U.S. Department of the Interior
U.S. Geological Survey

Three-Dimensional Hydrogeologic Framework Model for Use With a Steady-State Numerical Ground-Water Flow Model of the Death Valley Regional Flow System, Nevada and California

Water-Resources Investigations Report 01-4254

Prepared in cooperation with the
NEVADA OPERATIONS OFFICE,
U.S. DEPARTMENT OF ENERGY, under
Interagency Agreement DE-AI08-96NV11967

science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

Three-Dimensional Hydrogeologic Framework Model for Use With a Steady-State Numerical Ground-Water Flow Model of the Death Valley Regional Flow System, Nevada and California

By Wayne R. Belcher, Claudia C. Faunt, and Frank A. D’Agnese

Water-Resources Investigations Report 01-4254

Prepared in cooperation with the
NEVADA OPERATIONS OFFICE,
U.S. DEPARTMENT OF ENERGY, under
Interagency Agreement DE-AI08-96NV11967

Denver, Colorado
2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
333 West Nye Lane, Room 203
Carson City, NV 89706-0866
e-mail: GS-W-NVpublic-info@usgs.gov

A portable document format (PDF) version of this report may be downloaded from URL:
http://pubs.water.usgs.gov/wri014254

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square hectometer	2.471	acre
square kilometer (km^2)	0.3861	square mile
cubic hectometer	811.030	acre-foot
meters per year (m/yr)	3.281	foot per year
meters per second (m/s)	3.281	foot per second
cubic hectometer per year	811.030	acre-foot per day
cubic meter per second (m^3/s)	3,048,780.49	cubic foot per day
liter per second (L/s)	15.85	gallons per minute

Temperature in degree Celsius (^oC) can be converted to degree Fahrenheit (^oF) as follows:

$$^oF = 1.8\ (^oC) + 32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets across the United States and Canada, formerly called Sea Level Datum of 1929.

Coordinates: Coordinates are referenced to Universal Transverse Mercator projection, Zone 11, in meters.

SYMBOL DEFINITIONS AND ACRONYMS

2.5D	Two-and-a-half dimensional
3D	Three-dimensional
DEM	Digital elevation model
DOE	Department of Energy
DOE/NV	Department of Energy/Nevada Operations Office
DOE/YMSCO	Department of Energy/Yucca Mountain Site Characterization Office
DVRFS	Death Valley regional flow system
DVS	Death Valley section
ER	Environmental Restoration
ESRI	Environmental Science Research Institute
GIS	Geographic information system
GSIS	Geoscientific information system
HFM	Hydrogeologic framework model
HRMP	Hydrologic Resources Management Program
HUF	Hydrogeologic-unit flow package
LCA	Lower carbonate aquifer
LCCU	Lower clastic confining unit
LVVSZ	Las Vegas Valley shear zone
Mvs	Mesozoic volcaniclastic and sedimentary rocks
NTS	Nevada Test Site
NWIS	National Water Information System
pCgm	Precambrian granite and metamorphic rocks
QTal	Quaternary-Tertiary alluvium
QTp	Quaternary-Tertiary playas
SGM	Stratigraphic Geocellular Modeler
SWNVF	Southwest Nevada Volcanic Field
TBA	Belted Range aquifer
TBCU	Basal confining unit
TBQ	Basal aquifer
TC	Tuff cone
TCB	Bullfrog confining unit
TJi	Tertiary-Jurassic intrusives
TMA	Timber Mountain aquifer
TS	Tertiary sediments
TSDVS	Tertiary sediments/Death Valley section
UCA	Upper carbonate aquifer
UCCU	Upper clastic confining unit
UGTA	Underground Test Area
UTM	Universal Transverse Mercator
VA	Volcanic aquifer
VCU	Volcanic confining unit
VU	Undifferentiated volcanics
YMP	Yucca Mountain Project

Three-Dimensional Hydrogeologic Framework Model for Use with a Steady-State Numerical Ground-Water Flow Model of the Death Valley Regional Flow System, Nevada and California

By Wayne R. Belcher, Claudia C. Faunt, and Frank A. D'Agnese

ABSTRACT

The U.S. Geological Survey, in cooperation with the Department of Energy and other Federal, State, and local agencies, is evaluating the hydrogeologic characteristics of the Death Valley regional ground-water flow system. The ground-water flow system covers an area of about 100,000 square kilometers from latitude 35° to 38° 15' North to longitude 115° to 118° West, with the flow system proper comprising about 45,000 square kilometers. The Death Valley regional ground-water flow system is one of the larger flow systems within the Southwestern United States and includes in its boundaries the Nevada Test Site, Yucca Mountain, and much of Death Valley. Part of this study includes the construction of a three-dimensional hydrogeologic framework model to serve as the foundation for the development of a steady-state regional ground-water flow model. The digital framework model provides a computer-based description of the geometry and composition of the hydrogeologic units that control regional flow. The framework model of the region was constructed by merging two previous framework models constructed for the Yucca Mountain Project and the Environmental Restoration Program Underground Test Area studies at the Nevada Test Site.

The hydrologic characteristics of the region result from a currently arid climate and complex geology. Interbasinal regional ground-water flow occurs through a thick carbonate-rock sequence of Paleozoic age, a locally thick volcanic-rock sequence of Tertiary age, and basin-fill alluvium of Tertiary and Quaternary age. Throughout the system, deep and shallow ground-water flow may be controlled by extensive and pervasive regional and local faults and fractures.

The framework model was constructed using data from several sources to define the geometry of the regional hydrogeologic units. These data sources include (1) a 1:250,000-scale hydrogeologic-map compilation of the region; (2) regional-scale geologic cross sections; (3) borehole information, and (4) gridded surfaces from a previous three-dimensional geologic model. In addition, digital elevation model data were used in conjunction with these data to define ground-surface altitudes. These data, properly oriented in three dimensions by using geographic information systems, were combined and gridded to produce the upper surfaces of the hydrogeologic units used in the flow model. The final geometry of the framework model is constructed as a volumetric model by incorporating the intersections of these gridded surfaces and by applying fault truncation rules to structural features from the geologic map and cross sections. The cells defining the geometry of the hydrogeologic framework model can be assigned several attributes such as lithology, hydrogeologic unit, thickness, and top and bottom altitudes.

INTRODUCTION

In the early 1990s, two numerical models of the Death Valley regional ground-water flow system (DVRFS) (fig. 1) were developed by the U.S. Department of Energy (DOE). One, designated the YMP/HRMP model, was developed collaboratively for the Yucca Mountain Site Characterization Office (DOE/YMSCO) and the Nevada Operations Office Hydrologic Resources Management Project (DOE/NV–HRMP). Another, designated the UGTA model, was developed for the Nevada Operations Office Underground Test Area (DOE/NV–UGTA) subproject of the Environmental Restoration (ER) Project. The regional model for the DOE/YMSCO and DOE/NV–HRMP was developed by the U.S. Geological Survey (USGS) using MODFLOWP (Hill, 1992) and is documented in D'Agnese and others (1997). The model for the DOE/NV–UGTA (U.S. Department of Energy, 1997) was developed by the ER Support Services Contractor (IT Corporation and its subcontractors); HSI/GeoTrans Inc. had primary responsibility for the flow model, which was developed using MODFLOW (McDonald and Harbaugh, 1988).

In general, the two models are based upon the same basic hydrologic data set. The geologic data sets differ somewhat in detail of interpretation, but the same general hydrogeologic framework is apparent in both models. Differences occur in the hydrogeologic framework where data are sparse and results are highly interpretive. Estimates of recharge are also highly interpretive and vary significantly throughout the model domains. These differences appear to affect ground-water flow paths and flux through the models.

In 1998, the DOE requested that the USGS develop and maintain a ground-water flow model of the DVRFS in support of DOE/YMSCO and DOE/NV programs. The purpose of developing this second-generation regional model was to enhance the knowledge and understanding of the DVRFS as new information and tools are developed. Furthermore, the USGS has been encouraged by DOE to cooperate to the fullest extent with other Federal, State and local entities in the region, including the National Park Service, the U.S. Fish and Wildlife Service, the Bureau of Land Management, and Nevada and California counties, to take advantage of the benefits of their knowledge and expertise.

Short-term objectives of the DVRFS project include the construction and calibration of a steady-state model that represents predevelopment conditions for the Death Valley regional ground-water flow system and will (1) provide the foundation and boundary conditions for the site-scale models at Yucca Mountain and the Underground Test Area on the Nevada Test Site (NTS), (2) characterize regional three-dimensional (3D) ground-water flow paths, (3) define discharge and recharge locations, (4) estimate magnitude of subsurface flux, and (5) represent the effects of regional geologic structural features on regional flow.

Long-term objectives of the DVRFS project involve the construction and calibration of a transient model that simulates the ground-water conditions of the study area over time and that could be utilized to (1) evaluate the effects of changes in system flux, regardless of whether the changes are natural or manmade; (2) provide a technical basis for decisions on the quantity of water available for defense and economic development activities on the NTS; (3) determine the potential effect of increased offsite water use on NTS water supplies; (4) provide a framework for determining effective source plume, ambient trend, and point-of-use ground-water-quality monitoring locations; and (5) provide an opportunity for other Federal, State, and local agencies and organizations to take a step toward developing a cooperative, regional Death Valley Ground-Water Management District.

This report documents efforts to merge the two existing hydrogeologic framework models (HFMs) for YMP (D'Agnese and others, 1997) and the NTS UGTA program (U.S. Department of Energy, 1997) to produce a single, integrated HFM. The study area is large enough to encompass the DVRFS domain and is limited to the area bounded by 35° to 38° 15' North latitude and 115° to 118° West longitude (fig. 1). The model area covers a large part of southern Nevada and southeastern California. The HFM is centered around the NTS and Yucca Mountain and ranges from the Panamint Range to the Sheep Range and from Baker, California, to just south of Tonopah, Nevada. The HFM itself covers an area of approximately 82,000 square kilometers (km^2) within the DVRFS. In UTM Zone 11 coordinates, the model extents in meters (m) are:

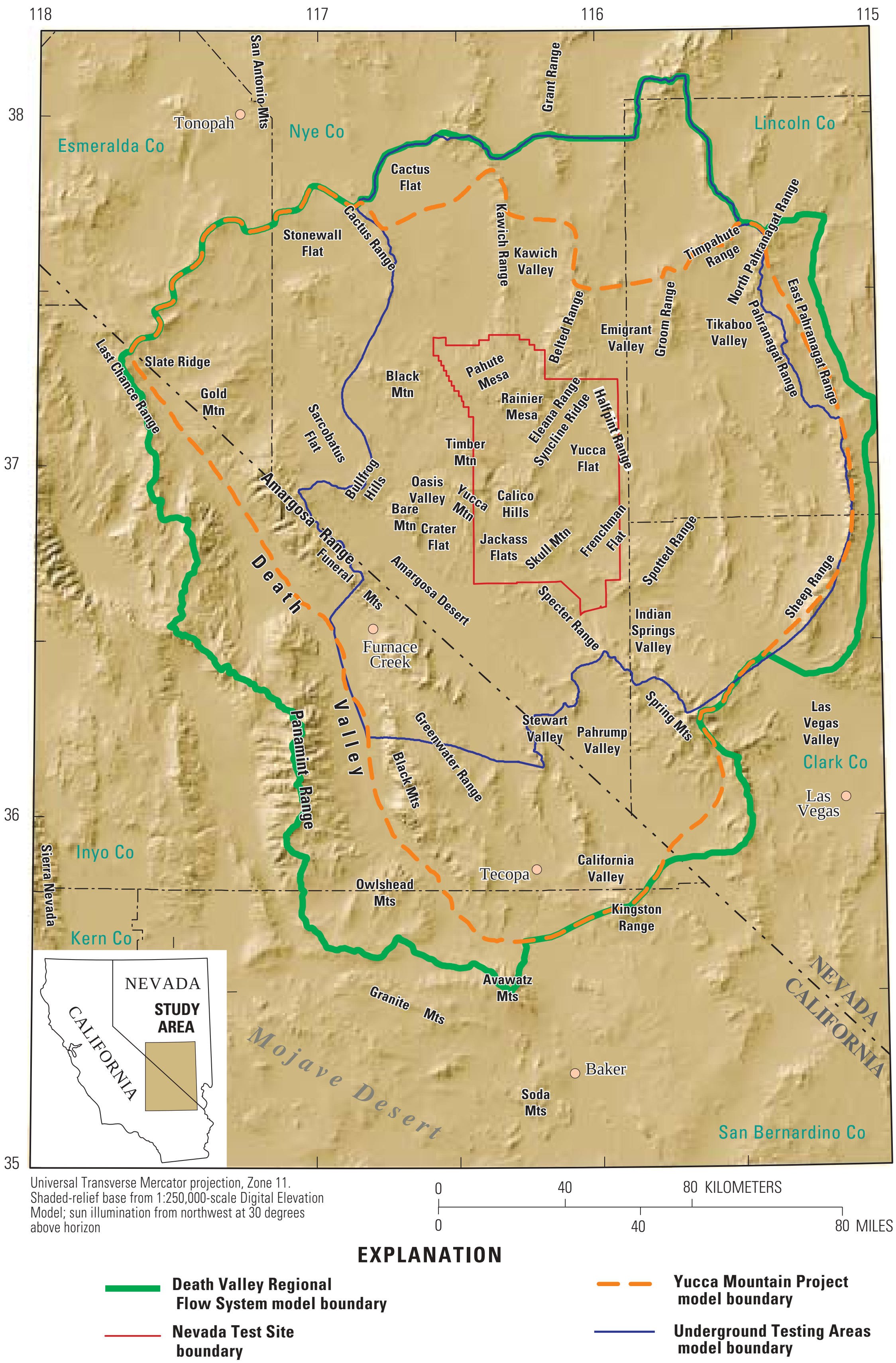

Figure 1. Boundaries of hydrogeologic framework and ground-water flow models, geographic, and prominent topographic features of the Death Valley region, California and Nevada.

X_{min}	=	408,500 m
X_{max}	=	677,000 m
X_{extent}	=	268,500 m
Y_{min}	=	3,928,000 m
Y_{max}	=	4,235,500 m
Y_{extent}	=	307,500 m

This area is rectangular due to the need to produce gridded surfaces for the construction of the HFM. The HFM, however, properly only consists of the region contained within the DVRFS boundary depicted in figure 1.

The depth of the HFM extends to 4,000 m below sea level. Some small areas in Tikaboo Valley and the northern Pahranagat Range (fig. 1) may have hydrogeologic units designated as aquifers that extend deeper than this. These truncated units occur in relatively small areas and are relatively thin sections of potential aquifer material. They should have little, if any, effect on the flow-model simulations.

The domain includes the following rocks, from older to younger: Precambrian and Paleozoic crystalline and sedimentary rocks, Mesozoic sedimentary rocks, Mesozoic to Cenozoic intrusive rocks, Cenozoic tuffs and lavas, and late Cenozoic alluvium filling valleys between the nearby ranges of Cenozoic, Mesozoic, and Paleozoic rocks. Because the HFM is meant to support a regional study, data sources contain geological details typically shown on regional-scale maps (typically 1:250,000 to 1:100,000 scale). Details of the geology and structure were obtained from surface maps, borehole information, geophysics, cross sections, IT Corporation's (U.S. Department of Energy, 1997) existing digital geologic model, and the YMP HFM (D'Agnese and others, 1997). The HFM is the result of merging the two existing framework models.

This report focuses on understanding the geologic components controlling ground-water flow and describing the development of a digital 3D HFM. HFMs describe the geometry, composition, and physical properties of the materials forming the natural hydrogeologic system. These models serve as a critical information source for the development of numerical ground-water flow models. The selection of required numerical modeling parameters is facilitated by using attribute data, such as hydrogeologic unit and geometric information, stored in the data base that is part of the HFM.

This report describes the digital HFM constructed for the Death Valley region in southern Nevada and southeastern California. The complex geology, arid climate, and the presence of the NTS and the potential high-level nuclear waste repository at Yucca Mountain makes the Death Valley region of interest with regard to water-resource and potential contaminant-migration issues.

SITE DESCRIPTION

The Death Valley region (fig. 1) includes several large prominent valleys: Amargosa Desert, Pahrump Valley, and Death Valley. The region also includes several major mountain ranges including the Panamint Range, the Spring Mountains, the Sheep Range, the Amargosa Range, the Kawich Range, the Kingston Range, the Pahranagat Range, the Timpahute Range, and the Last Chance Range. These major physiographic and geologic features, combined with a regional topographic gradient toward Death Valley, result in a complex ground-water system.

Physiography

The Death Valley region is situated within the southern Great Basin, a subprovince of the Basin and Range physiographic province (Fenneman, 1931). Late Cenozoic tectonic activity and faulting accounts for much of the topographic relief (Grose and Smith, 1989). Altitudes range from 86 m below sea level at Badwater in Death Valley to 3,600 m above sea level at Charleston Peak in the Spring Mountains. The relief between valleys and adjoining mountains locally exceeds 1,500 m (Bedinger and others, 1989a). Most of the principal mountain ranges have distinct northwest-southeast (NW/SE) trends, although the trends of intermediate-scale topographic features are quite variable. The ranges occupy only about 25 percent of the landscape in the study area (Peterson, 1981). The remainder of the landscape is occupied by broad intermontane basins formed from tectonically downdropped grabens. The basins are filled with alluvium and some interbedded volcanic deposits that gently slope from the valley floors to the bordering mountain ranges forming piedmonts (Peterson, 1981).

The valley bottoms are local depositional centers, usually containing playa lakes that act as catchments for surface-water runoff (Grose and Smith, 1989). Most of the basins seldom contain perennial surface water. Playas and alluvial fans lying within these basins constitute about 10 percent of the region (Bedinger and others, 1989a). Numerous playas contain saline deposits that indicate the evaporation of surface water and(or) shallow ground water from the playa surface. Some of the playas that have been deformed by Quaternary faulting contain springs where ground water is forced to the surface by juxtaposed lake sediments and alluvial aquifers (Bedinger and others, 1989a).

Geologic History

The Death Valley region has a long and active geologic history, including intermittent marine and nonmarine sedimentation, large-scale compressive deformation, plutonism, volcanism, and extensional tectonics (Stewart, 1980; Mifflin, 1988). Knowledge of the geologic diversity beneath the alluvial basins is indirect in most of the region.

