Idaho, Nevada, and Utah were used as input to the 3D-hydrogeologic framework. Geologic data from the five state maps, ranging in scale from 1:500,000 to 1:1,000,000, were cross-correlated to generate an integrated geologic map database for the Western U.S. (Ludington and others, 1996), including the GBCAAS study area. Each geologic unit from the integrated dataset was assigned to a HGU using the criteria discussed in Chapter B and from published unit descriptions in the primary source data for the digital maps (fig. A1–1 and fig. B–2 of Chapter B).

HGU data from the surficial geologic map were processed in a GIS by locating nodes (points) along adjacent HGU polygon boundaries (fig. A1–1). Each node was assigned an HGU corresponding to the geologically oldest HGU polygon located at that point. Cross-correlating the NED at that point results in the top altitude of the HGU at that point relative to the surficial geologic map. The process assumes younger geologic units overlie older units. In order to simplify and reduce the number of data points from this data source, each HGU point within a radius of 402.3 m (1,320 ft) of another was combined and represented spatially as the geometric mean of the overlapping points.

Well Stratigraphic Data

Stratigraphic log data from 441 wells throughout the GBCAAS study area were compiled and HGU contacts at each well were delineated for input to the 3D-hydrogeologic framework. Well stratigraphic data came from a variety of sources and databases including Nevada and Utah oil and gas exploration wells (Hess and others, 2004; Utah Division

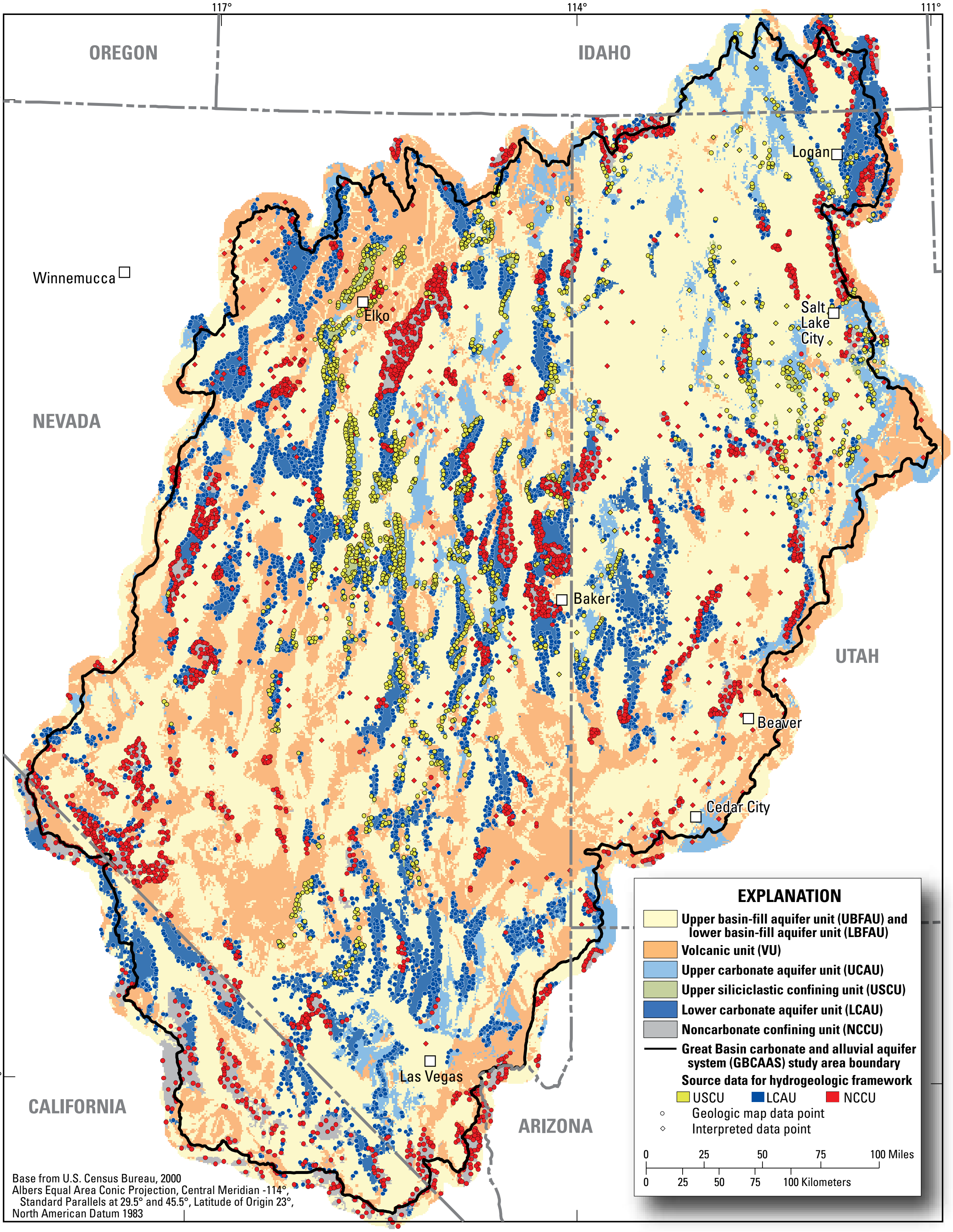

Figure A1–1. Surficial hydrogeologic units and locations of geologic map data used to create the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area.

of Oil, Gas, and Mining, 2008), the MX missile program (Tumbusch and Schaefer, 1996), Southern Nevada Water Authority exploration and production wells (Nevada Division of Water Resources, 2008), and water wells in Utah (Utah Division of Water Rights, 2008). Thousands of wells have been drilled in the study area; however, only a small fraction of these wells have detailed lithologic and stratigraphic data with HGU contact altitudes. Locations of wells used for constructing the hydrogeologic framework are shown in figure A1–2.

Cross Sections

The contacts between HGUs were manually picked from 245 cross sections compiled from 99 separate sources and used as input data for developing the 3D-hydrogeologic framework (fig. A1–2). References for each of the cross sections used are listed in Auxiliary 1. A scanned image of each cross section was scaled and georeferenced in a GIS along the cross-section trace of the digital source map. Geologic units on each cross section were correlated to the HGUs defined for the GBCAAS study area. HGU contacts along the cross-section trace were used to pick points representing the oldest HGU at the contact. The altitude of the top surface of each HGU point represented in cross section was interpolated from the cross section vertical scale.

Existing Geologic Frameworks

The existing 3D-hydrogeologic framework for the Death Valley regional flow system (DVRFS) model (Faunt and others, 2004) was incorporated into the GBCAAS hydrogeologic framework (fig. A1–2). The DVRFS hydrogeologic model consists of 27 separate HGUs. Individual HGUs in the DVRFS model were grouped and assigned to the nine HGUs for this study (table A1–1). The grouped HGU surfaces from the Death Valley framework were resampled to a 2.59 km^2 (1 mi^2) grid cell size used in this study.

Depth-to-Basement Surface

Regional gravity studies were used to delineate the boundary between the pre-Cenozoic basement rocks and the Cenozoic volcanic and sedimentary basin-fill deposits. Gravity data were used to estimate the shape and extent of the Cenozoic basins in three dimensions. There is a large density contrast between the pre-Cenozoic basement rocks and the overlying Cenozoic volcanic rocks and sedimentary basin fill that is used to estimate the depth-to-basement in Cenozoic basins (Saltus and Jachens, 1995). The regional Saltus and Jachens (1995) depth-to-basement surface for Arizona, California, Nevada, and Utah was joined with a depth-to-basement surface for Idaho (Mankinen and others, 2004). The resulting surface was combined with three higher resolution datasets from more recent regional studies of the Basin and Range carbonate-rock aquifer system (BARCAS) (Ponce and others, 2001; Welch and others, 2007), the DVRFS (Belcher, 2004), and geophysical framework investigations in east-central Nevada and west-central Utah (Watt and Ponce, 2007) (fig. A1–3). In areas where the detailed studies overlapped the regional Saltus and Jachens (1995) data, the original Saltus and Jachens data were replaced with the more recent data using a common 500-m^2 grid cell size of the Saltus and Jachens (1995) data. The depth-to-basement surface was compared to the HGU surficial geology map and modified so that the depth-to-basement surface altitude was equal to the NED altitude where pre-Cenozoic rocks outcrop on the HGU map. The final merged map was resampled using a 2.59 km^2 (1 mi^2) grid cell size to be consistent with the HGU map. The end result is a single “depth-to-basement” surface that incorporates multiple datasets to represent the altitude of the pre-Cenozoic rock surface. The final gridded surface used in the hydrogeologic framework defines both the top of pre-Cenozoic rocks and the base of the Cenozoic sedimentary basin-fill deposits and volcanic rocks. The thickness of the Cenozoic rocks was derived by subtracting the depth-to-basement surface from the NED DEM (fig. A1–3).

Fault and Caldera Boundaries

Structural features, including faults and calderas, are abundant within the GBCAAS study area and affect the extent and depth of HGUs (see “Hydrogeologic Units” in Chapter B). Fault boundaries were compiled from and modified after Raines and others (1996), Hintze and others (2000), Potter and others (2002), Workman and others (2002), Page and others (2005), Ludington and others (1996), and Beard and others (2007), and were simplified to represent the regional scale of the study (fig. A1–4).

Caldera boundaries were compiled from numerous published sources (Shawe, 1972; Lindsey, 1982; Steven and others, 1984; Best and Grant, 1987; Best and others, 1989; Loucks and others, 1989; Gans and others, 1989; Ludington and others, 1996; Raines and others, 1996; Williams and others, 1997; Workman and others, 2002; Page and others, 2005; Henry, 2008). Caldera boundaries were also generalized for use at a regional scale (fig. A1–5). The caldera boundary dataset was used to control the extent of pre-Cenozoic HGUs within a caldera boundary. Calderas were assumed to have similar hydrogeologic properties as the noncarbonate confining unit (NCCU); therefore, the area contained within a caldera boundary is designated as NCCU and extends vertically to the base of the volcanic unit (VU).