The Death Valley region consists of clastic and crystalline rocks of Middle Proterozoic to early Cambrian age; carbonate and clastic rocks of Paleozoic age; clastic, volcanic, and intrusive rocks of Mesozoic age; varied fluvial, paludal, and playa sedimentary deposits of Pliocene age; Tertiary volcanic, volcaniclastic, and sedimentary rocks; and Tertiary to Quaternary alluvium and colluvium, and eolian deposits of Quaternary age (Waddell, 1982). Literature on detailed geologic studies throughout this region is voluminous; yet only a few integrative, comprehensive, and summary papers exist that cover the entire region and address all of the structural-tectonic-volcanic elements incorporated in the hydrogeologic framework model. Burchfiel and Davis (1981) discussed tectonic regimes in the California area, and Stewart (1978) discussed the tectonics of the Nevada part of the region, concisely and comprehensively using structural mechanics principles. Grose and Smith (1989) described this geologic complexity and offered insight into the hydrogeologic and tectonic controls on ground-water flow. Wernicke and others (1988) have addressed the Cenozoic extensional history of the region; Carr (1990) attempted to integrate the Cenozoic volcanic history with the extensional history. Most of the study area has undergone deformation, and some parts have been nearly continuously active tectonically since the late Proterozoic (Grose and Smith, 1989).

Structural and tectonic features of the study area (fig. 2) reveal a long, complex tectonic evolution. Combinations of normal, reverse, and strike-slip faulting and folding episodes have resulted in complex distributions of rocks. Consequently, diverse rock types, ages, and deformational structures commonly are juxtaposed. As a result, subsurface conditions are variable and complex.

Proterozoic and Paleozoic Geologic Setting

Metamorphic basement rocks of middle Proterozoic age were deposited approximately 1.7 to 1.4 billion years ago in geosynclinal, orogenic, and magmatic arc-type terranes. Sedimentation patterns were also influenced by the NE/SW-trending transcontinental arch. During the late Proterozoic, the study area underwent a period of continental margin rifting (Grose and Smith, 1989).

This region was a stable, continental margin from late Proterozoic to Devonian time. Late Proterozoic to Early Cambrian continental quartzites and siltstones are overlain by Middle Cambrian through Devonian carbonate and calcareous shales in a westward-thickening clastic and carbonate sequence up to 8,000 m thick (Grose and Smith, 1989). The first major Phanerozoic tectonic event in the Death Valley region was the Antler orogeny (Grose and Smith, 1989). During the Antler orogeny (Devonian to Mississippian time), uplift north and west of the area resulted in a thick wedge of clastic rocks, derived from adjacent highlands, being deposited in a NE/SW-trending foreland basin. Shelf-type carbonate deposition continued during Mississippian time in the southeast part of the region (Spring Mountains). This basin is now defined by the location of the Chainman Shale, which dominantly consists of relatively impermeable argillites and shales (Grose and Smith, 1989). The Antler orogeny also caused eastward thrusting of a more than 100,000-m-wide allochthon of deep-ocean shales, chert, and volcanic rocks. The leading edge of the Roberts Mountain thrust, formed during the Antler orogeny, is in the northwestern part of the Death Valley region (Grose and Smith, 1989). During Pennsylvanian time, the basin was filled, and shallow marine carbonates were deposited on the Mississippian-aged clastic rocks (Grose and Smith, 1989). As a

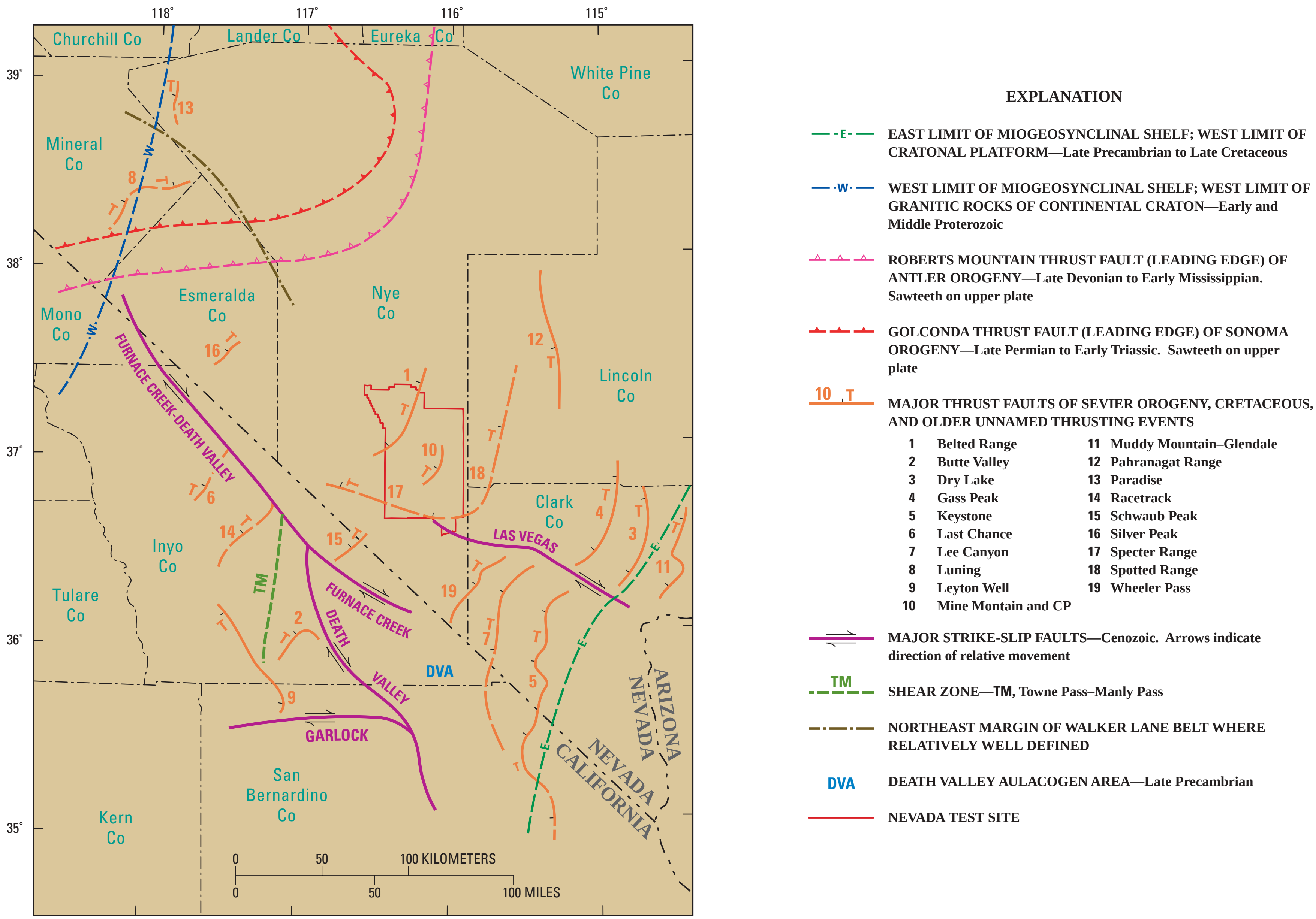

Figure 2. Tectonic features of the Death Valley region and vicinity (modified from Grose and Smith, 1989).

result of these events, more than 10,600 m of Paleozoic and late Proterozoic sediments were deposited over the model area (U.S. Department of Energy, 1997).

Mesozoic Geologic Setting

The Sonoma orogeny (Late Permian and Early Triassic time) resulted in the overthrusting of deep-ocean siliceous volcanic rocks toward the continent. Structures associated with the Sonoma orogeny occur mainly in the northwestern part of the Death Valley region (fig. 2). These events created scattered terranes of lower Mesozoic metasedimentary and metavolcanic rocks. The Sevier orogeny (Middle Jurassic and Late Cretaceous time) affected the entire area by contraction with regional detachments and was highlighted by north-south-trending thrust faulting (including the Pahranagat Range, Gass Peak, Lee Canyon, and Keystone thrusts within this study area) and simultaneous intrusions of granites of Mesozoic age throughout the Death Valley region (Grose and Smith, 1989) (fig. 2). Wernicke and others (1988) have documented that some of this thrusting activity may be as old as the Permian.

Tertiary and Quaternary Geologic Setting

In contrast to earlier compressional tectonism, regional uplift, erosion, volcanism, and extension occurred in the Tertiary. As a result, the Death Valley region now includes numerous north-south-trending valleys containing continental alluvial, paludal, and colluvial materials that are interstratified with lava flows, tuffs, and tuffaceous sediments. The study area underwent intense volcanism during the middle to late Tertiary period and was heavily scarred by massive volcano-tectonic and caldera depressions and voluminous ash flows of the Southwestern Nevada Volcanic Field (SWNVF) (Byers and others, 1976; Sawyer and others, 1994). Successive eruptions produced at least seven large, partially overlapping calderas, which were filled with syneruptive welded tuffs and posteruptive lava flows and which blanketed surrounding older rocks with vast deposits of tuff (U.S. Department of Energy, 1997). The SWNVF has significantly affected parts of the area either by altering or completely removing the preexisting rocks. Meanwhile, water levels in pluvial lakes rose and fell in response to climate fluctuations, and deposition of basin-fill material continued. Modern alluvial basins have been filled with as much as 3,000 m of coarse gravel, sand, and localized deposits of playa silt and clay (Grose and Smith, 1989).

Tertiary and Quaternary Tectonic Setting

Superimposed on the earlier pre-Tertiary structural features, the area in and around the NTS began to be pulled apart along normal and strike-slip faults associated with the formative stages of the modern Basin and Range (U.S. Department of Energy, 1997). Together with the volcanic features, these attributes dominate the topography and physiography of the present day study area (Grose and Smith, 1989). According to Dickinson and Snyder (1979), basin and range deformation occurred in two phases. The first phase began during late Eocene time and ended during middle Miocene time and is associated with the deposition of silicic volcanic rocks. The second phase of extensional tectonics was characterized by reduced volcanic activity and was important in shaping present-day topography. Late Cenozoic tilting and warping are also evident (Grose and Smith, 1989). Tectonic activity in the Basin and Range Province has continued to historical times, as indicated by historical faulting in the study area. Carr (1984) suggested that basin and range deformation has decreased in the last few million years because the amount of offset along normal faults decreases near the surface.

The basin and range tectonics are superimposed on the Walker Lane Belt, a NW/SE-trending, right-lateral, strike-slip shear zone located near the southern Nevada-California border (Locke and others, 1940; Longwell, 1960; Stewart, 1971, 1978). The Walker Lane Belt is part of a megastructure that crosses the Basin and Range Province from Texas to Oregon (Carr, 1990). The Walker Lane Belt separates the NW/SE structural-physiographic trends in the southwestern Great Basin, east of the Sierra Nevada, from the predominantly north-south trend of the more typical basin and range structure. The Walker Lane Belt has long been recognized as an area of active faulting containing patterns of faults that are anomalous with respect to the typical fault patterns in the Great Basin (Stewart, 1988). The Walker Lane Belt is dominated by strike-slip rather than dip-slip faulting; except for caldera structures, large vertical displacements are not characteristic (Carr, 1990). The Las

Vegas Valley shear zone and the Furnace Creek–Death Valley fault system (fig. 3) are major structural features associated with the Walker Lane Belt.

Within the study area, structural trends, styles, and tectonic activity (Carr, 1990) of the southern Great Basin are diverse. Carr divided the area into three major structural-physiographic subsections: the Inyo-Mono, the Walker Lane Belt, and Basin and Range (fig. 3). Within these subsections are two NE/SW-trending structural zones: the Spotted Range–Mine Mountain zone and the Pahranagat shear zone (fig. 3). Winograd and Pearson (1976) refer to a major potentiometric trough. The location of the trough is probably structurally controlled (Winograd and Thordarson, 1975, p. C71–C74) and is roughly coincident with part of the Spotted Range–Mine Mountain zone.

In addition to the Spotted Range–Mine Mountain zone and the Pahranagat shear zones, the Walker Lane Belt also contains a number of somewhat less-defined NE/SW-trending structural zones. Because

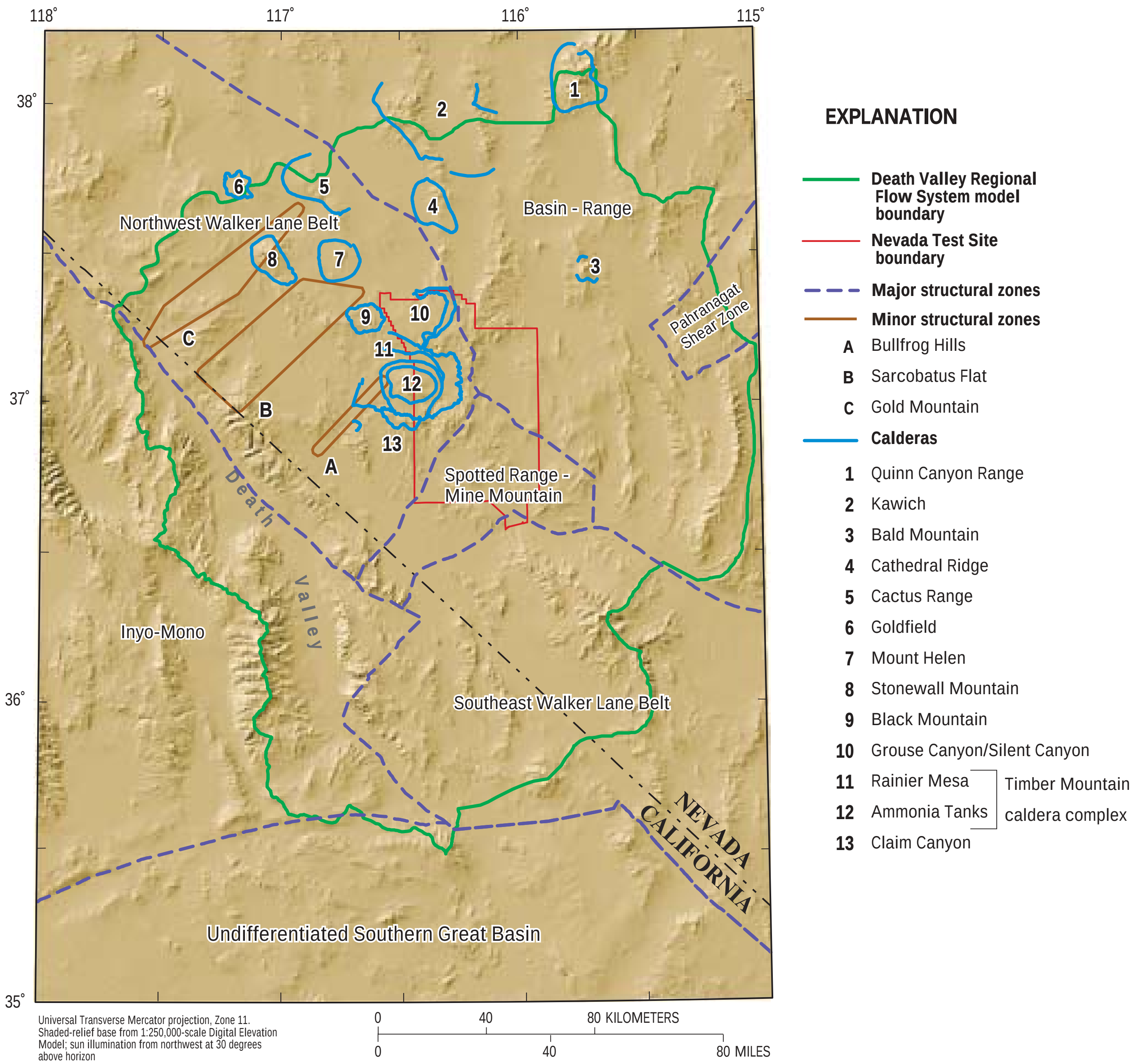

Figure 3. Structural-physiographic subsections of the southern Great Basin (modified from Carr, 1990, and Potter and others, 2002).

they contain highly fractured rocks with potentially large transmissivity, these less-defined zones may influence regional ground-water flow patterns (Faunt, 1994; Carr, 1984). These less-defined zones include: NE/SW-trending structural lineaments from the Bullfrog Hills across the Timber Mountain caldera complex which consists of the Rainier Mesa and Ammonia Tanks calderas (fig. 1; fig. 3,A), a similar trend from the southern Sarcobatus Flat to Black Mountain Caldera (fig. 1; fig. 3,B), and a NE/SW structural-topographic trend from Death Valley through the Gold Mountain–Slate Ridge area to Stonewall Flat (fig. 1; fig. 3,C).

HYDROGEOLOGIC UNITS

In this report, the rocks and deposits forming the framework for a ground-water flow system are termed hydrogeologic units. A hydrogeologic unit has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics. The physical characteristics of the region were used to classify the rocks and deposits into hydrogeologic units. Although all the major geological features are retained, many of the smaller geologic units were grouped into larger entities by generalizing both lithologic and hydrologic properties of the bedrock and basin-fill units.

Geologic formations of hydrologic significance in the subsurface and vicinity have been grouped into major hydrogeologic units by Winograd and Thordarson (1975). The entire sequence of hydrogeologic units may not be present in parts of the study area. Their absence may be due to lack of deposition, normal faulting, and melting and replacement from pluton or caldera formation. Parts of the sequence may be repeated due to faulting.

In competent rocks, the distinction between aquifers and confining units is generally related to observations and assumptions of the degree to which stratigraphic units tend to be fractured. This fracturing is both primary (such as cooling joints in volcanic rocks) and tectonic. The major units, defined by Winograd and Thordarson (1975), from oldest to youngest are the lower clastic aquitard (now termed the lower clastic confining unit), the lower carbonate aquifer, the Eleana confining unit (now termed the upper clastic confining unit), the upper carbonate aquifer, the tuff aquifers (now termed the volcanic aquifers) and volcanic aquitards (now termed the volcanic confining units), and the alluvial aquifer. The lower clastic confining unit forms the hydraulic basement and is generally present beneath the other units except in caldera complexes. The lower carbonate aquifer is the most extensive and transmissive aquifer in the region. It is present in most of the area, although it does not control ground-water flow within the caldera complexes. The upper clastic confining unit is present in the north-central section of the NTS and restricts flow between overlying and underlying units; the unit is associated with many of the steep gradients in and around the NTS. The volcanic aquifers and the volcanic confining units form a stacked series of alternating aquifers and confining units in and around the SWNVF (Laczniak and others, 1996). The volcanic aquifers are moderately transmissive and are saturated in the western sections of the NTS. The alluvial aquifer forms a discontinuous, albeit important, aquifer in the region.

The zones of saturation may be regional, semi-perched, or perched. Regional ground-water flow occurs primarily within the lower carbonate aquifer and the volcanic aquifers. Perched ground water is present locally throughout the NTS and occurs locally within the tuffs wherever confining units compose ridges or hills that lie above the regional zone of saturation (Winograd and Thordarson, 1975, p. C49–C50)

The hydrogeologic units contained in the framework model represent a combination of the hydrogeologic units contained within the YMP HFM (D’Agnese and others, 1997, p. 17–20) and the hydrogeologic units contained in the UGTA Phase I model (U.S. Department of Energy, 1997). Both collections of hydrogeologic units were loosely based on the hydrogeologic units defined by Winograd and Thordarson (1975). Table 1 presents the set of units used in both models and the resulting units used in the Death Valley model described in this report, including thrust-faulted units. Figure 4 shows the ground-surface (outcrop) distributions of hydrogeologic units, with some combined to aid the reader. Details of the hydrogeologic units are provided in the “Description of the Three-Dimensional Hydrogeologic Framework Model” section.

Table 1. Hydrogeologic units from top to bottom for hydrogeologic framework models

[Figure 4 shows thrusted units combined into the main unit and all volcanic units combined into “Tertiary Volcanics”; units are presented in stacking order, from top to bottom, for the hydrogeologic framework model; Abbreviations: UGTA, Underground Test Area; YMP, Yucca Mountain Project]

Hydrogeologic units	UGTA Units (U.S. Department of Energy, 1997)	YMP Units (D'Agnese and others, 1997)	Description of primary components
QTal	AA	QTvf	alluvium/valley fill
QTp	---	Qp	playa deposits
VU	VU	QTv, Tv	undifferentiated volcanic rocks
VA	VA	QTv, Tv	volcanic aquifer – southern Nevada Test Site
VCU	VCU	QTV, Tv	volcanic confining unit – southern Nevada Test Site
TMA	TMA	QTv, Tv	Timber Mountain aquifer
TC	TC	QTv, Tv	Paintbrush/Calico Hills tuff cone
TCB	TCB	QTv, Tv	Bullfrog confining unit (nonwelded tuffs)
TBA	TBA	QTv, Tv	Belted Range aquifer (welded tuffs)
TBCU	TBCU	QTv, Tv	basal confining unit (nonwelded tuffs)
TBQ	TBQ	QTv, Tv	basal aquifer (welded tuffs)
TSDVS	TSDVS	Tvs	Tertiary sediments/Death Valley section
Mvs	---	Mvs	Mesozoic volcaniclastic and sedimentary rocks
Mvs_LC	---	Mvs	Mesozoic volcaniclastic and sedimentary rocks – Lee Canyon thrust
Mvs_KS	---	Mvs	Mesozoic volcaniclastic and sedimentary rocks – Keystone thrust
UCA	LCA3	---	upper carbonate aquifer
UCCU	UCCU	ECU	upper clastic confining unit
LCA	LCA	P2	lower carbonate aquifer
LCCU	LCCU	P1, pCgm	lower clastic confining unit
LCA_T2	LCA_T1	---	lower carbonate aquifer – Schwaub Peak, Specter Range, and Wheeler Pass thrusts (upper plate)
LCCU_T2	LCCU_T1	---	lower clastic confining unit – Schwaub Peak, Specter Range, and Wheeler Pass thrusts (upper plate)
LCA_LC	---	---	lower carbonate aquifer - Lee Canyon thrust
LCA_GP	---	---	lower carbonate aquifer - Gass Peak thrust
LCA_T1	LCA_T2	---	lower carbonate aquifer - Schwaub Peak, Specter Range, and Wheeler Pass thrusts (lower plate)
LCCU_GP	---	---	lower clastic confining unit - Gass Peak thrust
LCCU_T1	LCCU_T2	---	lower clastic confining unit - Specter Range and Wheeler Pass thrusts (lower plate)
pCgm	LCCU	pCgm	Precambrian granites and metamorphic rocks
TJi	I	TJg	Tertiary-Jurassic intrusives

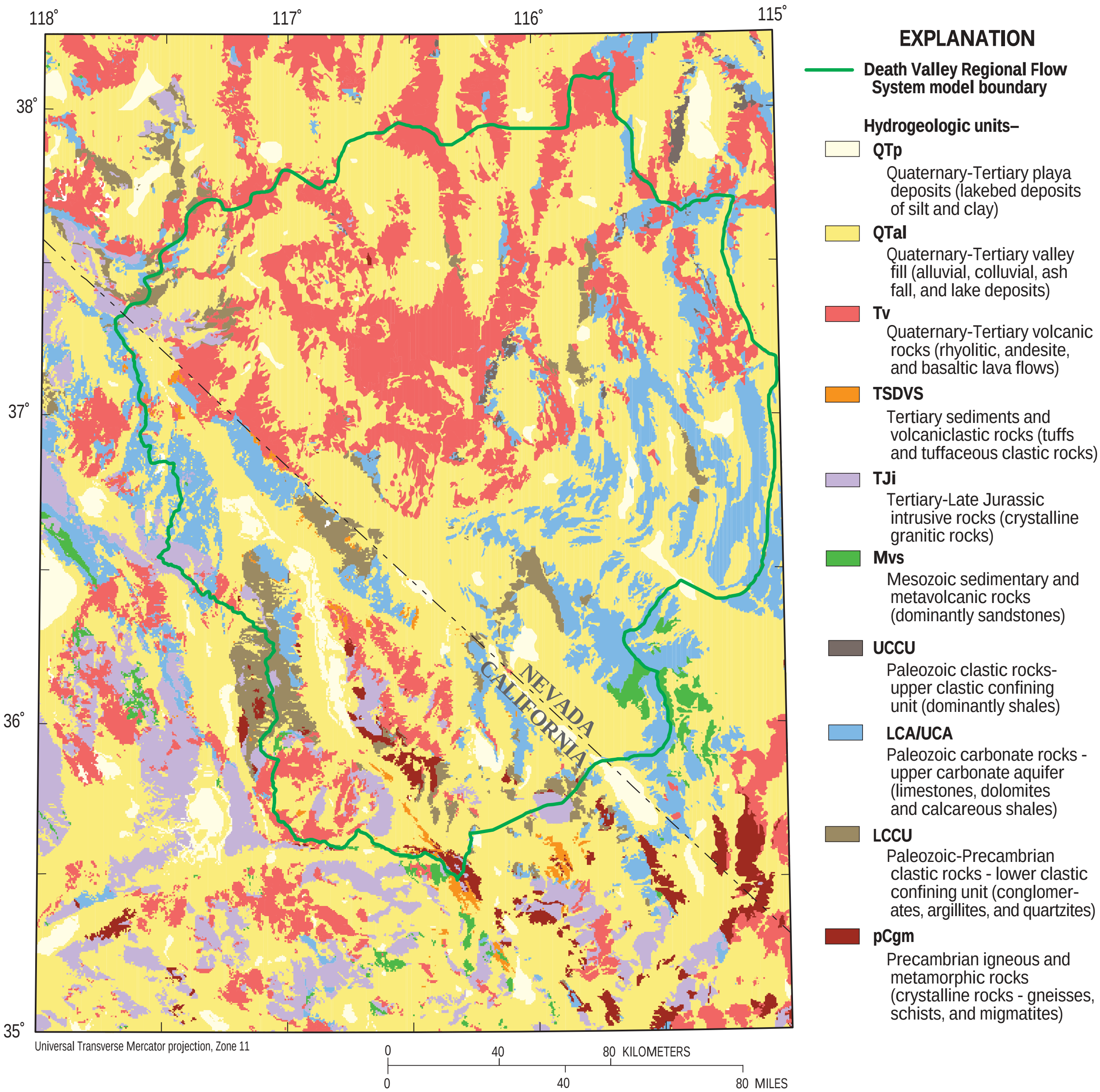

Figure 4. Outcrop area of hydrogeologic units of Death Valley region (modified from Faunt and others, 1997).

CONSTRUCTION OF THREE-DIMENSIONAL DIGITAL FRAMEWORK MODEL

The 3D HFMs developed for both the UGTA and YMP programs were based on an evaluation of existing data by many geologists. The methodology used in both cases consisted of data compilation, conceptual framework model development, and digital framework model development.

The merged 3D HFM was developed using the same approach. The HFM construction began with the assembly of data: digital elevation models, geologic maps, cross sections, borehole information, the YMP hydrogeologic framework model, and the UGTA Phase I geologic model gridded interpretations. Data from digital elevations models, geologic maps, and cross sections were used to supplement data from the UGTA Phase I geologic model. Each of these data types were originally manipulated by a standard GIS;

however, the merging of these diverse data types to form a single coherent 3D digital model required more specialized software products. All horizontal coordinate values were reported in the Universal Transverse Mercator projection Zone 11 coordinates, while the vertical coordinates were reported in National Geodetic Vertical Datum of 1929 in meters.

Construction of the 3D hydrogeologic framework model involved six main stages:

1. A digital elevation model was combined with geologic maps to provide a series of points locating the outcropping surfaces of individual geologic formations.
2. Cross sections and borehole logs were properly located in 3D space to define locations of hydrogeologic units and faults in the subsurface.
3. Gridded surface interpretations for each of the hydrogeologic units were extracted from the UGTA Phase I geologic model (U.S. Department of Energy, 1997). These surfaces provided the central portion of the HFM. Outcrop, borehole and cross-section data were used to fill in where gridded surface interpretations did not exist.
4. A map depicting the trace of faults with significant offsets was developed for the study area.
5. Surface and subsurface data were interpolated using sophisticated gridding algorithms to define surfaces representing the tops of hydrogeologic units. These surfaces incorporate the effects of faults through offsets in their altitudes.
6. Using appropriate stratigraphic principles, a three-dimensional hydrogeologic framework model was developed to represent the stratigraphic and structural relations by stacking hydrogeologic units in stratigraphic order.

Tools for Hydrogeologic Framework Modeling

Traditional two-dimensional geographic information systems (GIS) are inadequate because of the three-dimensional aspects of hydrogeologic data but can be used as a base from which needed extensions are made. Due to the complex nature of the problem and the many types of data, several different GIS's and framework modeling tools were used during this study.

Manipulation of mapped GIS data (digital elevation model, outcrop, boreholes/wells, and so forth) was accomplished using ESRI’s ARC/Info GIS software, while cross-sectional hydrogeologic data were manipulated using Intergraph Corporation’s Modular GIS Environment (MGE). Gridded surfaces were constructed using the Petrosys Ltd. gridding software. The 3D volumetric HFM was constructed using the Stratamodel Stratigraphic Geocellular Modeler (SGM).

Visualization of the various digital models produced throughout this process was accomplished by using the capabilities of the various software products. Arrays representing hydrogeologic unit geometries of the numerical ground-water flow model were developed from the SGM representation of the regional hydrogeologic framework. These arrays were provided to the numerical ground-water model to define the distribution of the hydrogeologic units.

Use of Outcrop Data

A surface hydrogeology map (fig. 4) was constructed by simplifying geologic units into hydrogeologic units. Details are described by Faunt and others (1997). Stewart and Carlson (1978) served as the basis of the Nevada portion of regional structural and stratigraphic data. California Division of Mines and Geology’s 1:250,000-scale map sheets were used for the California portion (Jennings, 1961; Jennings and others, 1962; Strand, 1967; Streitz and Stinson, 1974).

The geometry of hydrogeologic unit outcrops was defined by integrating the hydrogeologic map and the DEM. The DEM defined an array of points in which each point was located by its x,y, and altitude (z) coordinates. Points falling within each outcrop area were tagged as the appropriate hydrogeologic unit. The resulting point map was exported as a series of ASCII files, each containing a series of x,y,z points for a single hydrogeologic unit.

Use of Cross-Section Data

The central part of the HFM was composed of the UGTA Phase I grids augmented with borehole and mapped outcrop information; in order to extend the hydrogeologic units beyond the limits of the UGTA Phase I model, it was necessary to incorporate cross sections from Grose (1983) and Grose and Smith (1989). The interpretive cross sections were developed at 1:250,000 scale. The sections were based on the hydrogeologic units defined by Bedinger and others (1989a) and reflect a consistent interpretation of regional structural style. The YMP hydrogeologic units (D'Agnese and others, 1997) and the UGTA Phase I hydrogeologic units (U.S. Department of Energy, 1997) were combined into the hydrogeologic units used for this study (table 1). Of the 32 cross sections developed by Grose (1983) and Grose and Smith (1989), only 14 were used in the HFM. These sections extended outside the UGTA Phase I geologic model. The following Grose (1983) and Grose and Smith (1989) cross sections were used in this work: NCT–8, NCT–9, CT–1, CT–2, CL–5, NCT–12, CL–2, NCL–2, NCT–10, NCT–3, CL–4, NT–8, NCT–1, and NCT–2. Cross-section data that extended into the UGTA Phase I geologic model area (NT–8, NCT–1, and NCT–2) were deleted from the data set before gridding to retain the UGTA geologic interpretation. The 52 cross sections developed as part of the UGTA Phase I geologic model (U.S. Department of Energy, 1997) were not used explicitly in the framework model. Because the gridded interpretations from the UGTA Phase I geologic model were used and these grids incorporated the cross-section interpretations, their use is implied in the framework model.

All cross sections used in the framework were constructed as digital files for use in the Intergraph MGE software. Map locations of each section trace were digitized and registered to geographic coordinates. The software allowed the sections to be placed accurately in 3D space by merging and scaling each section to fit its digitized trace. Each hydrogeologic unit was defined by a code within the database. The sections were then linked to this database or attributed by pointing to each displayed hydrogeologic unit top and keying in the appropriate hydrogeologic unit database code. This action formed an attributed section. Each attributed section was queried to determine the altitudes of points spaced every 500 m horizontally along the top of each hydrogeologic unit. These points were posted in their proper 3D geographic location. After all sections and hydrogeologic units had been queried, the database files were exported as a series of ASCII files, each containing x,y,z coordinates for a single hydrogeologic unit.

Use of Lithologic Borehole Data

Approximately 700 borehole logs in the region contain lithologic information that was used to help correlate between the sections. The geologic units shown in the borehole records were reclassified into the hydrogeologic units, and the locations defining the top of each hydrogeologic unit were extracted and placed in a separate file. Initially, these values defined location by x and y borehole coordinates and depth below the land surface. In order to be consistent with the other altitude data (DEM) being used in the HFM, the altitude of the top of each hydrogeologic unit was determined by subtracting its depth from the DEM at the borehole/well location. The x,y,z coordinates derived from all boreholes for each hydrogeologic unit were placed in individual ASCII files.

Use of UGTA Phase I Geologic Model Data

The UGTA Phase I geologic information in the form of gridded surfaces was given priority because of its detail and recent interpretation. Gridded interpretations from the UGTA Phase I geologic model were used in the interior of the framework model. The UGTA Phase I geologic model grids contained the same information as the cross sections (U.S. Department of Energy, 1997) from which they were derived. Because of this, the UGTA cross sections were not used explicitly. These data were exported from Intergraph MGE terrain model binary files to x,y,z ASCII files. The grid spacing of the UGTA Phase I geologic model surfaces was 2,000 m, somewhat larger than the 1,500-m spacing used in this HFM.

Interpolation of Structural Surfaces for Hydrogeologic Units

The surfaces defining the locations of the top of each hydrogeologic unit were interpolated and extrapolated from available land-surface and subsurface data points, while taking into account fault discontinuities. The Petrosys, Ltd., gridding system and fault-handling package was used to interpolate the hydrogeologic surfaces defined by the ASCII files containing x,y,z points from cross sections, borehole/well logs, surface exposures, and UGTA Phase I geologic model grids. Table 2 presents the various data types used to construct each hydrogeologic unit surface.

The regional geologic maps showed far too many faults to be processed during the 3D model construction (fig. 5). Faults were examined to determine those that appeared significant to both the 3D

Table 2. Data sources for Death Valley regional ground-water flow system hydrogeologic framework model

[Abbreviations: HFM, hydrogeologic framework model; UGTA, Underground Test Area]

HFM units	UGTA grid data	Outcrop data	Borehole data	Cross-section data
QTal		X		
QTp		X	X	
VU	X	X		
VA	X			
VCU	X			
TMA	X			
TC	X			
TCB	X			
TBA	X			
TBCU	X			
TBQ	X			
TSDVS	X	X		X
Mvs		X	X	
Mvs_LC		X		X
Mvs_KS		X		X
UCA	X		X	
UCCU	X	X	X	
LCA	X	X	X	X
LCCU	X	X	X	X
LCA_T2	X			
LCCU_T2	X			
LCA_LC		X		X
LCA_GP		X		X
LCA_T1	X			
LCCU_GP		X		X
LCCU_T1	X			
pCgm		X		X
TJi	X	X	X	X

framework and numerical flow model definitions. Faults were eliminated if the amount of displacement was not great enough to juxtapose different hydrogeologic units. Faults were considered insignificant to the 3D model construction process if their mapped traces were shorter than 5,000 m, or if they had less than 750 m of vertical offset, or if they did not appear to cause offsets of any units in the cross sections. Named regional faults were retained, even when they did not meet these criteria.

The simplified fault-trace map (fig. 6) was compared with the faults shown on the cross sections. Some fault traces on the map were extended where necessary to connect to section faults, and some faults shown on the sections required interpretation of the fault trace when they lacked mapped surface expressions. When fault selection and construction were completed, approximately 300 faults remained for constructing the framework model.