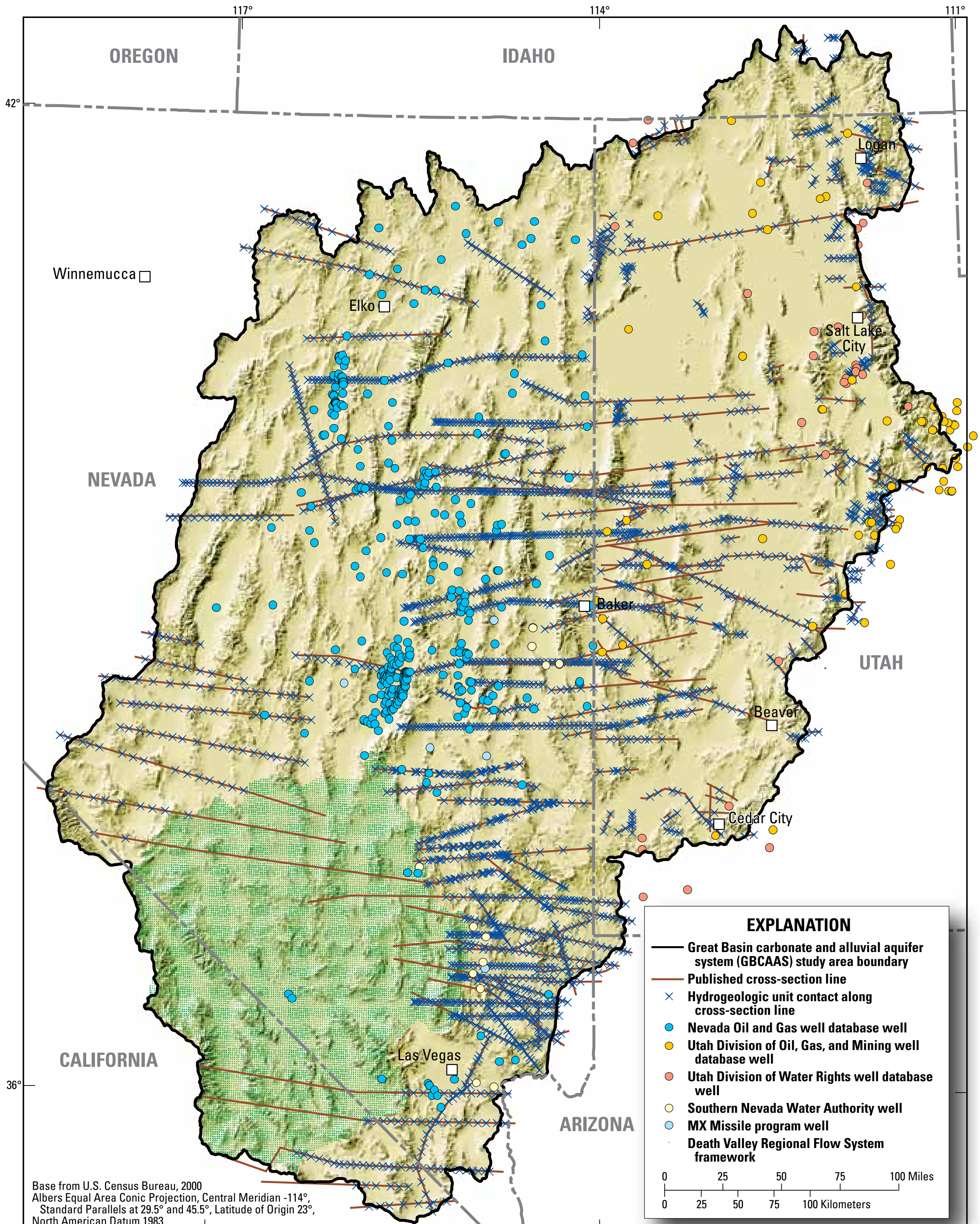

Figure A1–2. Locations of wells and cross sections used to create the three-dimensional hydrogeologic framework in the Great Basin carbonate and alluvial aquifer system study area.

Table A1–1. Correlation of hydrogeologic units between the Great Basin carbonate and alluvial aquifer system study and Death Valley regional flow system study.

[DVRFS HGU designations from Faunt and others, 2004, table E-1. Abbreviations: GBCAAS, Great Basin carbonate and alluvial aquifer system; DVRFS, Death Valley regional flow system; HGU, hydrogeologic unit; UBFAU, upper basin-fill aquifer unit; LBFAU, lower basin-fill aquifer unit; VU, volcanic unit; TLCAU, thrusted lower carbonate aquifer unit; TNCCU, thrusted noncarbonate confining unit; UCAU, upper carbonate aquifer unit; USCU, upper siliciclastic confining unit; LCAU, lower carbonate aquifer unit; NCCU, noncarbonate confining unit; NED, National Elevation Dataset]

GBCAAS HGU	DVRFS HGU	Stacking order	Calculation of top of HGU
UBFAU	YAA, YACU, OAA, OACU, LA, LFU, YVU, Upper VSU	9	Equals altitude of NED grid where UBFAU HGU exists.
LBFAU	YAA, YACU, OAA, OACU, LA, LFU, YVU, Upper VSU	8	Equals altitude of NED minus two-thirds the thickness of the basin-fill deposits (where thickness equals altitude of UBFAU grid minus altitude of depth-to-basement grid).
VU	TMVA, PVA, CHVU, WVU, CFPPA, CFBCU, CFTA, BRU, OVU, Lower VSU	7	Equals altitude of NED grid where VU HGU exists.
TLCAU	LCA_T1	6	Equals altitude of depth-to-basement grid.
TNCCU	LCCU_T1	5	Equals altitude of TLCAU grid minus thickness of TLCAU.
UCAU	SCU, UCA	4	Equals altitude of TNCCU grid minus thickness of TNCCU.
USCU	UCCU	3	Altitude of USCU grid is interpolated. Altitude set equal to UCAU or LCAU if the interpolated grid extended above or below the respective surfaces.
LCAU	LCA	2	Altitude of LCAU grid is interpolated. Altitude set equal to UCAU or NCCU if the interpolated grid extended above or below the respective surfaces.
NCCU	LCCU, XCU, ICU	1	Altitude of NCCU grid is interpolated. Altitude set equal to UCAU if the interpolated grid extended above respective surface.

Hydrogeologic Unit Gridded Surface Construction

In the hydrogeologic framework, individual HGUs are represented by an interpolated gridded surface of the top altitude of each HGU. Gridded surfaces were interpolated from the data described in the previous sections and modified in specific areas where data were limited. Different approaches were used for developing the upper basin-fill and lower basin-fill aquifer units (UBFAU and LBFAU) and the VU surfaces than were used for gridding the pre-Cenozoic HGU surfaces due to differences and limitations of the data. Each of the nine individual HGU gridded surfaces covers the entire GBCAAS study area with an altitude represented in each grid cell. If the HGU does not exist in a cell, the next lower HGU has the same altitude value in that cell, thereby producing a thickness of zero between the HGUs.

Cenozoic Hydrogeologic Units

Cenozoic HGUs include the UBFAU, the LBFAU, and the VU. Point data sources such as geologic contacts from wells and cross sections often do not clearly define contacts between volcanic rock and basin-fill deposits, thereby limiting the accuracy of the interpolated HGU gridded surface. Because of this limitation, the Cenozoic units were delineated using the NED surface, depth-to-basement surface, and surficial HGU map (fig. A1–1). Gridded surfaces were created from the surficial geology of Cenozoic sedimentary and volcanic units shown on the surficial HGU map (fig. A1–1). The altitude of the UBFAU gridded surface, representing the uppermost unit in the hydrogeologic framework, is defined by the NED and bounds the uppermost extent of all the lower HGUs. The two basin-fill aquifer HGUs have a combined thickness equal to the NED minus the depth-to-basement surface (fig. A1–4) where Cenozoic sediments are present on the HGU map (fig. A1–1). Point data sources such as geologic contacts from wells and cross sections rarely delineate volcanic ash deposits, lava flows into valley centers, or semiconsolidated basin-fill deposits at depth; therefore, the basin-fill aquifer HGUs are divided into an upper unit (UBFAU) and a lower unit (LBFAU) to represent potential differences in hydrogeologic properties. The UBFAU is defined as the upper two-thirds of the total basin-fill thickness, and the LBFAU as the lower one-third of the total basin-fill thickness. Wherever VU is present (fig. A1–1), it is represented as the thickness equal to the NED surface minus the depth-to-basement surface (fig. A1–5). The bottom surfaces of the LBFAU and VU are bounded by the depth-to-basement surface.

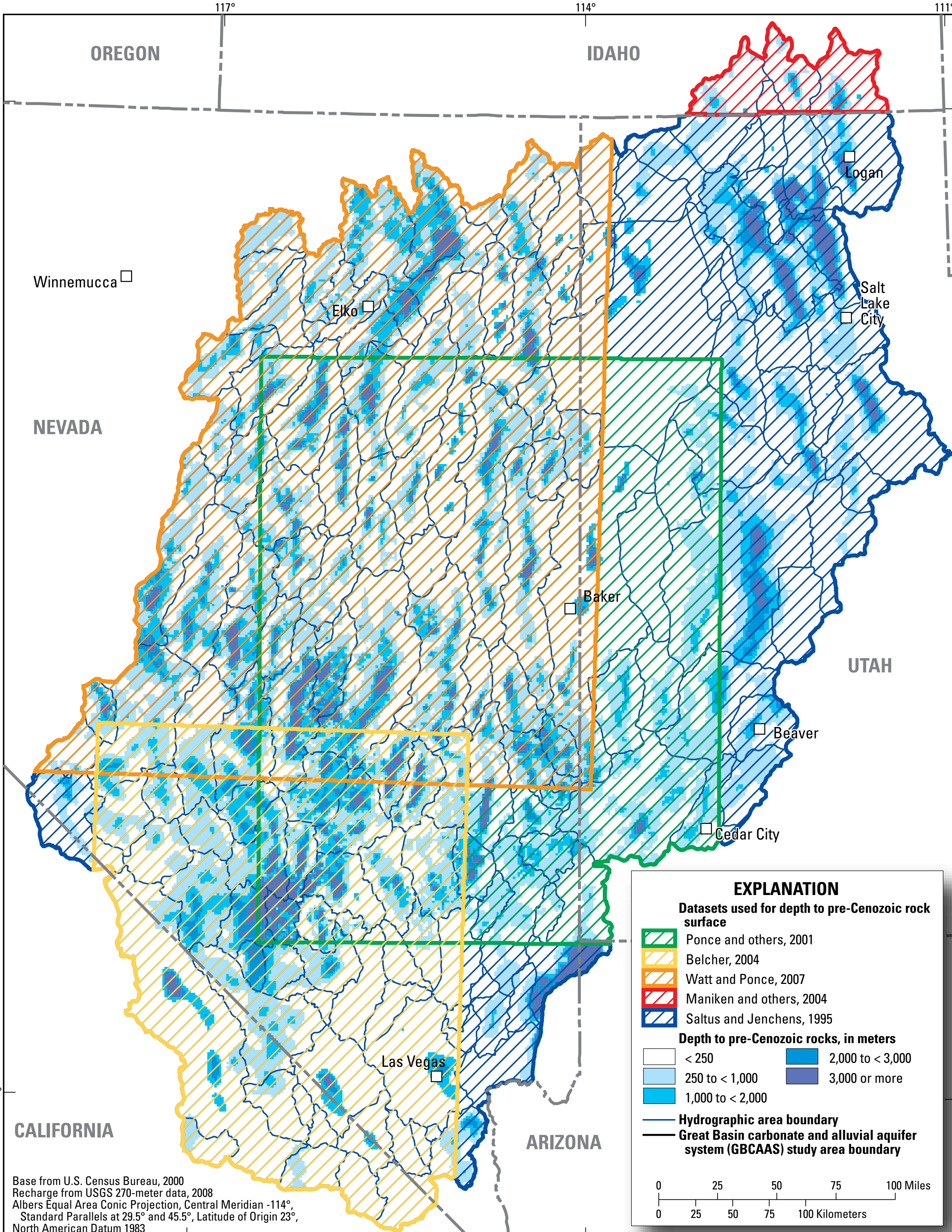

Figure A1–3. Locations of published datasets and estimated thickness of Cenozoic deposits (depth to pre-Cenozoic rocks) in the Great Basin carbonate and alluvial aquifer system study area.