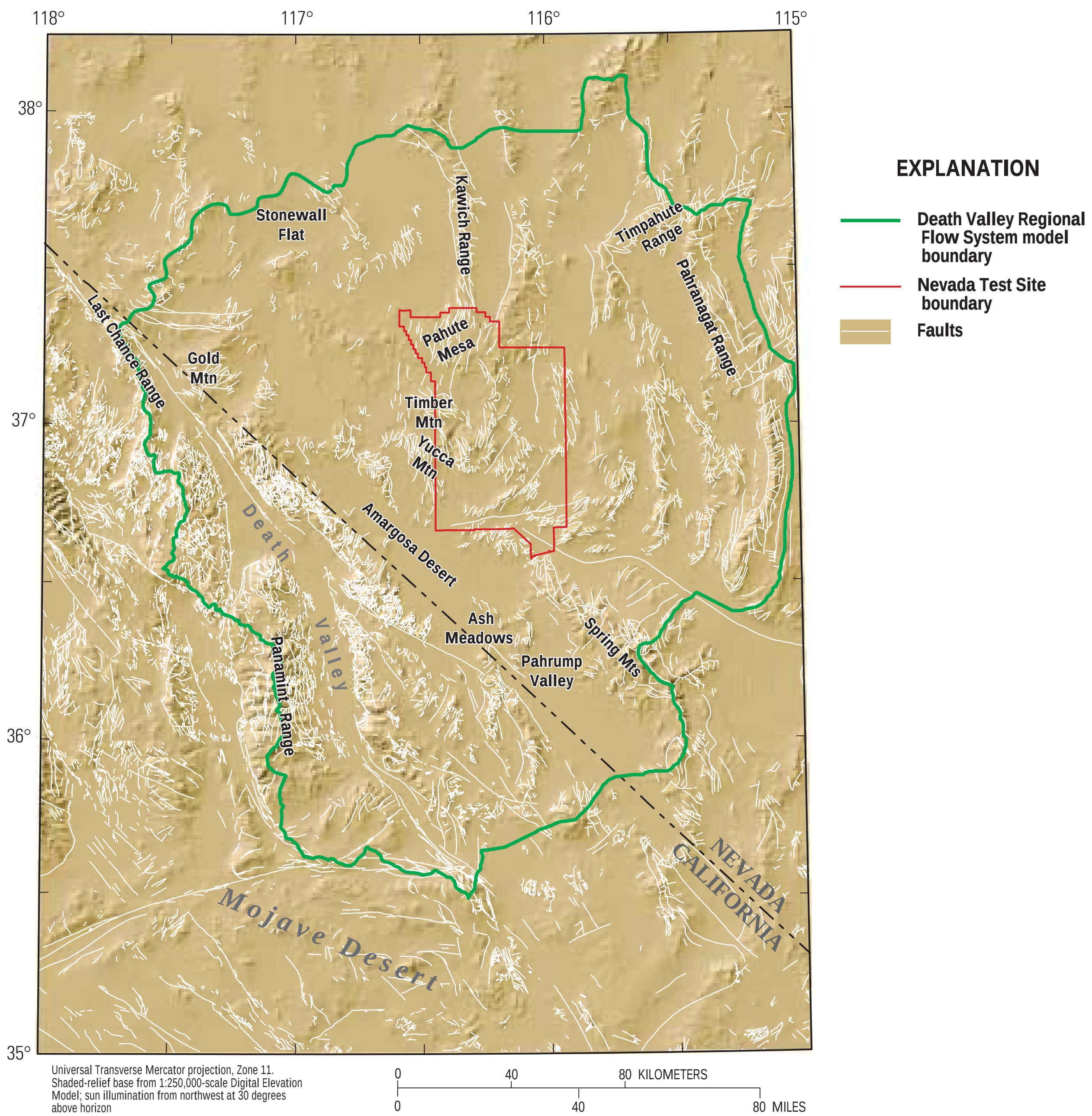

Figure 5. Traces of mapped faults in the study area (modified from D'Agnese and others, 1997).

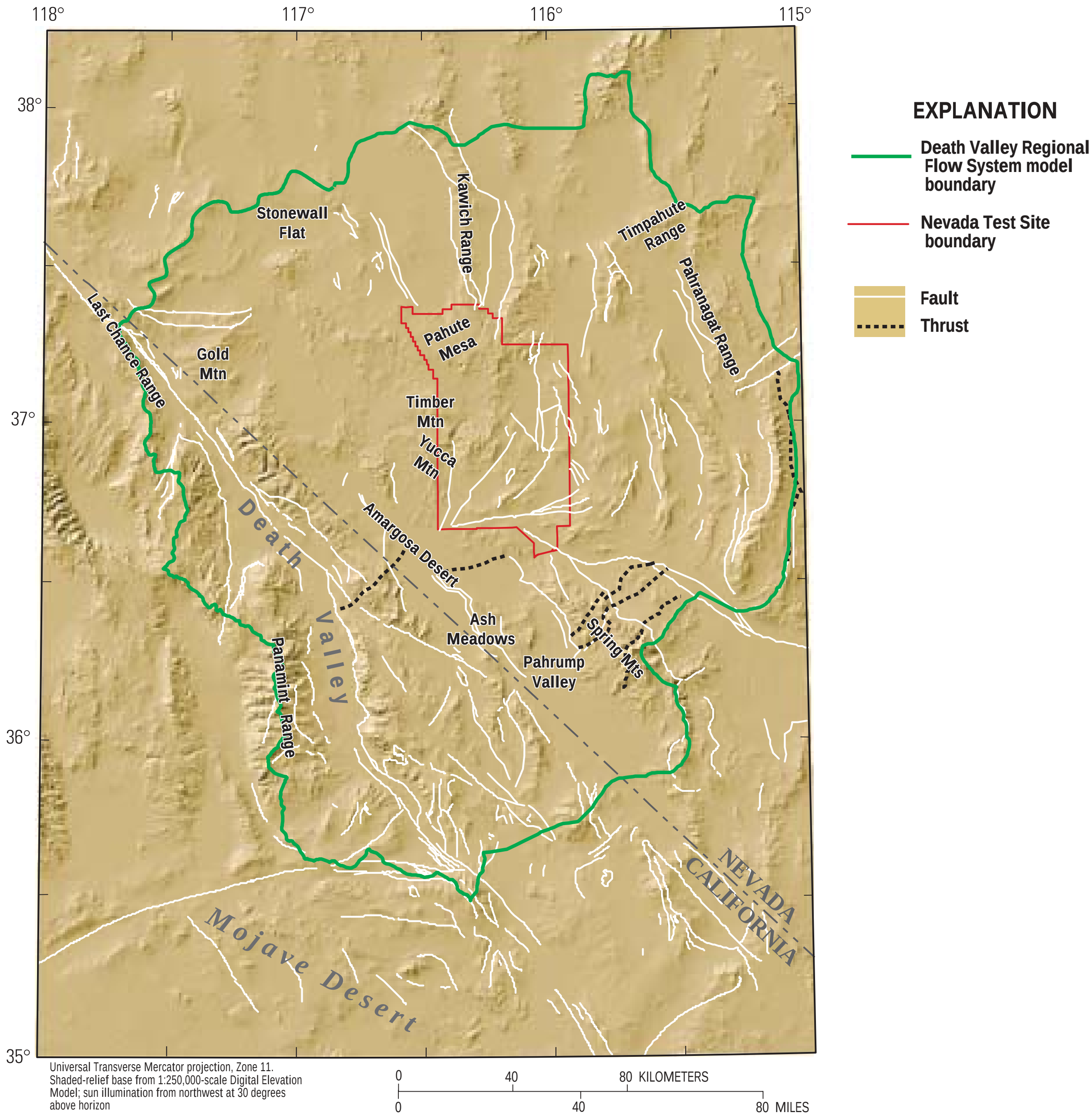

Figure 6. Traces of faults used to create hydrogeologic framework model (modified from D'Agnese and others, 1997).

A hybrid gridding algorithm was used to calculate the grid. The hybrid gridding algorithm is a combination of the minimum curvature and a first-order least-squares algorithm. It uses first-order least squares within one grid cell of a fault and minimum curvature to calculate all other nodes. The minimum curvature process involves several iterations to converge on an optimal grid definition by fitting a minimum curvature spline through the data points at either side of the point being determined, preserving the rate of change of slope. The first-order least-squares gridding process fits a plane through the data points at either side of the point being determined. Faults were assumed to be vertical, and the fault-trace map was used in all iterations of the gridding process (fig. 6). The first iteration of the hybrid gridding process generates a coarse grid that is progressively refined. During each iteration, the goodness-of-fit between the grid and the data was monitored to determine if more iterations were necessary. The effect of this iterative process caused a trendlike solution in areas of sparse data, while the grid accurately represented existing data points. A grid for the top surface of each hydrogeologic unit in the framework model was defined with an increment of 1,500 m; this resulted in a grid with 180 columns and 206 rows.

A "clipping" distance was applied to each gridded surface to limit the extent of extrapolation beyond the distribution of the data used to construct the gridded surface. These clipping distances varied for each interpreted gridded surface with assumed extents of the units and data density. Professional judgment also provided input for manual editing of the gridded surfaces to clip back areas where the gridding algorithms overextrapolated the hydrogeologic unit extents. As an example, figure 7 presents a perspective view of the gridded surface of the lower carbonate aquifer.

The quality of individual gridded surfaces depends on the available defining data points. Some hydrogeologic unit surfaces were relatively well defined by numerous well-distributed data points. Other surfaces, including those units that crop out in few places, were less well defined and were extrapolated from sparser data. In general, the lower a unit is stratigraphically, the less well defined it is.

In areas with higher concentrations of data, the computer-generated contours are generally thought to be acceptable. In areas with sparse data and where the cross sections and land-surface data are relatively far apart, computer-generated contouring is more suspect. In these suspect areas, each grid was examined and compared with gravity data. Manual editing was done to ensure that the grids followed structural trends and honored faults, surface data, and subsurface data.

Development of Three-Dimensional Hydrogeologic Framework Model

The HFM was constructed from the set of interpolated surfaces representing the tops of individual hydrogeologic units. Because these surfaces primarily were developed independently from each other (ignoring geologic interactions), they may extend beyond their actual limits. SGM, which uses geologic rules to help define the geographic extent and intersection of surfaces, was specifically developed to accurately represent stratigraphic and structural relations of sedimentary basins. These relations include onlap and proportional units as well as truncation of units and faulting. The basic hydrogeologic framework was constructed by importing gridded surfaces to define the geologic horizons, discontinuities, and the appropriate stratigraphic sequence.

In the eastern and southern part of the area, the domain contains vertically repeated hydrogeologic units due to thrust faulting. Because of constraints inherent in the software, repeated layers in these thrust plates had to be named and mapped separately. Where units were repeated by thrust faults, two different grids were created for the same hydrogeologic unit, for example, units 5a and 5b in figure 8. A unit extent boundary trace was then added to define an outline for the edge of the thrust sheet. Within this boundary, the hydrogeologic unit altitude values defined unique additional units, which could later be given the same attributes as their corresponding hydrogeologic unit. SGM is not designed to handle the time-stratigraphic emplacement of intrusions. In order to model these features, they were inserted into the SGM model out of their correct time sequence (fig. 8). Therefore, the youngest intrusion represented the lowest ("oldest") deposition surface. Although this did not affect the resulting model, it did affect the order the units were put into the model. Only the geologic units and structures above 4,000 m below sea level were modeled. The resulting model had numerous volumetric units defined by the intersecting hydrogeologic surfaces. Table 1 presents the "stacking" order, from top to bottom, of the framework model.

Description of the Three-Dimensional Hydrogeologic Framework Model

The HFM contains the 3D geometric conceptualization of the Death Valley regional hydrogeologic units. This section describes the geometry of hydrogeologic units as depicted in the HFM. The surface expression of these units is presented in figure 4. The descriptions of the units described below are adapted from IT Corporation (U.S. Department of Energy, 1997).

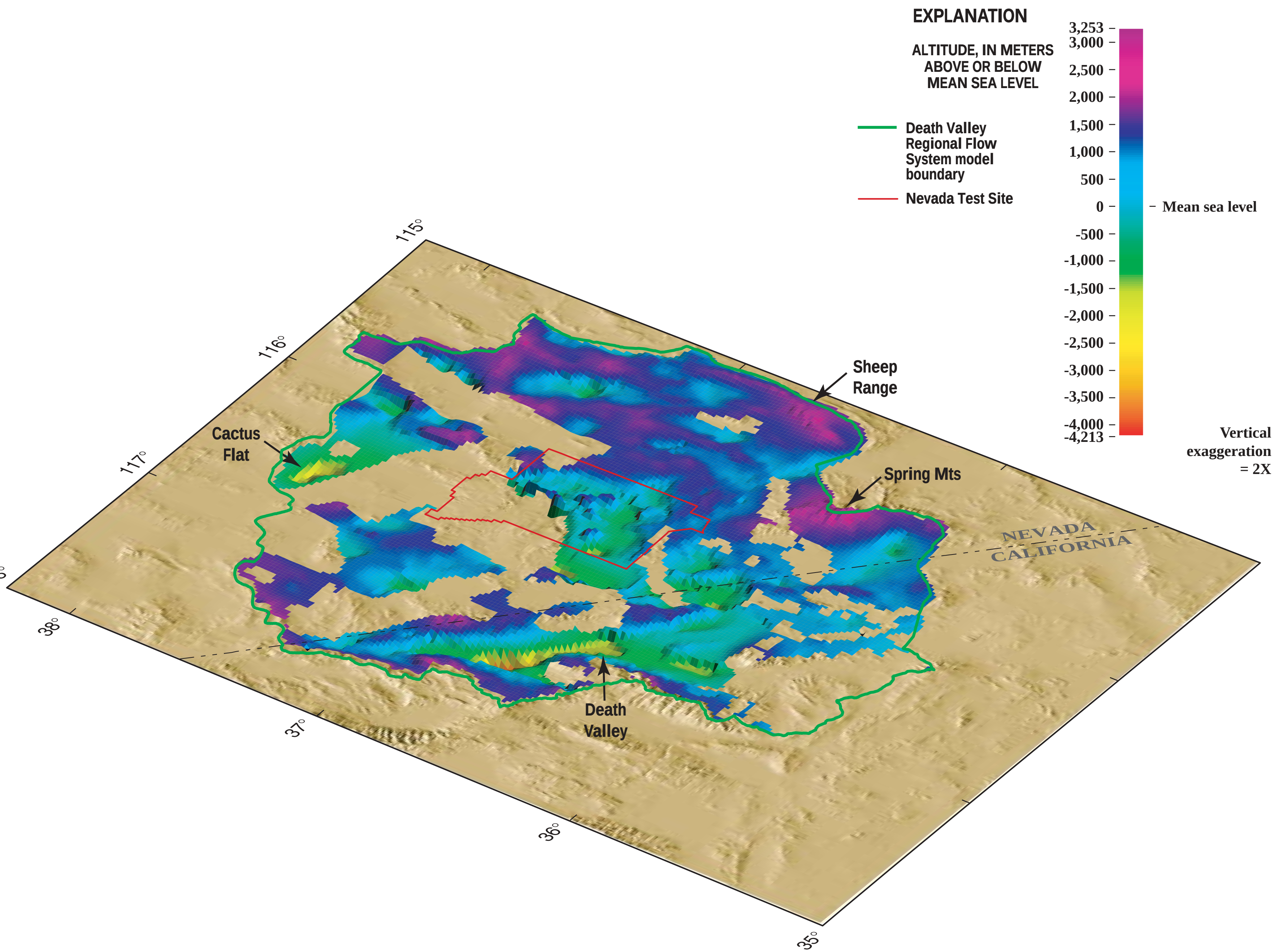

Figure 7. Oblique perspective view of gridded surface of the lower carbonate aquifer (LCA).

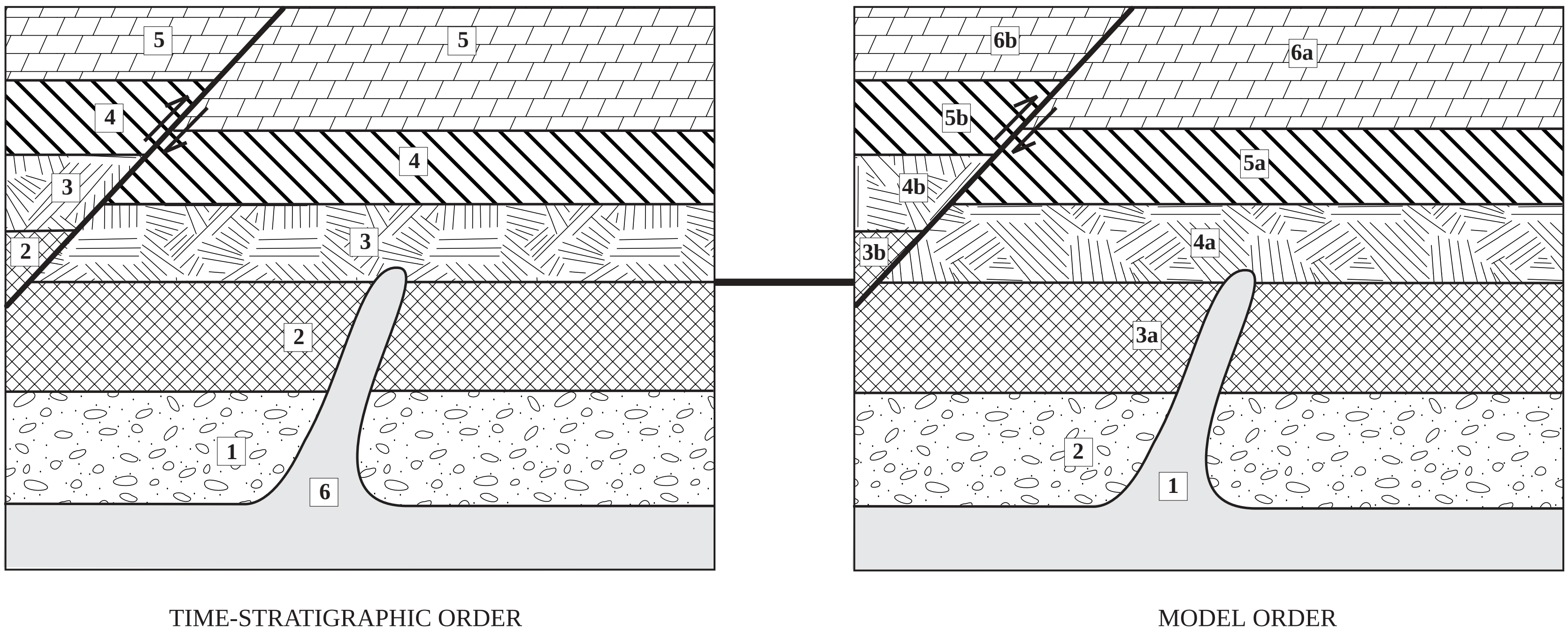

Figure 8. Time-stratigraphic and model order of geologic events (from D'Agnese and others, 1997).