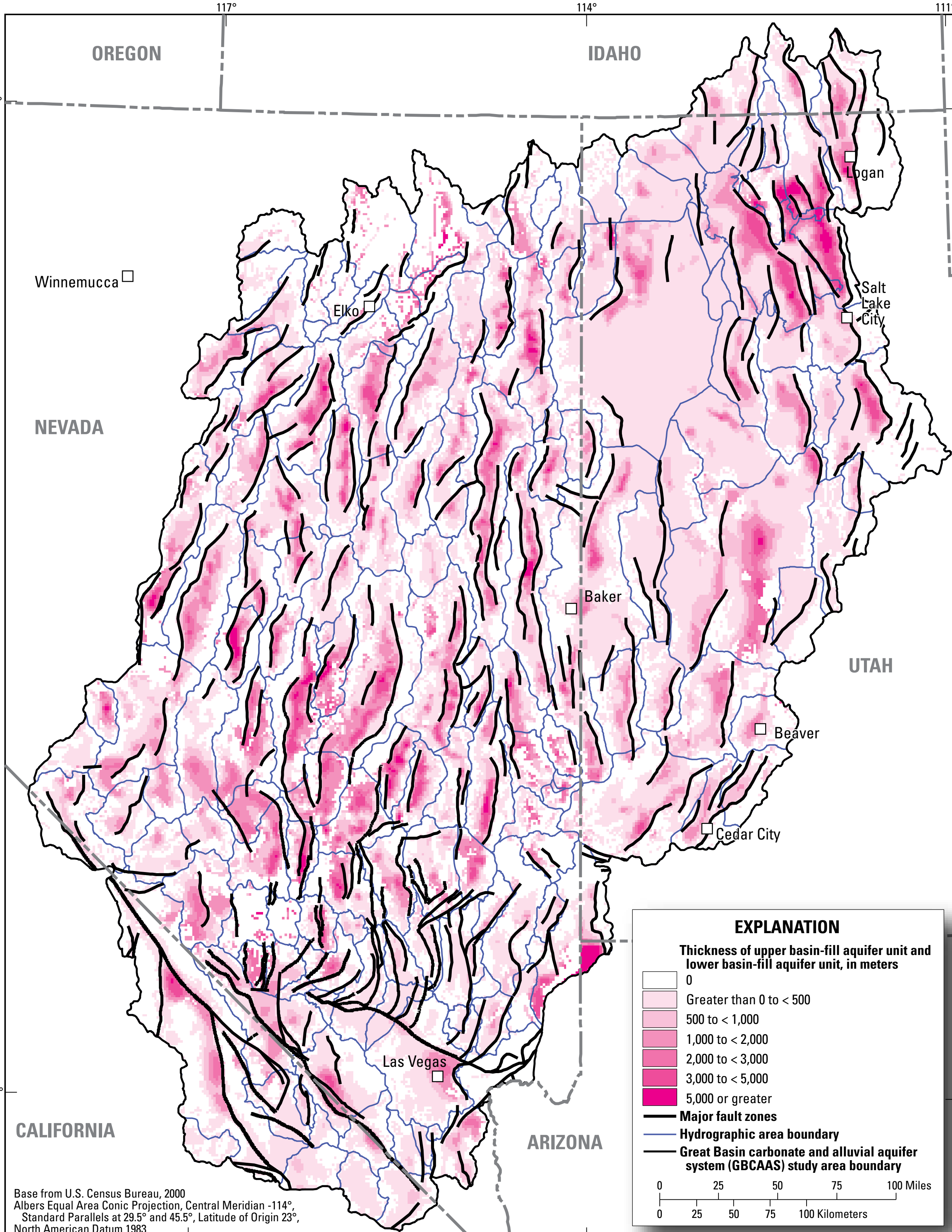

Figure A1–4. Extent and thickness of the upper basin-fill (UBFAU) and lower basin-fill (LBFAU) aquifer units (combined) and major fault zones in the Great Basin carbonate and alluvial aquifer system study area.

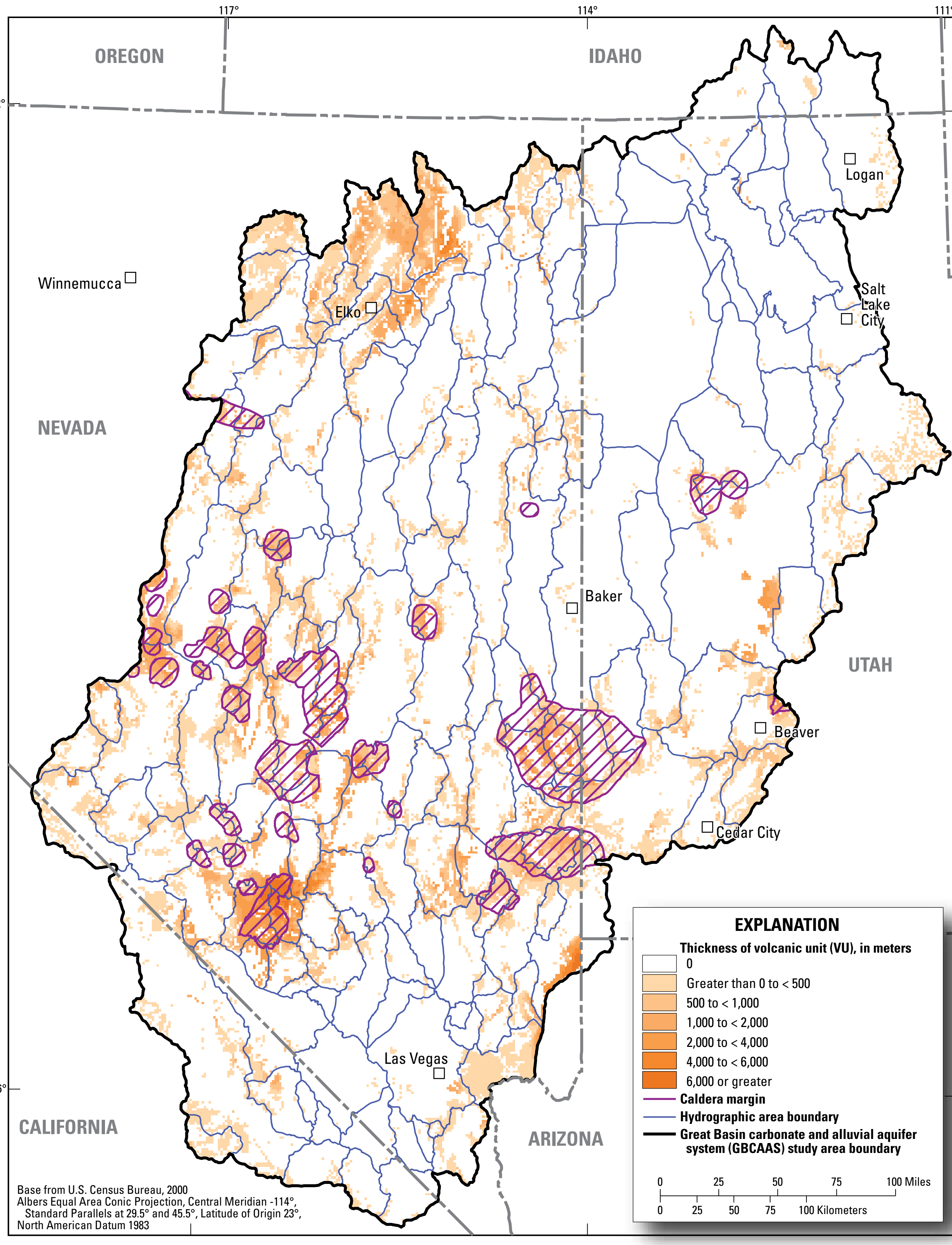

Figure A1–5. Extent and thickness of the volcanic unit (VU) and caldera boundaries in the Great Basin carbonate and alluvial aquifer system study area.

Pre-Cenozoic Units

Surfaces representing the top altitude were created for each of the pre-Cenozoic HGUs—NCCU, the lower carbonate aquifer unit (LCAU), the upper siliciclastic confining unit (USCU), the upper carbonate aquifer unit (UCAU), the thrusted noncarbonate confining unit (TNCCU), and the thrusted lower carbonate aquifer unit (TLCAU). The depth-to-basement surface is the top of the uppermost pre-Cenozoic unit surface (table A1–1).

The TNCCU and TLCAU spatial geometries (fig. A1–6) were interpolated by delineating the extent and thickness of two major thrust belts within the study area, the Roberts Mountain thrust and the Sevier thrust (see Chapter B). The TLCAU thickness was subtracted from the altitude of the depth-to-basement surface to determine the altitude of the top of the TNCCU. Subsequently, the TNCCU thickness was subtracted from the altitude of the top of the TNCCU to determine the altitude of the top of the UCAU gridded surface.