Modifications that were made with this HFM make the gridded surfaces somewhat different than those of the UGTA Phase I geologic model. The greatest difference results from the addition of outcrop data to the gridded interpretations used in the UGTA Phase I geologic model. Because of the smoothed nature of the UGTA Phase I gridded interpretations (2000-m grid spacings) and the emphasis to conform to the geology below the saturated zone, the UGTA Phase I gridded interpretations often do not adequately represent the hydrogeologic units at land surface. This apparently did not create a problem with the information fed into the UGTA Phase I flow model. The addition of mapped outcrop data to the UGTA Phase I gridded interpretations causes the shape and the extents of the gridded surfaces used to construct the HFM to be somewhat different than the UGTA Phase I geologic model grids.

Quaternary-Tertiary Valley-Fill Alluvium (QTal)

The Quaternary-Tertiary valley fill alluvium (QTal) is a heterogeneous mixture of fine-grained playa and lakebed deposits containing evaporites (of limited areal extent), fluvial deposits, heterogeneous debris flows and fan deposits, and volcanic tuffs (Bedinger and others, 1989a). Accordingly, the ground water flowing within these deposits may exhibit matrix flow as a result of the permeable unconsolidated materials and fault- and fracture-controlled flow in consolidated deposits (Downey and others, 1990). The valley fill was accumulated largely in structural basins. As a result, the valley-fill deposits range in thickness from zero at the margins of valleys to several hundred meters in valley lowlands. The fill in many basins is greater than 1,300 m thick and may be as thick as 2,000 m (Bedinger and others, 1989a).

Valley-fill aquifers constitute a regional system because of the similarities between basins and because they are the most developed source of ground water in the region. Well yields within the valley fill seem to be related to physiographic setting (Plume and Carlton, 1988). The hydrologic properties of these deposits can differ greatly over short distances, both laterally and vertically, because of abrupt changes in grain size and consolidation (D'Agnese and others, 1997).

Valley-fill alluvium occurs in the valleys between the ranges in the model area and has a maximum thickness of 4,600 m in the flow model area of the HFM in Pahrump Valley. In the HFM, it tends to be somewhat overrepresented in map view (fig. 9). The gridding algorithm tends to extend grid cells one cell farther where the QTal onlaps onto bedrock units at the edges of basins. This overlapping creates thin accretions of the QTal on the flanks of mountain ranges. Because these extensions are thin and above the water table, they are thought to have very little effect on ground-water flow modeling.

Quaternary-Tertiary Valley-Fill Playa Deposits (QTp)

Quaternary-Tertiary playa deposits (QTp) are relatively homogeneous deposits composed primarily of sand, silt, and clay-sized particles (Denny and Drewes, 1965). The unit not only includes fine-grained playa deposits but also lacustrine limestones and evaporites. Accordingly, the unit can exhibit matrix flow in the permeable unconsolidated deposits and fault- and fracture-controlled flow in consolidated deposits (Downey and others, 1990). The playa deposits were deposited contemporaneously with the younger alluvial sediments. As a result, the deposits grade into each other. In some of the valleys, the unit is several hundred meters thick (D'Agnese and others, 1997).

The playa deposits occur in the topographically low areas of many of the basins in the region and have a maximum thickness of 4,200 m in the flow model area of the HFM in Pahrump Valley. Large playas occur primarily in Death Valley, Pahrump Valley, Amargosa Desert, around Tecopa, Calif., and near Indian Springs, Nev. (Faunt and others, 1997). Because the playa deposits are modeled where outcrop data occur (along with some borehole lithologic data), they tend to fill in the basins where they occur from the land surface to the bottom of the basin (fig. 10). This bottom of the basin was either formed by the base of the HFM (– 4,000 m below sea level) or by units existing deeper in the HFM. This creates a wall of QTp beneath the mapped extent. In some basins, however, the low-dimensional geometry of some playa deposits may need to be refined as more detailed subsurface information and interpretations are obtained.

Volcanic Rocks

Volcanic rocks of the Southwest Nevada Volcanic Field (SWNVF) overlie most of the Paleozoic rocks of the NTS area and major parts of the

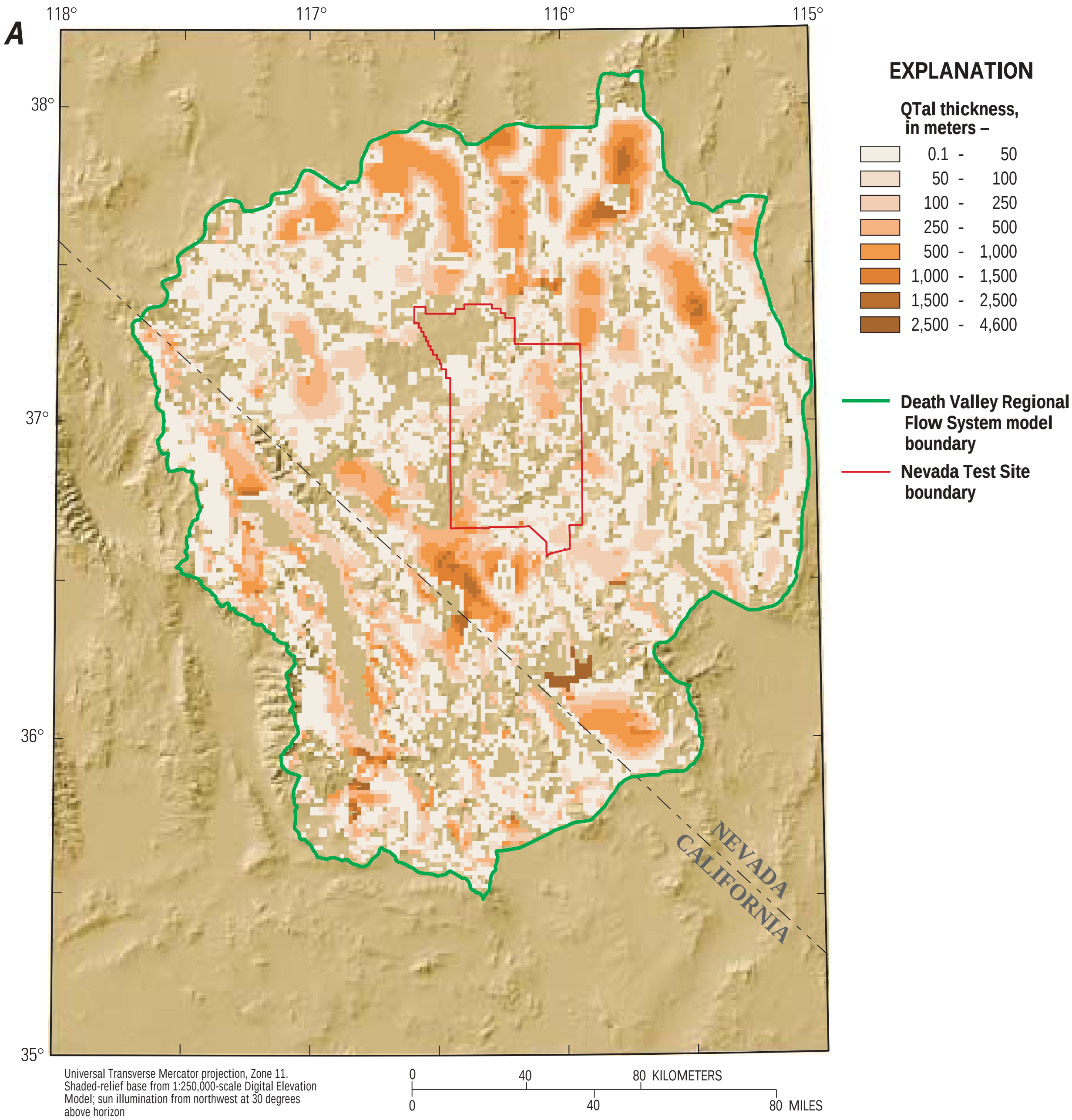

Figure 9. (***A***) Thickness of Quaternary-Tertiary valley-fill alluvium (QTal).

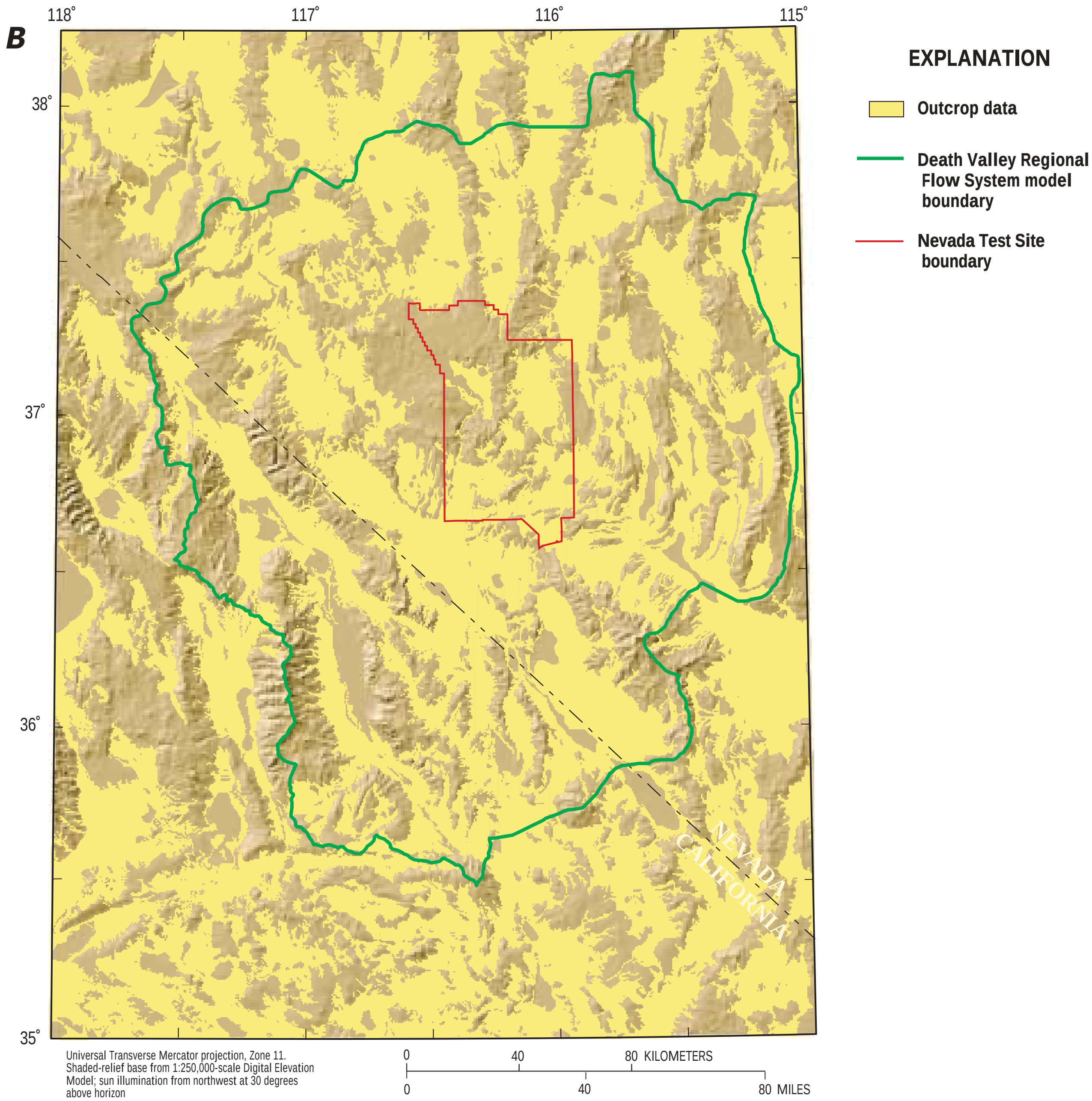

Figure 9–Continued. (***B***) Data sources used to construct gridded surface.

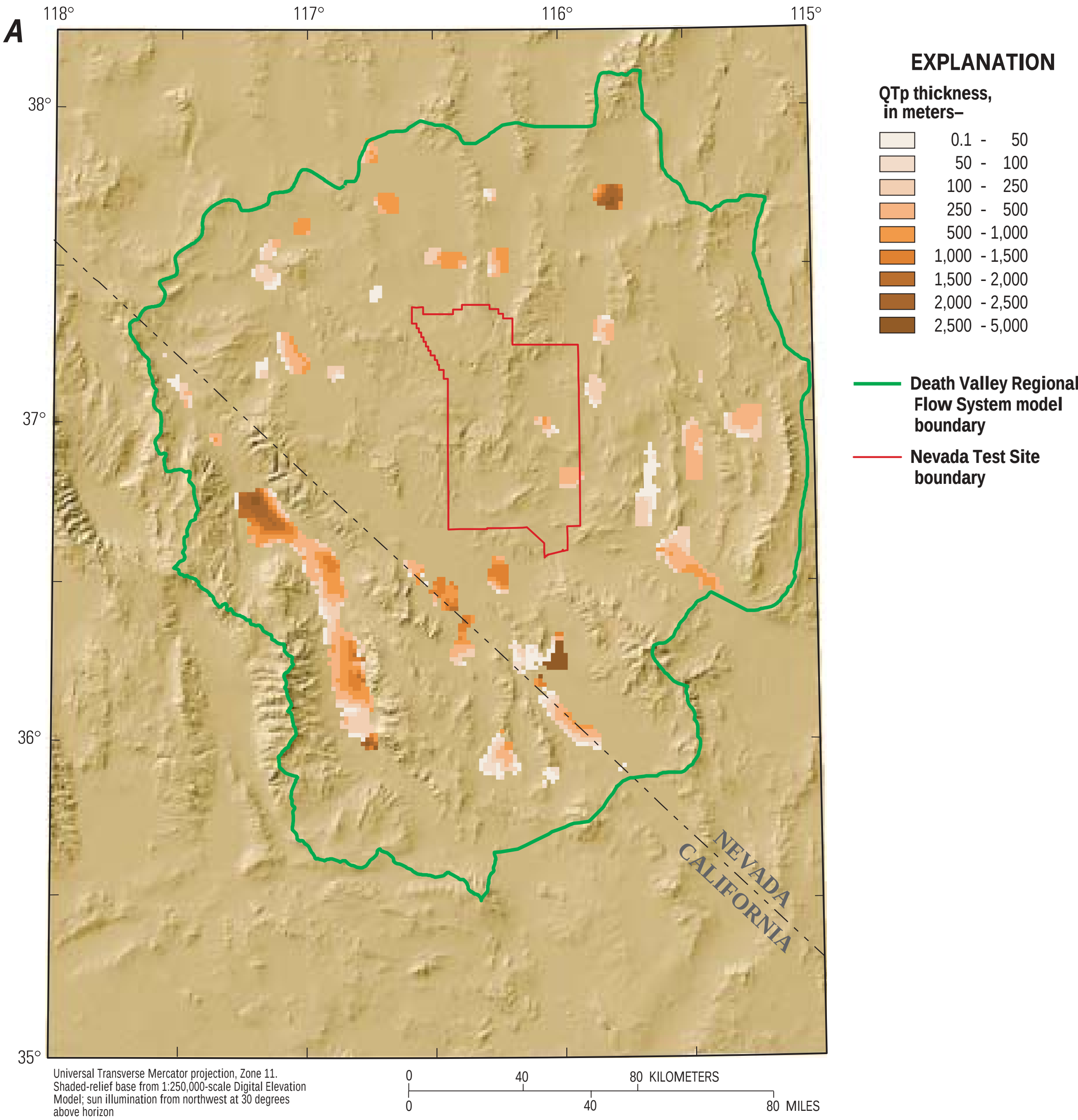

Figure 10. (***A***) Thickness of Quaternary-Tertiary playa deposits (QTp).

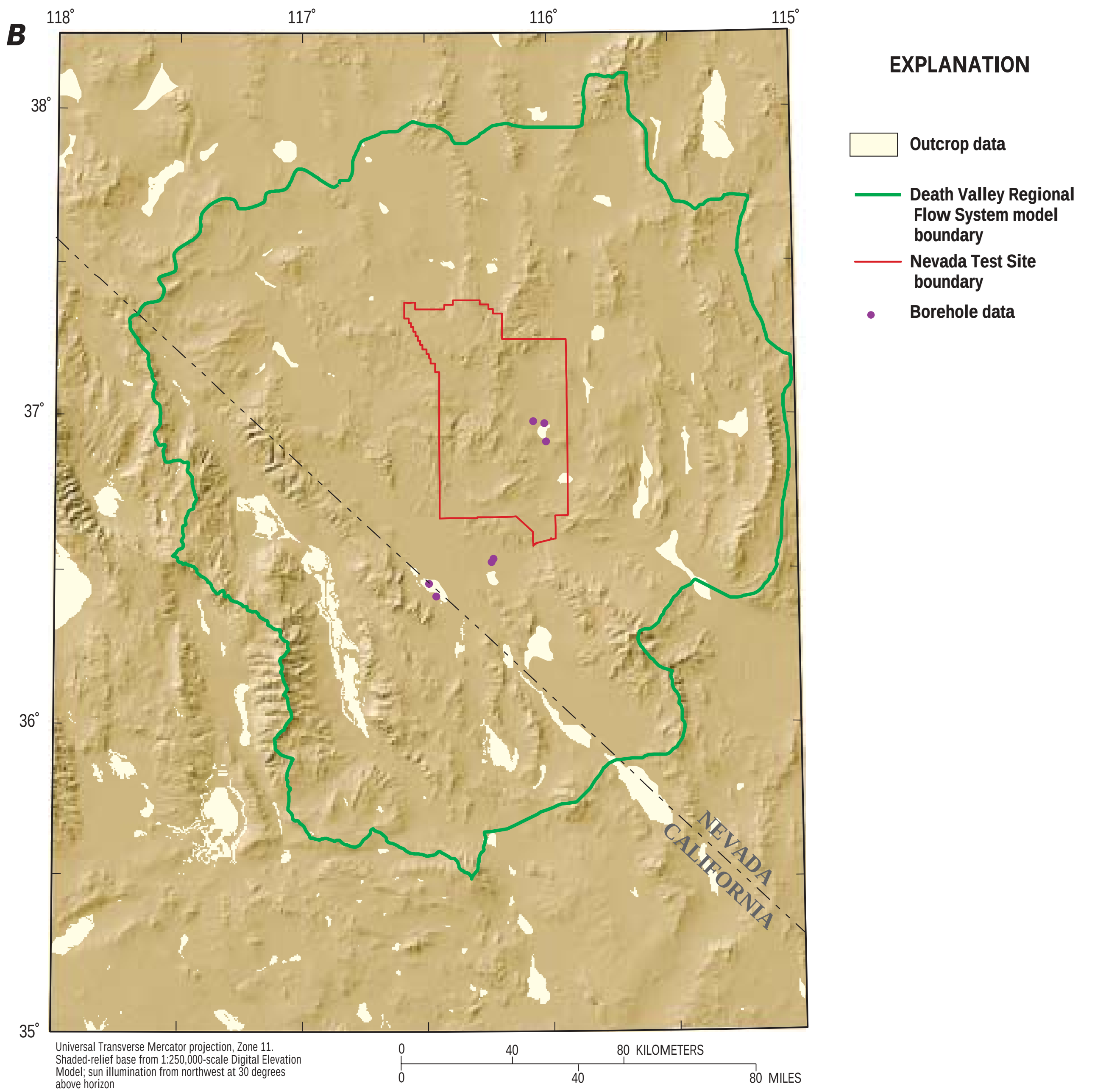

Figure 10–Continued. (***B***) Data sources used to construct gridded surface.

Death Valley region. Volcanic units vary widely in distribution, thickness, lithology, and degree of welding with respect to distance from their source caldera. At most localities, only a partial section is present. Thus, the volcanic stratigraphy is very complex and has been the subject of numerous studies. Stratigraphic nomenclature of the SWNVF can be found in Ferguson and others (1994) and Sawyer and others (1994).

Grouping the Tertiary volcanic rocks into a regional hydrogeologic hierarchy required considerable simplification to be manageable for modeling purposes. Because physical characteristics of the volcanic stratigraphy and the amount of data available on the rocks vary with geographic area, the hydrogeologic differentiation varied across the region. Volcanic units in the UGTA Phase I geologic model were defined by spatial locations—volcanic rocks outside the Nevada Test Site, the southern NTS/Yucca Flat, and the Pahute Mesa/Timber Mountain area (U.S. Department of Energy, 1997). This scheme was retained in the framework model, with additional data to define volcanic units outside the limits of the UGTA Phase I model. The volcanic units, with the exception of the undifferentiated volcanics unit, are represented exclusively by the gridded data from the UGTA Phase I geologic model.

The caldera complexes in the vicinity of Timber Mountain and Pahute Mesa are represented as a series of structural blocks in the framework model, as they were in the UGTA Phase I geologic model (U.S. Department of Energy, 1997). The Timber Mountain caldera complex is composed of the Rainier Mesa and Ammonia Tanks calderas, and the Silent Canyon caldera complex is essentially composed of the Grouse Canyon caldera (fig. 3). The basis for this structural block differentiation is the observation, defined largely on the basis of gravity data, that caldera boundaries coincide with linear basin and range structures in the subsurface due to the extensional nature of the Basin and Range physiographic province (U.S. Department of Energy, 1997). Seventy structural blocks within the SWNVF have been defined. The structural block model for the SWNVF covered an area larger than the Silent Canyon and Timber Mountain caldera complex areas. Within the Pahute Mesa area, there do not appear to be any major discontinuities within the blocks.

Volcanic lithostratigraphic units occurring in each structural block consist of tilted, tapering sequences. Because volcanic stratigraphy and its physical features are genetically related to the location of the units with respect to particular structural blocks and volcanic centers, the hydrogeologic units were defined on the basis of stratigraphic position within the volcanic pile and on lithologic properties related to depositional environment, postdepositional alteration, and degree of welding. Outside the caldera complex, the block model was used as guidance for mapping volcanic hydrogeologic units, but structural relations were taken from the hand-drawn geologic sections (U.S. Department of Energy, 1997).

McKee and others (1999) has interpreted the structure of the caldera complexes as being of the more conventional circular volcano-tectonic model. McKee and others (1999, p. 1) summarize their interpretation of the Silent Canyon caldera complex as follows:

> The structural framework of Pahute Mesa, Nevada is dominated by the Silent Canyon caldera complex, a buried, multiple collapse caldera complex. Using the boundary surface between low density Tertiary volcanogenic rocks and denser granitic and weakly metamorphosed sedimentary rocks (basement) as the outer fault surfaces for the modeled collapse caldera complex, it is postulated that the caldera complex collapsed on steeply dipping arcuate faults two, possibly three times following eruption of at least two major ash-flow tuffs. The caldera and most of its eruptive products are now deeply buried below the surface of Pahute Mesa. Relatively low-density rocks in the caldera complex produce one of the largest gravity lows in the western conterminous United States. Gravity modeling defines a steep-sided, cup-shaped depression as much as 6,000 meters (19,800 feet) deep that is surrounded and floored by denser rocks. The steeply dipping surface located between the low-density basin fill and the higher density external rocks is considered to be the surface of the ring of faults of the multiple calderas. Extrapolations of this surface upward to the outer, or topographic rim, of the Silent Canyon caldera complex define the upper part of the caldera complex structure.

The greatest difference between the circular caldera model proposed by McKee and others (1999) and the structural block model (Warren, 1994) is the presence of proposed east-west structures contained in the structural block model. These hypothetical structures have been modeled as faults in the structural block model. If these faults, which do not exist in the

USGS interpretation, act as barriers or conduits to flow, they will be important features to be included in the flow model. The same stratigraphic data are used to produce both interpretations of the caldera complexes; ultimately, this information is being modeled in the HFM. The stratigraphic data are independent of the structural model of the caldera complex. For this reason, the inclusion of the gridded surfaces from the UGTA Phase I geologic model, while based on the structural block model, does not constitute an endorsement of the structural block model by the USGS and should make little difference in the flow model.

Undifferentiated Volcanic Rocks (VU)

Undifferentiated volcanic rocks (VU) include those volcanic units of Tertiary and Quaternary age other than those on or very near the NTS. Surficial exposure information was obtained from Stewart and Carlson (1978) with subsurface interpretations from UGTA Phase I cross sections (U.S. Department of Energy, 1997). Erosional remnants of volcanic rocks drape across the mountain ranges where the underlying lower clastic confining unit or lower carbonate aquifer is exposed. This unit includes volcanic rocks of the SWNVF. In some locations, thin remnants of VU were deleted from the map (U.S. Department of Energy, 1997).

This unit was represented in the framework model by the gridded interpretation from the UGTA Phase I model (U.S. Department of Energy, 1997) supplemented with outcrop data for areas outside the UGTA Phase I model (fig. 11). The VU unit has maximum thickness of 5,300 m in the flow model area of the HFM in the central Kawich Range. Volcanic units to the south of the UGTA Phase I geologic model boundaries were added to extend this unit. Because these volcanic rocks to the south of the UGTA Phase I geologic model tend to be flows and volcanic centers, only outcrop data were used to extend the VU to the south. Some cross sections (Grose, 1983) from this region in the southern part of the HFM area show volcanic rocks underlying valley-fill units; however, all of these occur outside the flow model boundary or occur with volcanic lithologic units that are included in other hydrogeologic units. Because of the smoothed nature of the UGTA Phase I gridded interpretations and the addition of outcrop data to produce this grid, it exists over the more detailed volcanic units discussed below. This does not affect the steady-state ground-water flow model, however, because the overextrapolated VU in the southern NTS area is above the saturated zone.

Southern Nevada Test Site/Yucca Mountain Volcanic Units (VA and VCU)

Volcanic strata in the southern part of the NTS and the Yucca Mountain area have been organized into two volcanic hydrogeologic units, the volcanic aquifer (VA) and the underlying volcanic confining unit (VCU). In general, the altered (typically zeolitized) volcanic rocks are the confining units, and the unaltered rocks constitute the aquifers. These two units have approximately the same distribution in Yucca Flat and occur as erosional remnants preserved in the deeper parts of the Tertiary basin (U.S. Department of Energy, 1997). Both the VA and VCU were represented in the framework model by the gridded interpretations from the UGTA Phase I geologic model (U.S. Department of Energy, 1997). Table 3 presents the lithostratigraphic units making up the volcanic hydrogeologic units in the southern NTS area.

The volcanic aquifer (VA) and the volcanic confining unit (VCU) cover most of the southern NTS from Frenchman Flat to Bare Mountain and have a maximum thickness of 1,300 m and 2,100 m, respectively, in the flow model area of the HFM (figs. 12 and 13). The maximum thickness of the VA occurs near Skull Mountain, while the maximum thickness for the VCU occurs in the northern part of Jackass Flats. Between Yucca Mountain and the Timber Mountain caldera complex and between Calico Hills and the Timber Mountain caldera complex, the volcanic confining unit directly overlies the lower clastic confining unit. This stacking of confining units thus provides a relative barrier to southward flow of ground water (U.S. Department of Energy, 1997). The VCU occurs in deeper areas and is generally overlain by the VA. Near the Timber Mountain caldera complex the volcanic rocks are zeolitized, even at the surface. In that area the VA is not present and all the volcanic rocks are considered to be the volcanic confining unit (U.S. Department of Energy, 1997).

Timber Mountain/Pahute Mesa Volcanic Units

The caldera-related volcanic units complex, as described here, includes the nested calderas that underlie Pahute Mesa as well as the Timber Mountain

Table 3. Volcanic hydrogeologic units of the southern Nevada Test Site/Yucca Mountain area (U.S. Department of Energy, 1997)

Hydrogeologic unit	Description	Lithostratigraphic unit
VA	Volcanic aquifer	
	(Yucca Mountain)	Timber Mountain Group (Tm)
		Paintbrush Group (Tp)
		Crater Flat Group (Tc)
	Volcanic aquifer	
	(Wahmonie Center)	Timber Mountain Group (Tm)
		Paintbrush Group (Tp)
		Wahmonie Formation (Tw)
		Crater Flat Group (Tc)
	Volcanic aquifer	Timber Mountain Group (Tm)
	(Frenchman Flat)	Paintbrush Group (Tp)
VCU	Volcanic confining unit	Tunnel Formation (Tn)
	(Yucca Mountain)	Volcanics of Oak Spring Butte (To)
		Pavits Spring Formation (Tps)
	Volcanic confining unit	Tunnel Formation (Tn)
	(Wahmonie Center)	Volcanics of Oak Spring Butte (To)
		Pavits Spring Formation (Tps)
	Volcanic confining unit	Wahmonie Formation (Tw)
	(Frenchman Flat)	Crater Flat Group (Tc)
		Pavits Spring Formation (Tps)

caldera complex. The definition of hydrogeologic units in this area is based on the structural block model developed by Warren (1994) and the hydrogeologic units documented in the UGTA Phase I geologic model. The rationale for the block model is presented in Appendix E–3 of the Regional Geologic Model Documentation Package (U.S. Department of Energy, 1997). The basis for the differentiation is that volcanic stratigraphy and its physical features are related to its location with respect to particular structural blocks and volcanic centers. The units were defined on the basis of their stratigraphic position within the volcanic pile, lithologic properties related to depositional environment, postdepositional alteration, and degree of welding.

Within each structural block, the Timber Mountain volcanic hydrogeologic units have very low dips and are essentially horizontal. From top (stratigraphically) to bottom the volcanic hydrogeologic units in the Timber Mountain/Pahute Mesa area are:

Timber Mountain aquifer (TMA)
Paintbrush/Calico Hills tuff cone (TC)
Bullfrog confining unit (TCB)
Belted Range aquifer (TBA)
Basal confining unit (TBCU)
Basal aquifer (TBQ)

Table 4 presents the volcanic hydrogeologic units from the Timber Mountain/Pahute Mesa area and their lithostratigraphic equivalents. All of these units are represented in the HFM by the gridded interpretations in the UGTA Phase I geologic model (U.S. Department of Energy, 1997).

The volcanic hydrogeologic units occurring in the Timber Mountain/Pahute Mesa area have maximum thicknesses ranging from 1,600 m to 4,000 m for the various hydrogeologic units contained within the flow model area of the HFM (figs. 14 to 19).

The structural relations of the Timber Mountain caldera complex with hydrogeologic units in the neighboring calderas and surrounding areas show thick TC (composed of Paintbrush Group and Calico Hills Formation) north of Timber Mountain (fig. 15*A*). A thick section of TC also occurs south of Timber Mountain in the Claim Canyon caldera (fig. 15*A*). The Timber Mountain caldera complex is interpreted by IT Corporation (U.S. Department of Energy, 1997) to be filled with TMA. The TMA inside the Timber Mountain caldera complex, however, has pervasive zeolitization and may behave more like a confining unit than an aquifer (U.S. Department of Energy, 1997). The Grouse Canyon caldera (fig. 3) is filled with a thick section of TBA (fig. 17*A*). The inner collapse zone of the Grouse Canyon caldera is represented with large vertical offset and the thickest section of TBA (U.S. Department of Energy, 1997; Sawyer and others, 1994).

Aquifers of the Timber Mountain caldera complex are bounded on the east by the structurally high lower clastic confining unit (LCCU), upper clastic confining unit (UCCU), or TBCU. There is a possibility that the lower carbonate aquifer (LCA) is locally in contact with the TBQ along the eastern caldera boundary. To the west exist structurally high TBQ and TBCU. In the model, the TBQ is in contact with the LCA on the western margin of the Black Mountain caldera. There is a high uncertainty regarding the TBQ thickness and the presence and thickness of LCA in this area (U.S. Department of Energy, 1997).

Tertiary Sediments/Death Valley Section (TSDVS)

The Tertiary sediments/Death Valley section (TSDVS) is the combination of Tertiary-aged sediments and similar sediments in the Death Valley area. Tertiary sediments (TS) and the Death Valley section (DVS) were mapped together because they are similar deposits and because they are in geographically exclusive areas. The TS includes clastic and volcaniclastic sediments of the Horse Spring Formation lithologic equivalent (the Oligocene rocks of Winapi Wash) and the Titus Canyon Formations. In the northern Amargosa Desert area, the TS includes Tertiary sediments and buried, highly distended tectonic blocks of Tertiary volcanic rocks. The volcanic rocks are included with the TS because the blocks are undifferentiable at the present mapping/modeling scale. The Death Valley section consists of the Artist Drive, Furnace Creek, and Funeral Formations and the Greenwater Volcanics in Death Valley and Furnace Creek areas. Extents of these units were taken from geologic-section interpretations (U.S. Department of Energy, 1997) and from McAllister (1970, 1973). The sediments of Tertiary age cover a more extensive area than depicted in figure 20. For instance, the modeled TSDVS unit does not include Tertiary-aged sediments known to exist in Frenchman Flat and Rock Valley (Laczniak and others, 1996). IT Corporation

Table 4. Volcanic hydrogeologic units of the Timber Mountain/Pahute Mesa Caldera Complex (U.S. Department of Energy, 1997)

Hydrogeologic unit	Description	Lithostratigraphic unit
Timber Mountain aquifer	Upppermost welded tuffs	Timber Mountain Group (Tm)
(TMA)		Volcanics of Fortymile Canyon (Tf)
Thirsty Canyon Group (Tt)		
Paintbrush Group (Tp)		
Paintbrush/Calico Hills	Laterally variable	Paintbrush Group (Tp)
tuff cone	Volcanics of Area 20 (Ta)	
(TC)		Crater Flat Group (Tc)
Bullfrog confining unit	Nonwelded tuff	Bullfrog Tuff (Tcb)
(TCB)		
Belted Range aquifer	Welded tuffs above BCU	Belted Range Group (Tb)
(TBA)		Tub Springs Tuff (Tub)
		Bullfrog Tuff—Stockade lobe (Tcbs)
		Tram Ridge Group (Tr)
Basal confining unit	Nonwelded tuffs	Tunnel Formation (Tn)
(TBCU)		Tub Springs Tuff (Tub)
		Volcanics of Oak Spring Butte (To)
		Tram Ridge Group (Tr)
		Volcanics of Quartz Mountain (Tq)
Basal aquifer	Welded tuffs	Volcanics of Oak Spring Butt (To)
(TBQ)		tuffaceous paleocolluvium (Tlt)
		Dacite of Mt. Helen (Tqm)

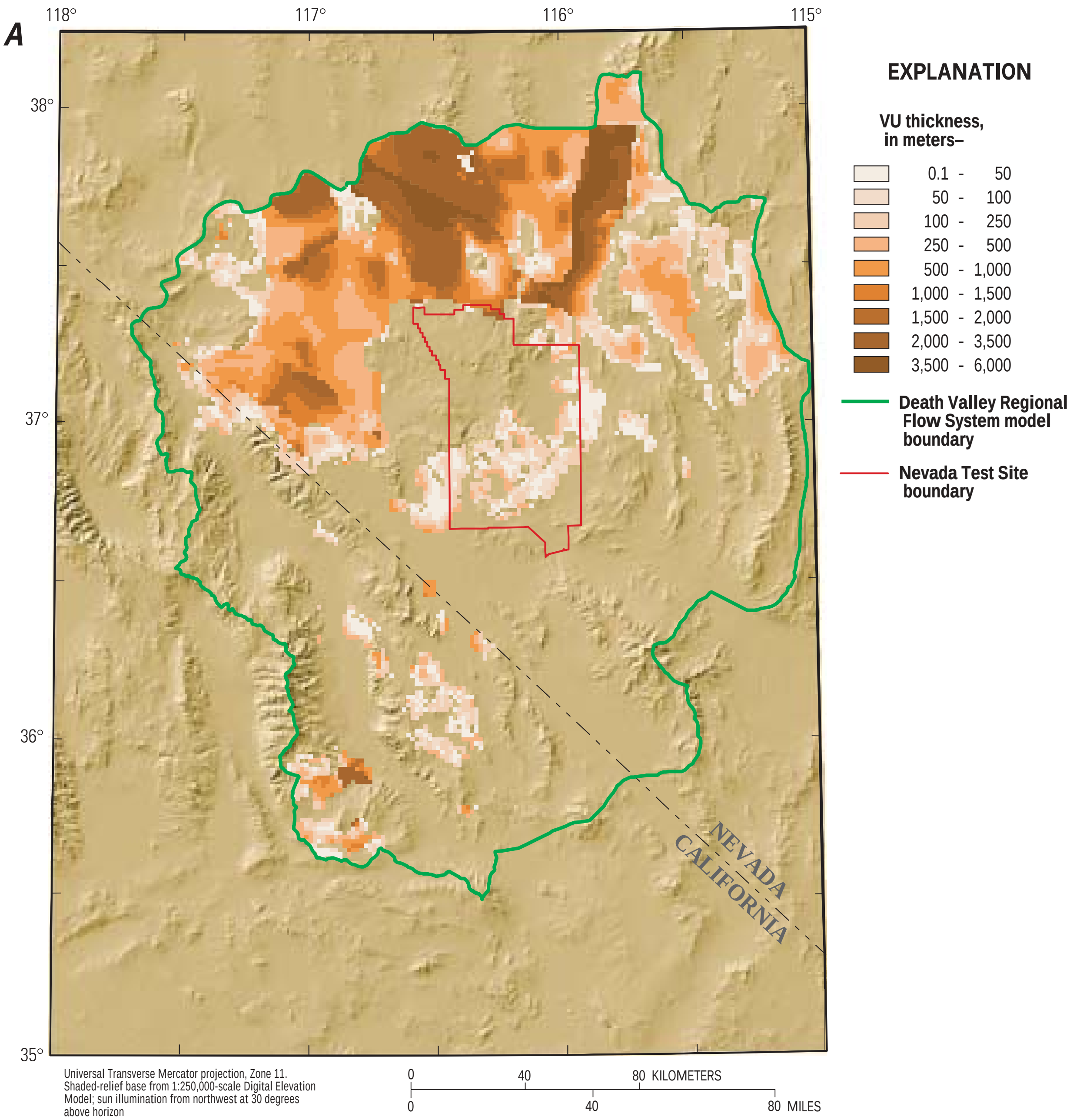

Figure 11. (***A***) Thickness of undifferentiated volcanic rocks (VU).