The altitudes of the NCCU, LCAU, and USCU gridded surfaces were interpolated from the data for each HGU using an inverse distance weighted algorithm. The algorithm also uses linear features as x-y pairs to represent major structural controls such as faults that act as barriers in the interpolation routine. The inverse distance weight across the linear feature was increased by a factor of 100, thereby limiting the unit interpolation across these structures.

The NCCU is stratigraphically the lowest unit and is the base of the 3D-hydrogeologic framework; therefore, the altitude of the NCCU surface defines the basal extent of all the pre-Cenozoic HGUs. The NCCU surface was limited by the digital elevatiom model and the UCAU, TLCAU, and (or) TNCCU surfaces so that it could not extend above the depth-to-basement surface, the thrusted units, or the land surface datum. The NCCU surface within the caldera boundaries was set equal to the depth-to-basement surface because it is assumed that the caldera complexes have hydraulic properties similar to the NCCU HGU.

The LCAU and USCU surfaces are controlled by the altitude of the UCAU gridded surface, so that they cannot extend above the pre-Cenozoic surface. The extent and thickness of the interpolated LCAU HGU are controlled by the altitude of the LCAU surface minus the altitude of the NCCU surface (table A1–1). The thickness of the LCAU was arbitrarily truncated at 6,000 m in areas where the NCCU surface was interpolated to be deeper than is likely. The NCCU surface was sequentially modified to be equal to the LCAU surface minus the LCAU thickness in the truncated areas. The extent and thickness of the interpolated USCU HGU are controlled by the altitude of the USCU surface minus the altitude of the LCAU surface. The extent and thickness of the USCU and LCAU HGUs are shown in figures A1–7 and A1–8, respectively. The extent and thickness of the UCAU are defined by the altitude of the UCAU surface (depth-to-basement minus thrusted units) minus the altitude of the USCU surface (fig. A1–9).

The resulting pre-Cenozoic HGU surfaces were compared to the surficial HGU map (fig. A1–1). Each HGU surface was adjusted so that the top was equal to the NED if the respective HGU occurred on the surficial map at the same point.

Three-Dimensional Hydrogeologic Framework

The final 3D-hydrogeologic framework was compiled by stacking the individual HGU gridded surfaces and allowing the individual HGU surfaces to represent the top altitude of each respective HGU (Z coordinate). The stacking order is defined by the geologic age of the unit, from oldest (Precambrian) to most recent (Quaternary) (table A1–1). An exception to the stacking rule applies to the thrusted surfaces, TNCCU and TLCAU, which are stacked relative to time of movement (Mesozoic) rather than age of deposition. HGU thickness is represented by the difference between altitudes of successive HGU surfaces such that the bottom of an HGU is always equal to the top of the HGU directly below it in the stacking order. Where the thickness is zero at a location, the respective HGU does not exist at that location. Cross sections and fence diagrams of the stacked 3D-hydrogeologic framework are illustrated on figures B–10 and B–11, respectively, in Chapter B.

The hydrogeologic framework is a simplified 3D representation of the hydrogeology of the entire GBCAAS study area, encompassing 165 individual hydrographic areas (HAs). As such, it is suitable for regional analysis at the scale of the GBCASS study but it may not accurately represent smaller scale hydrogeology within individual HAs, as it is not intended to be utilized at that scale.

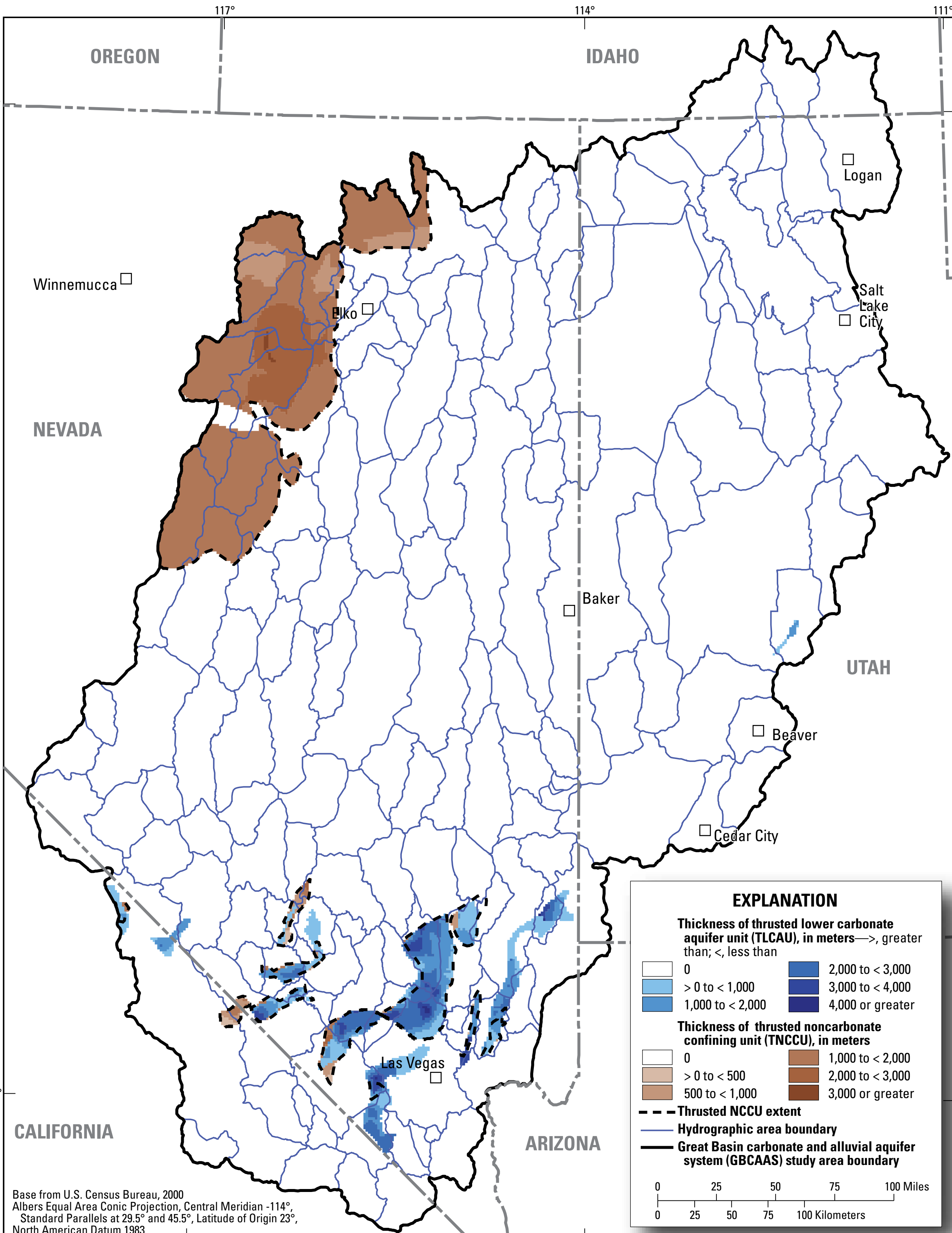

Figure A1–6. Extent and thickness of the thrusted lower carbonate aquifer unit (TLCAU) and thrusted noncarbonate confining unit (TNCCU) in the Great Basin carbonate and alluvial aquifer system study area.