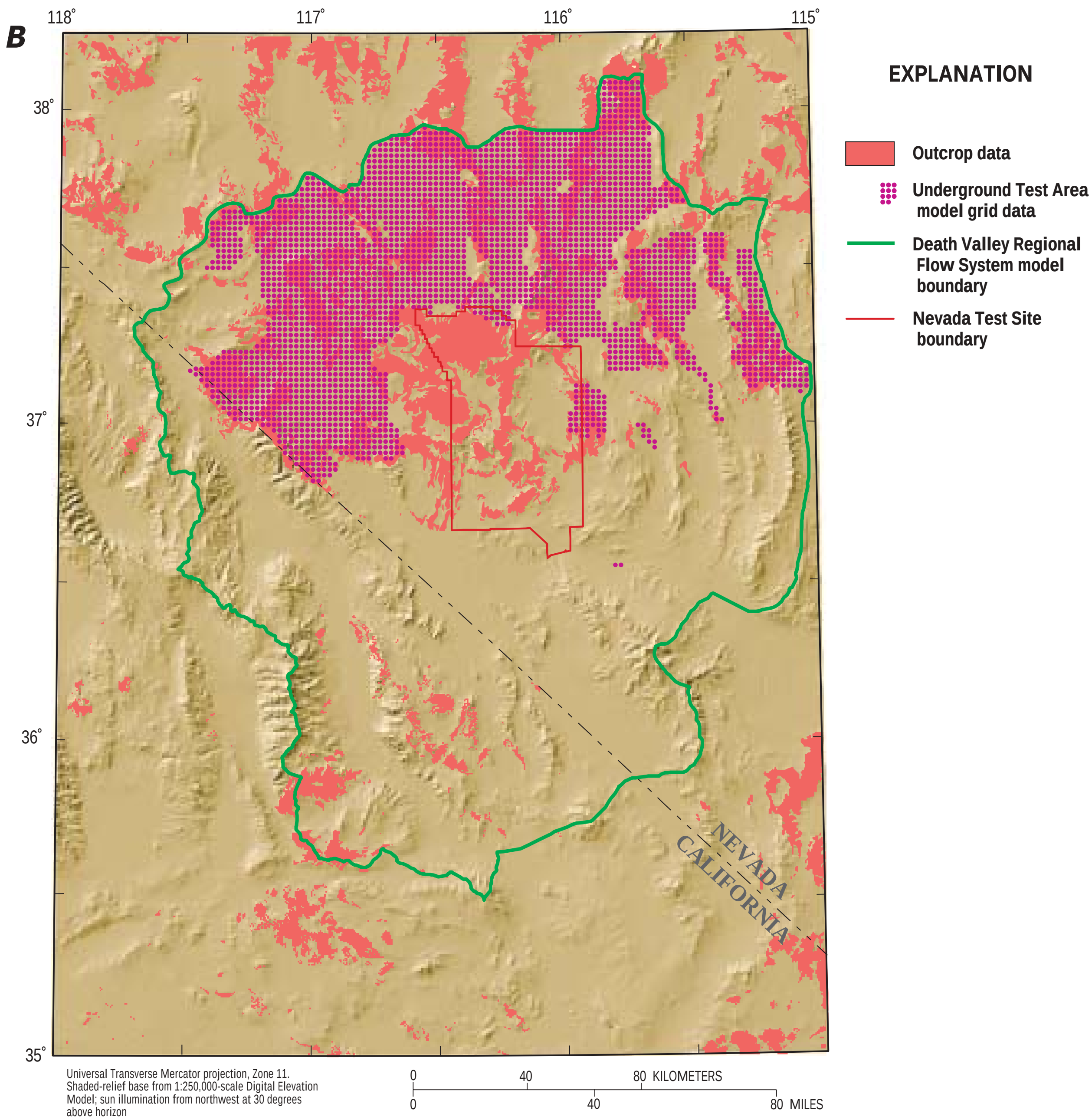

Figure 11–Continued. (***B***) Data sources used to construct gridded surface.

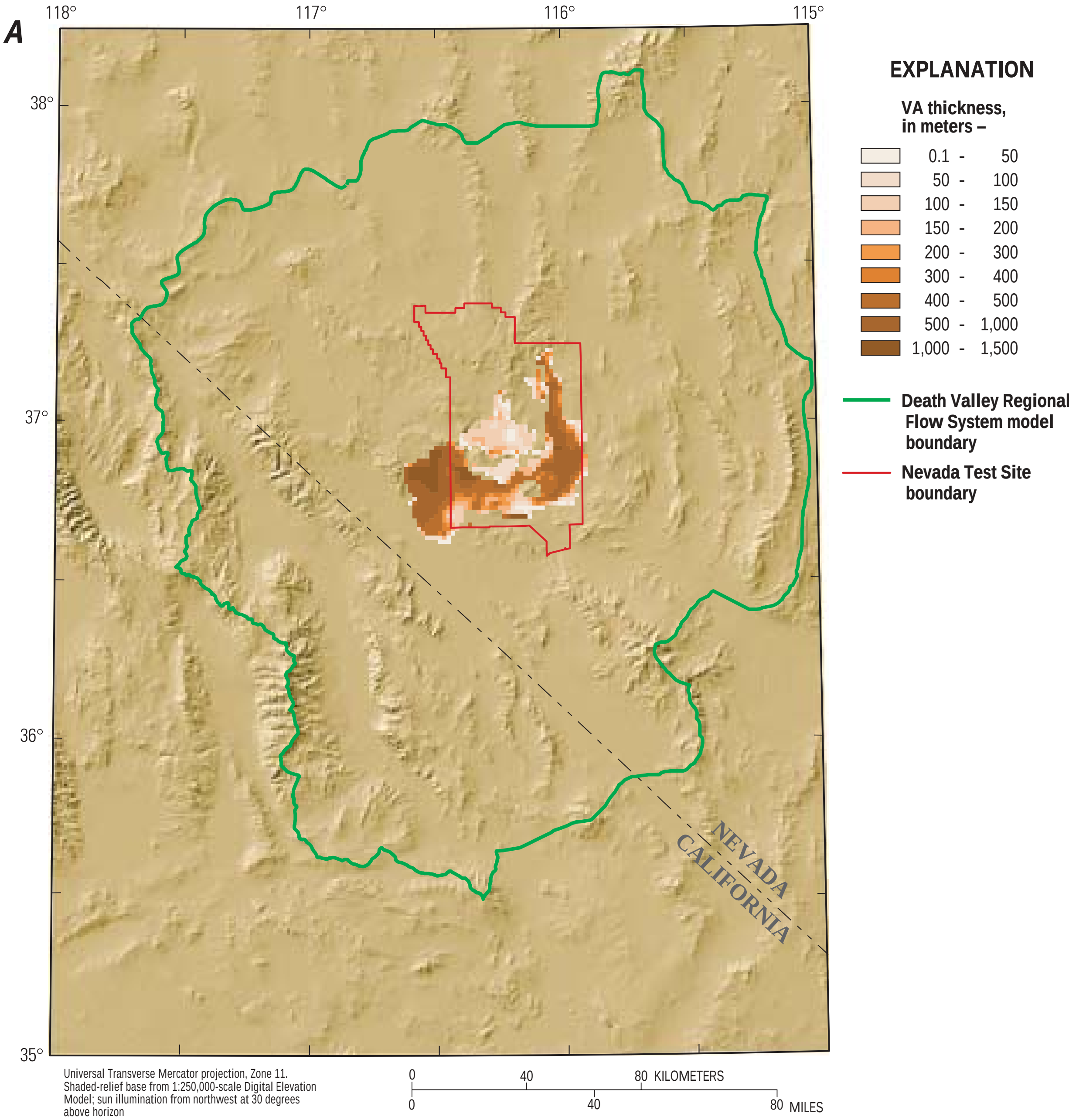

Figure 12. (***A***) Thickness of volcanic aquifer (VA).

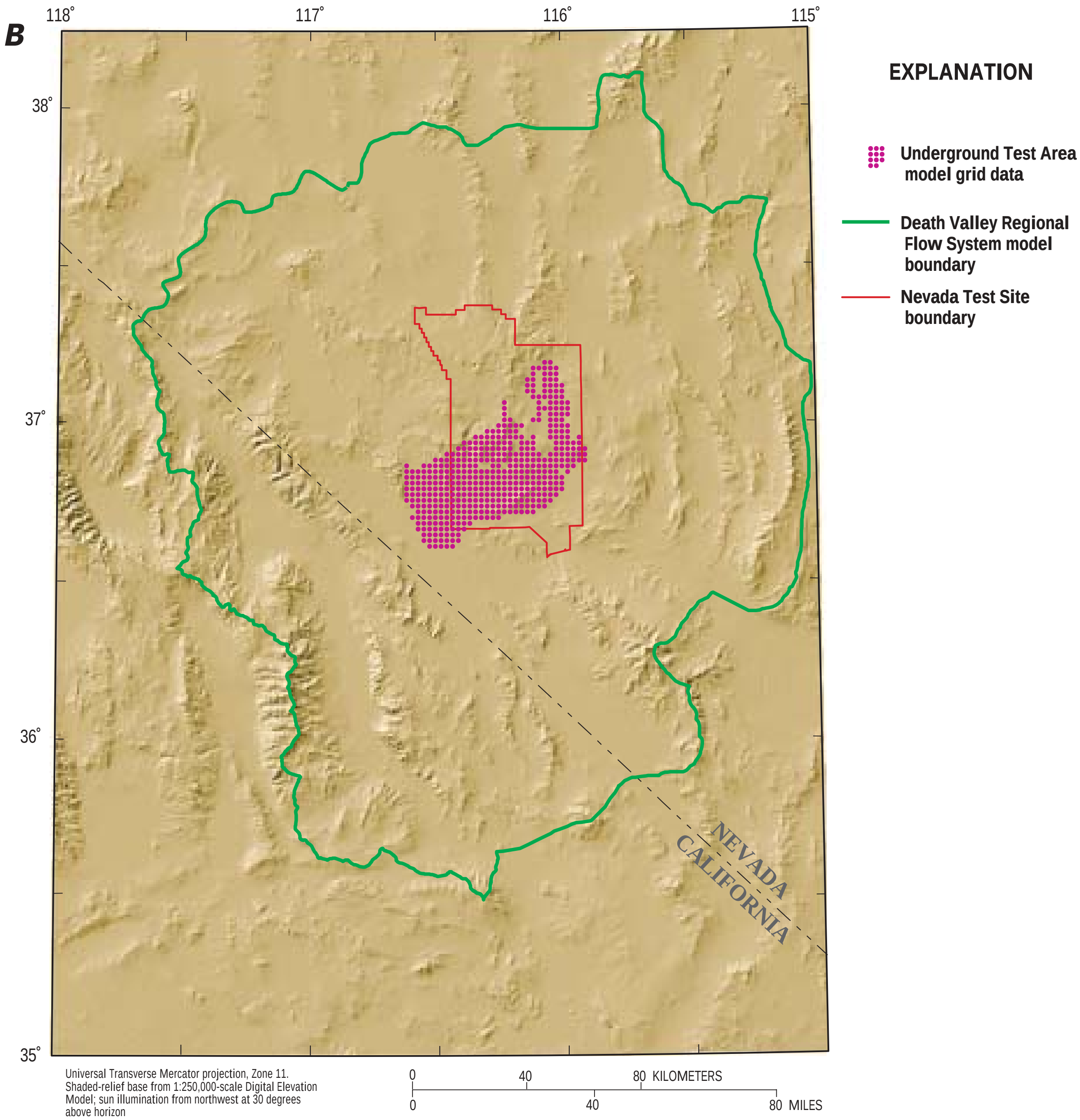

Figure 12–Continued. (***B***) Data sources used to construct gridded surface.

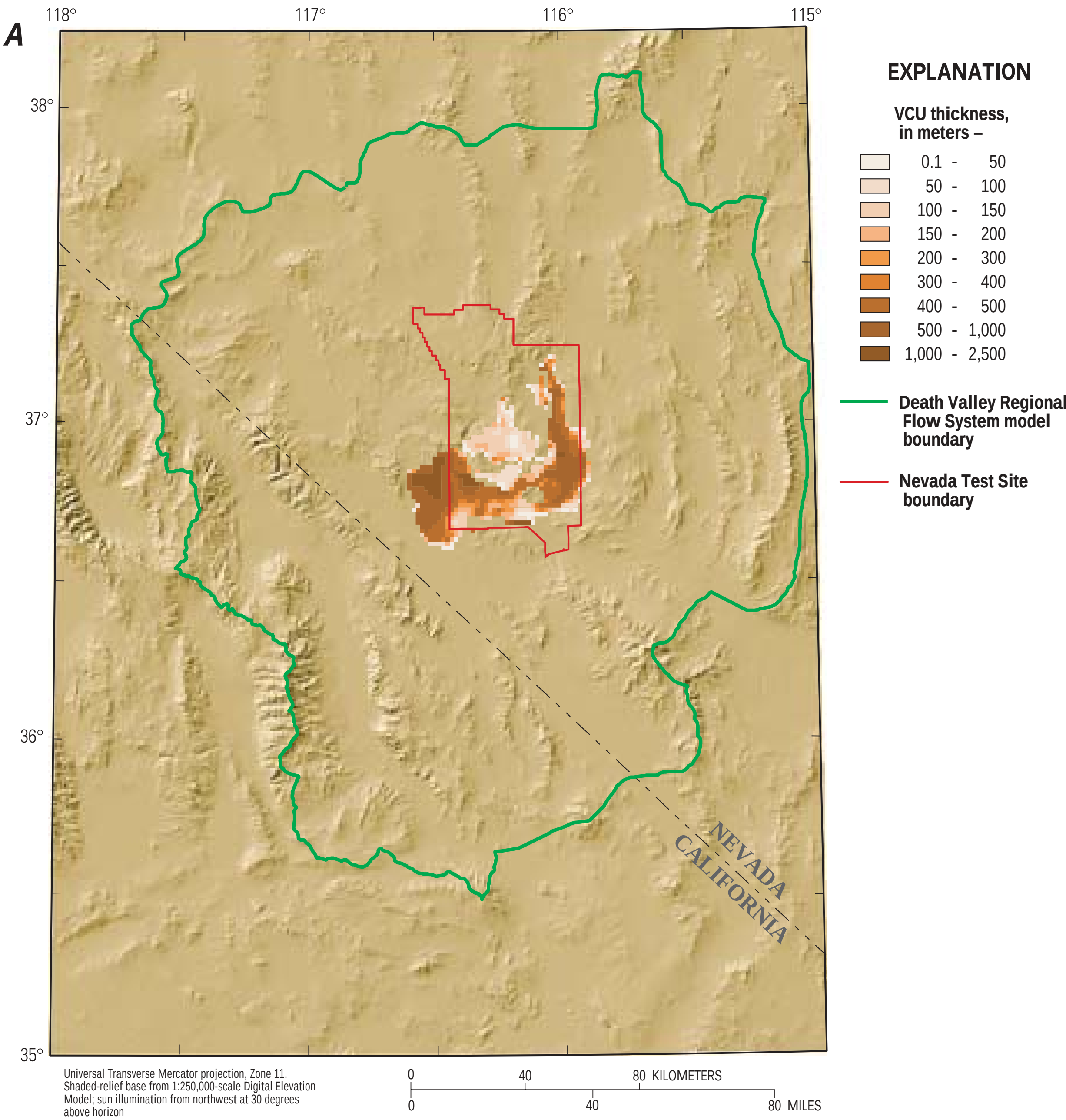

Figure 13. (***A***) Thickness of volcanic confining unit (VCU).