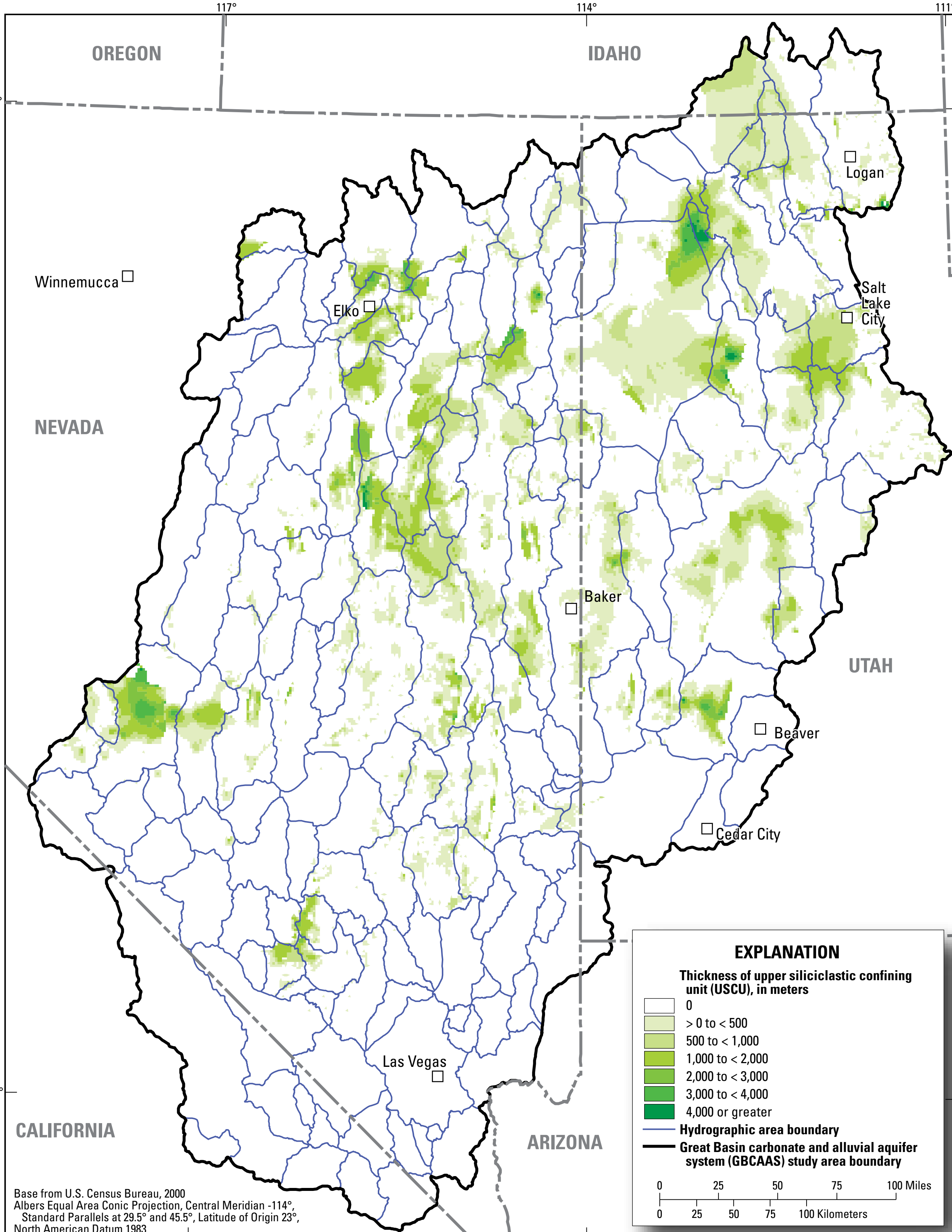

Figure A1–7. Extent and thickness of the upper siliciclastic confining unit (USCU) in the Great Basin carbonate and alluvial aquifer system study area.

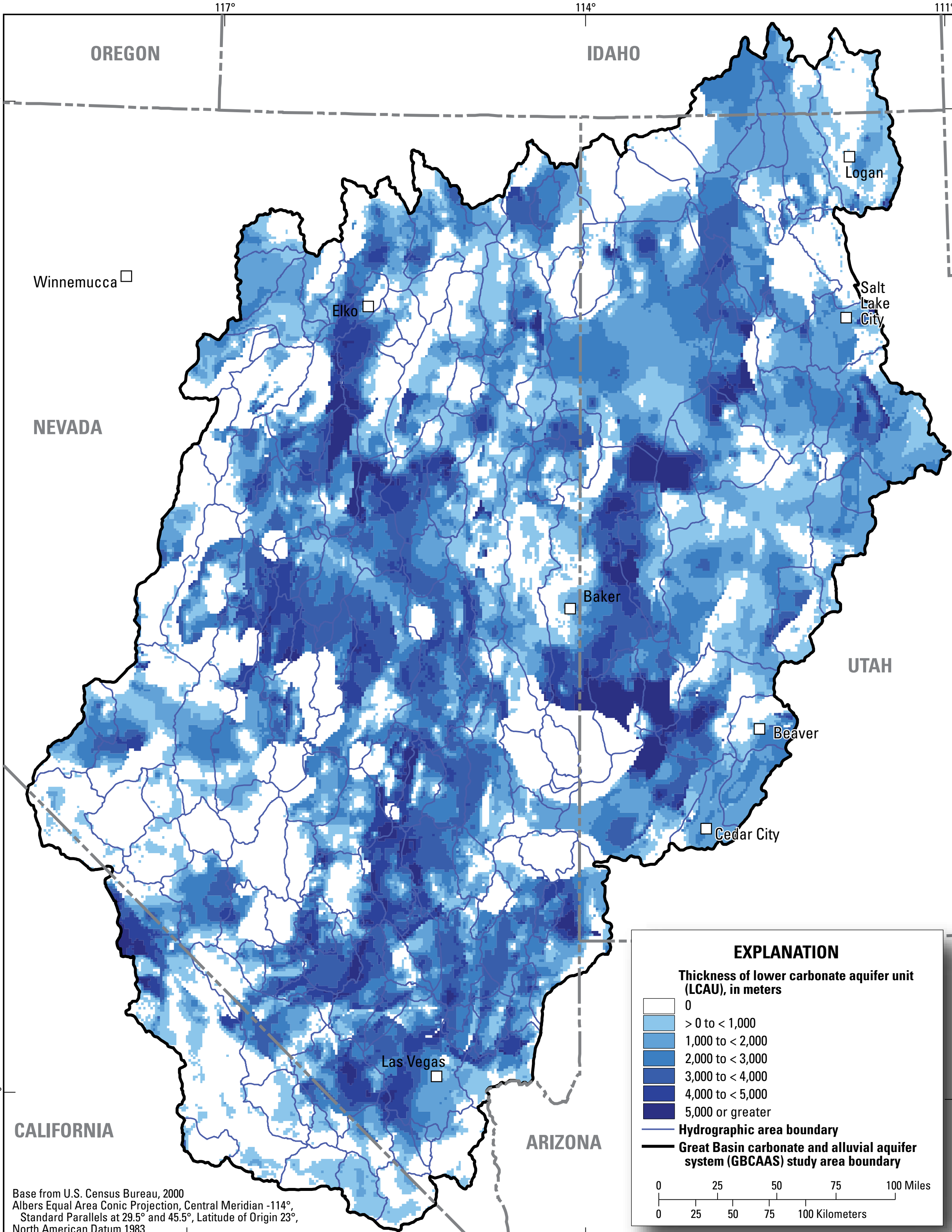

Figure A1–8. Extent and thickness of the lower carbonate aquifer unit (LCAU) in the Great Basin carbonate and alluvial aquifer system study area.

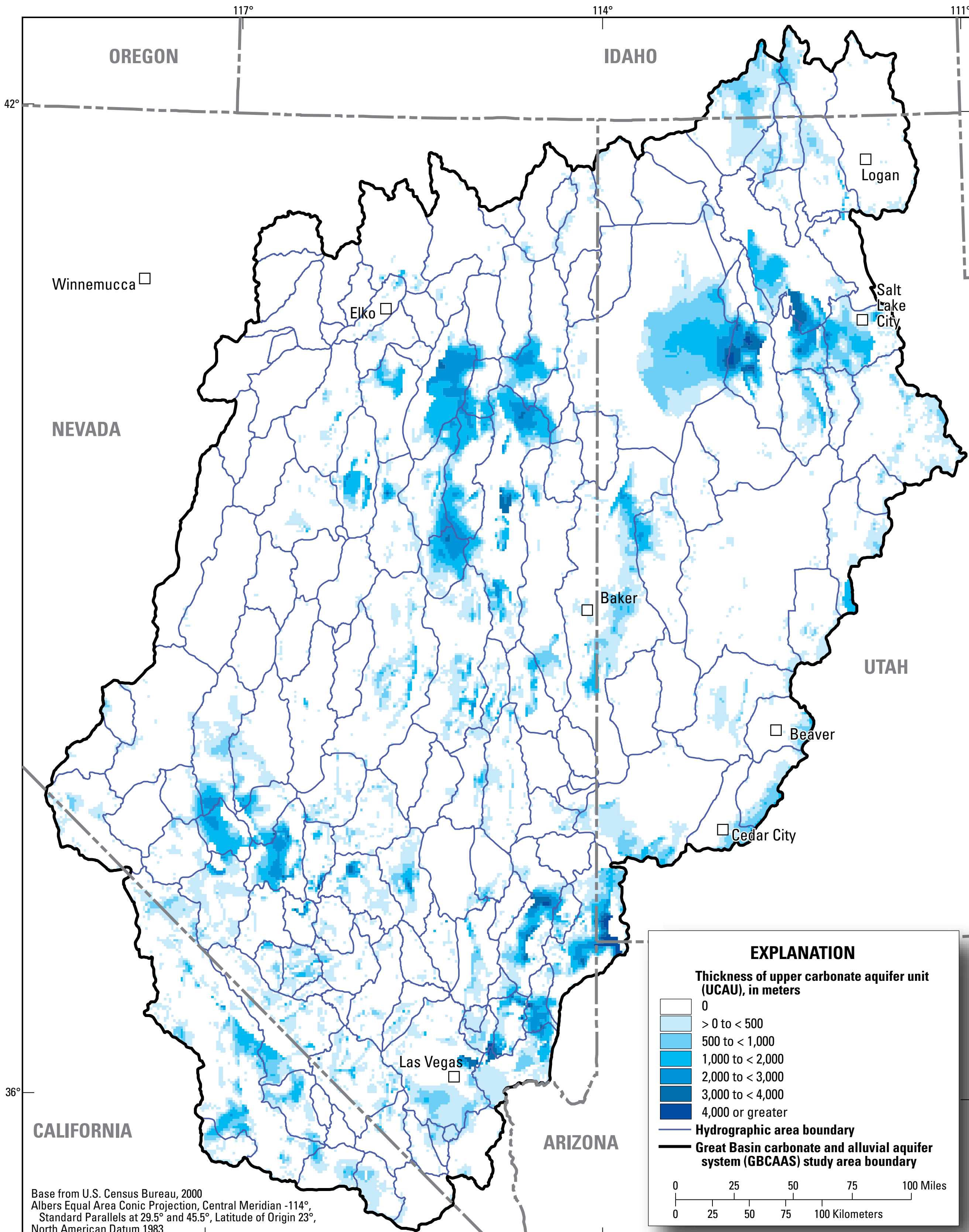

Figure A1–9. Extent and thickness of the upper carbonate aquifer unit (UCAU) in the Great Basin carbonate and alluvial aquifer system study area.

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