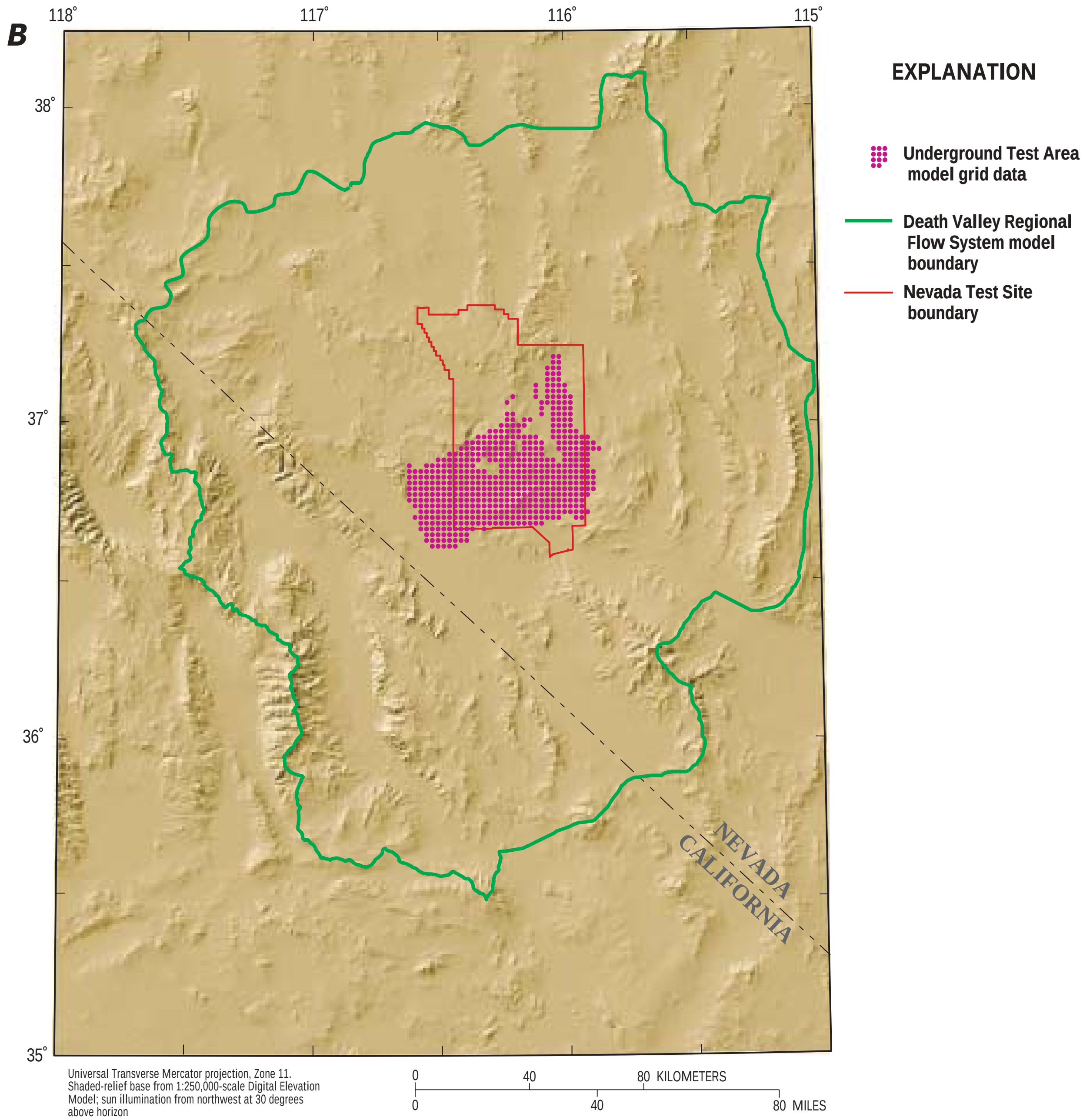

Figure 13–Continued. (***B***) Data sources used to construct gridded surface.

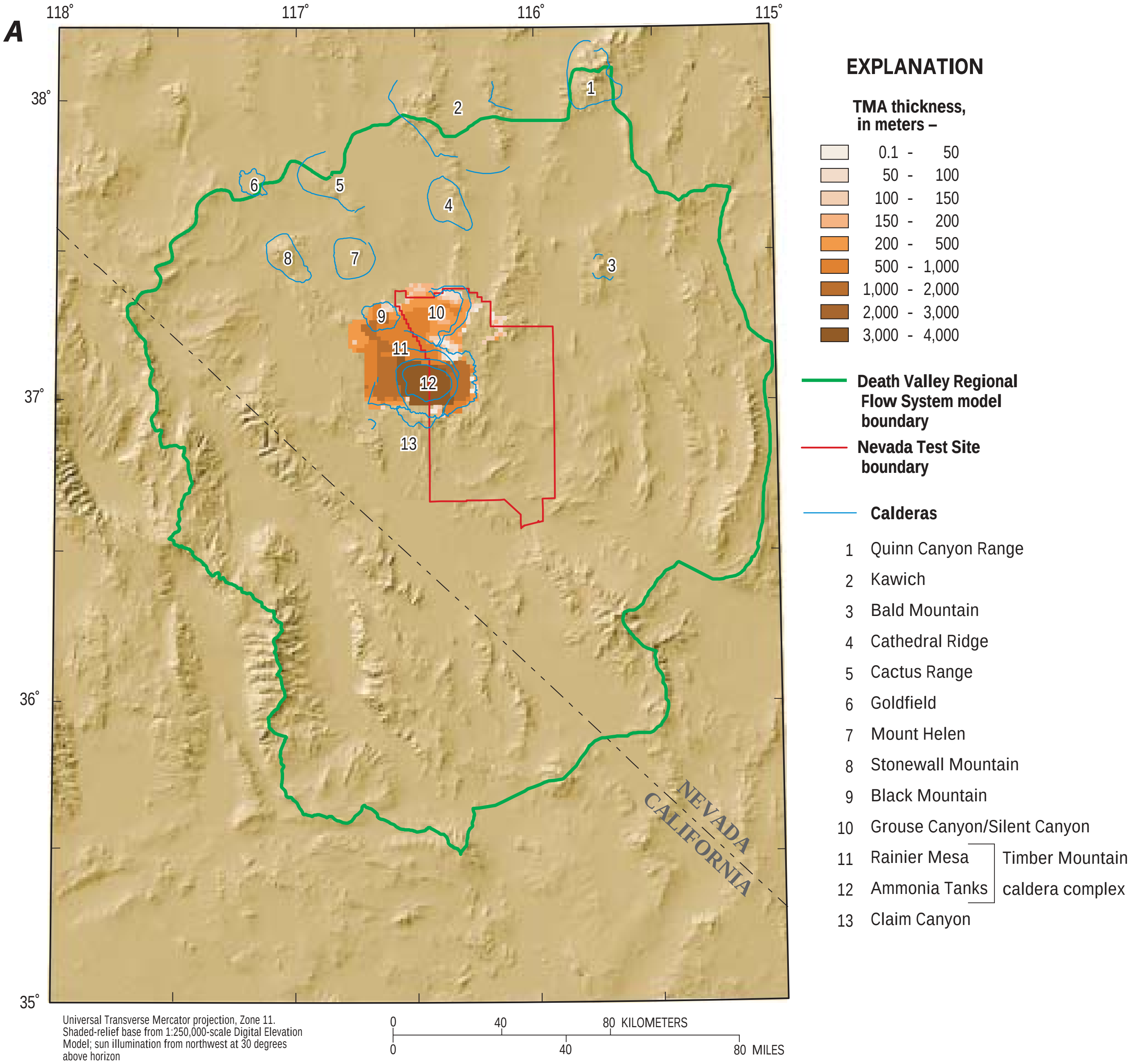

Figure 14. (***A***) Thickness of Timber Mountain aquifer (TMA).

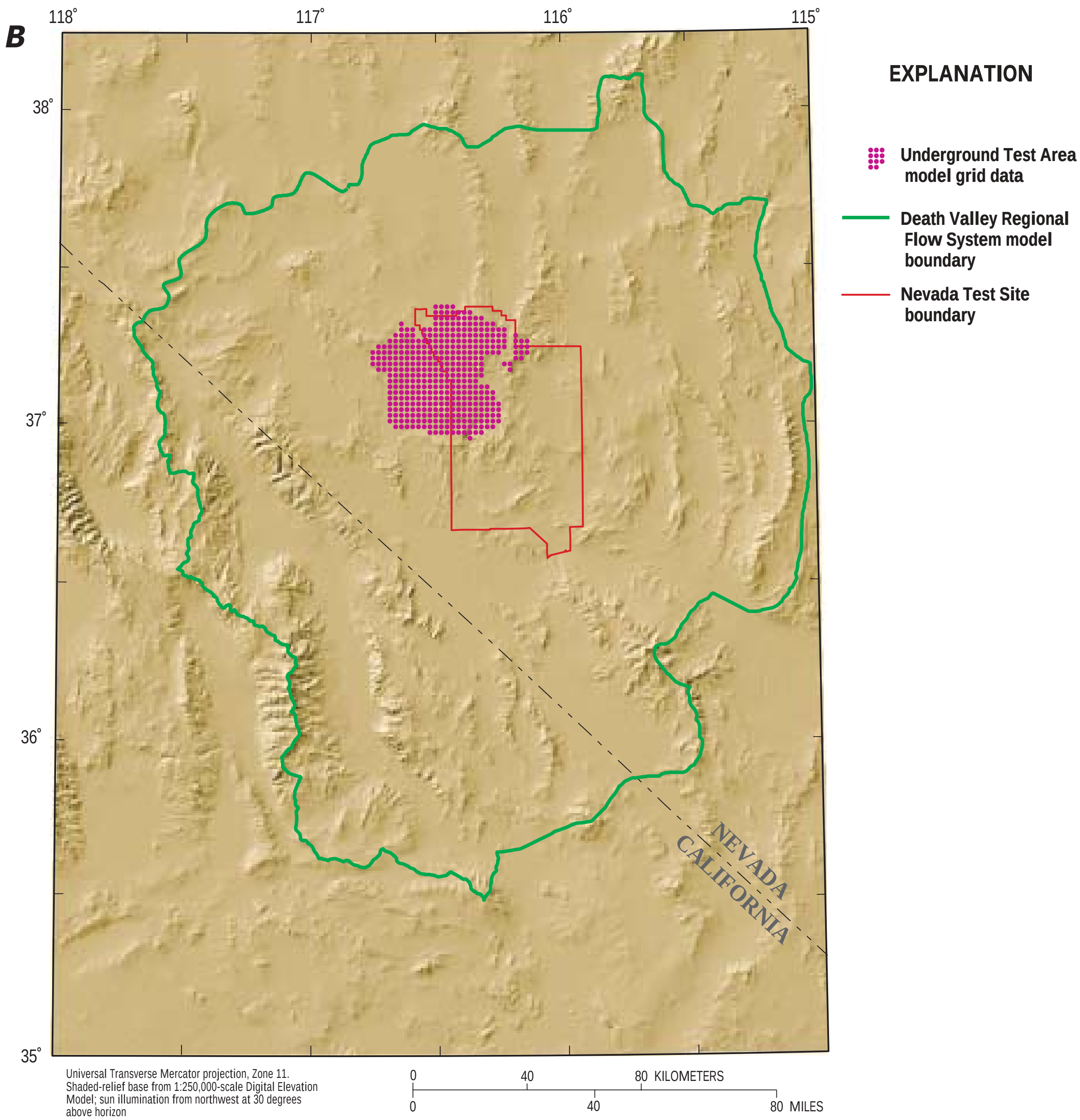

Figure 14–Continued. (***B***) Data sources used to construct gridded surface.

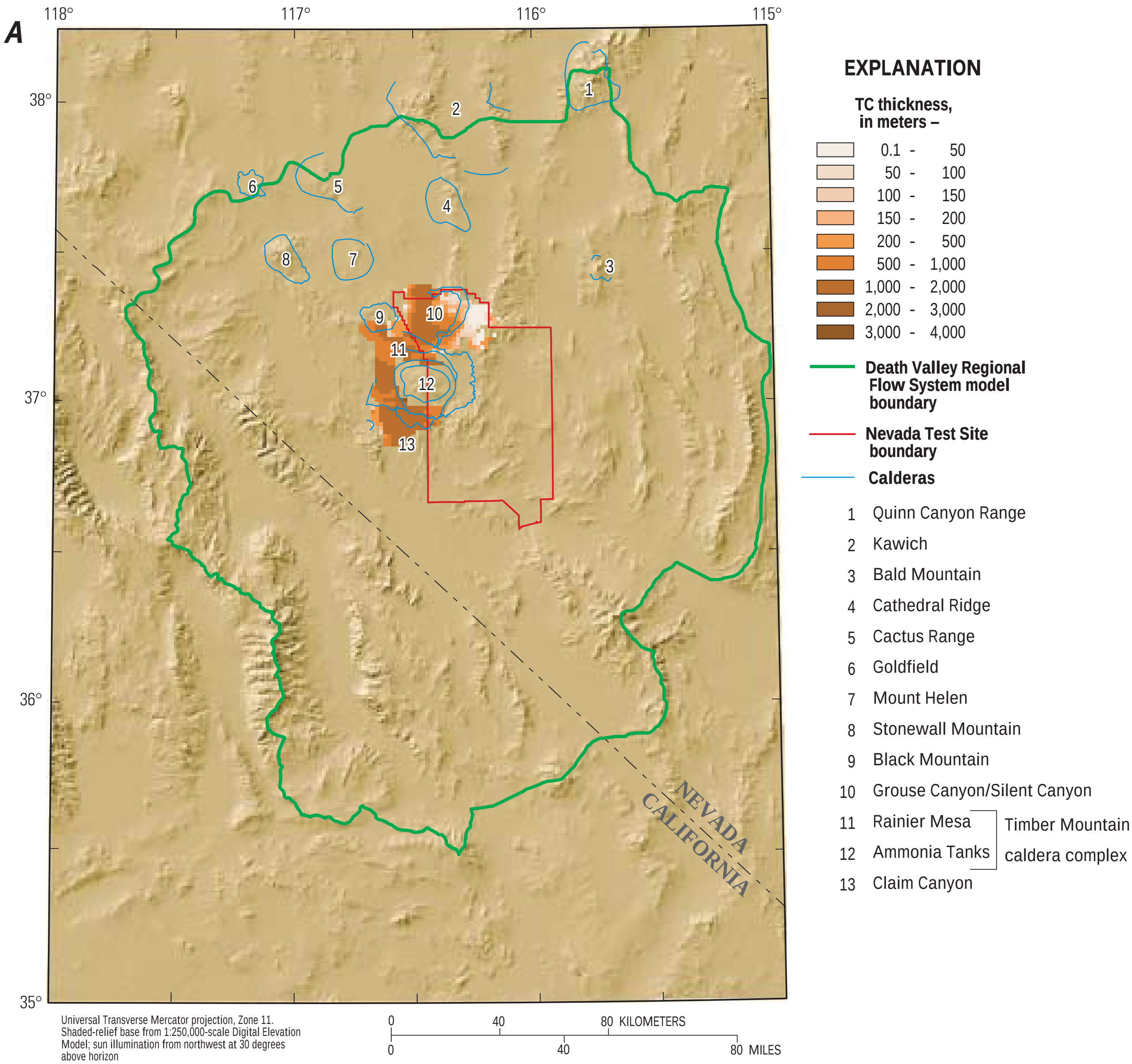

Figure 15. (*A*) Thickness of Paintbrush/Calico Hills tuff cone (TC).

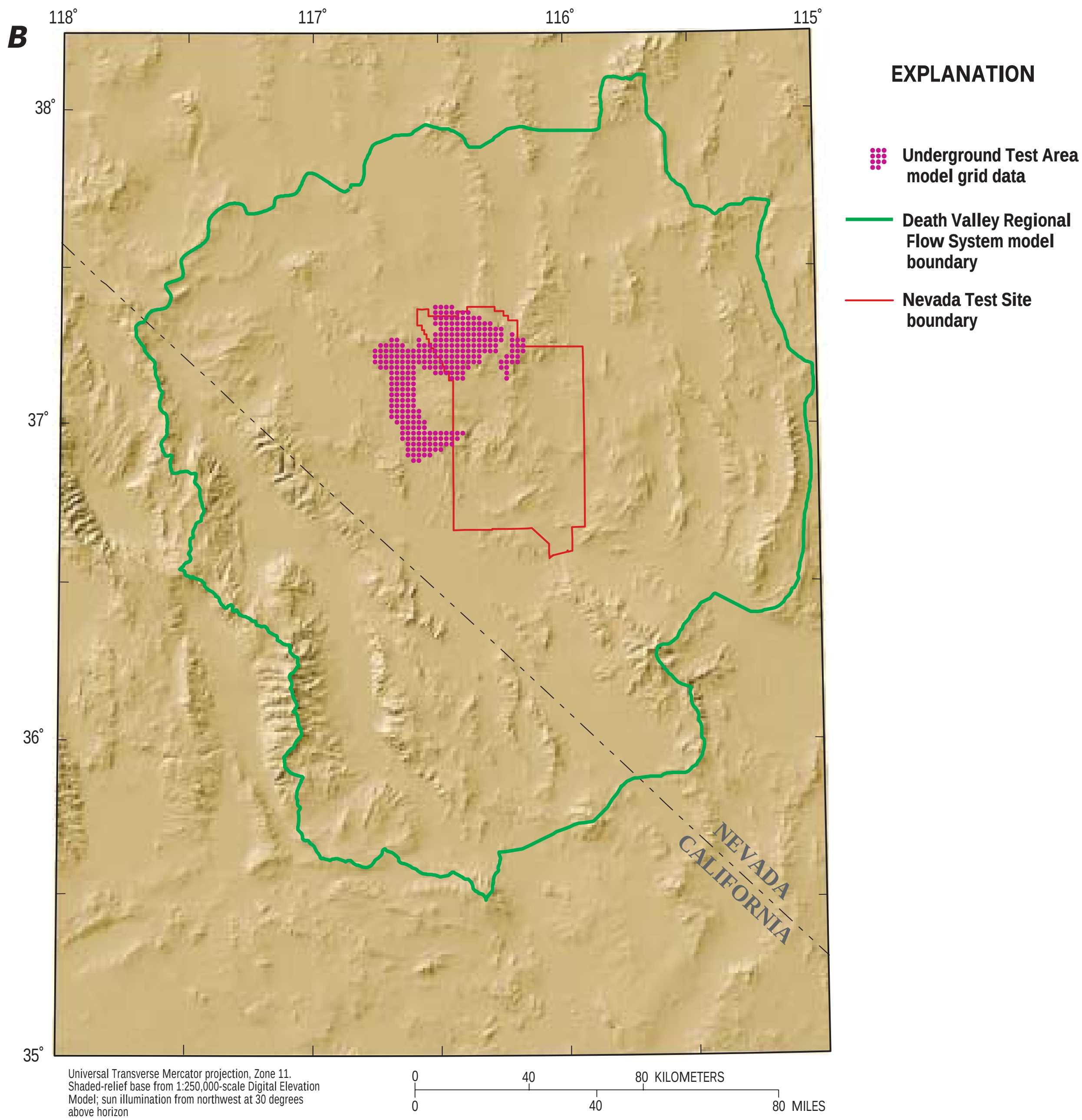

Figure 15–Continued. (***B***) Data sources used to construct gridded surface.

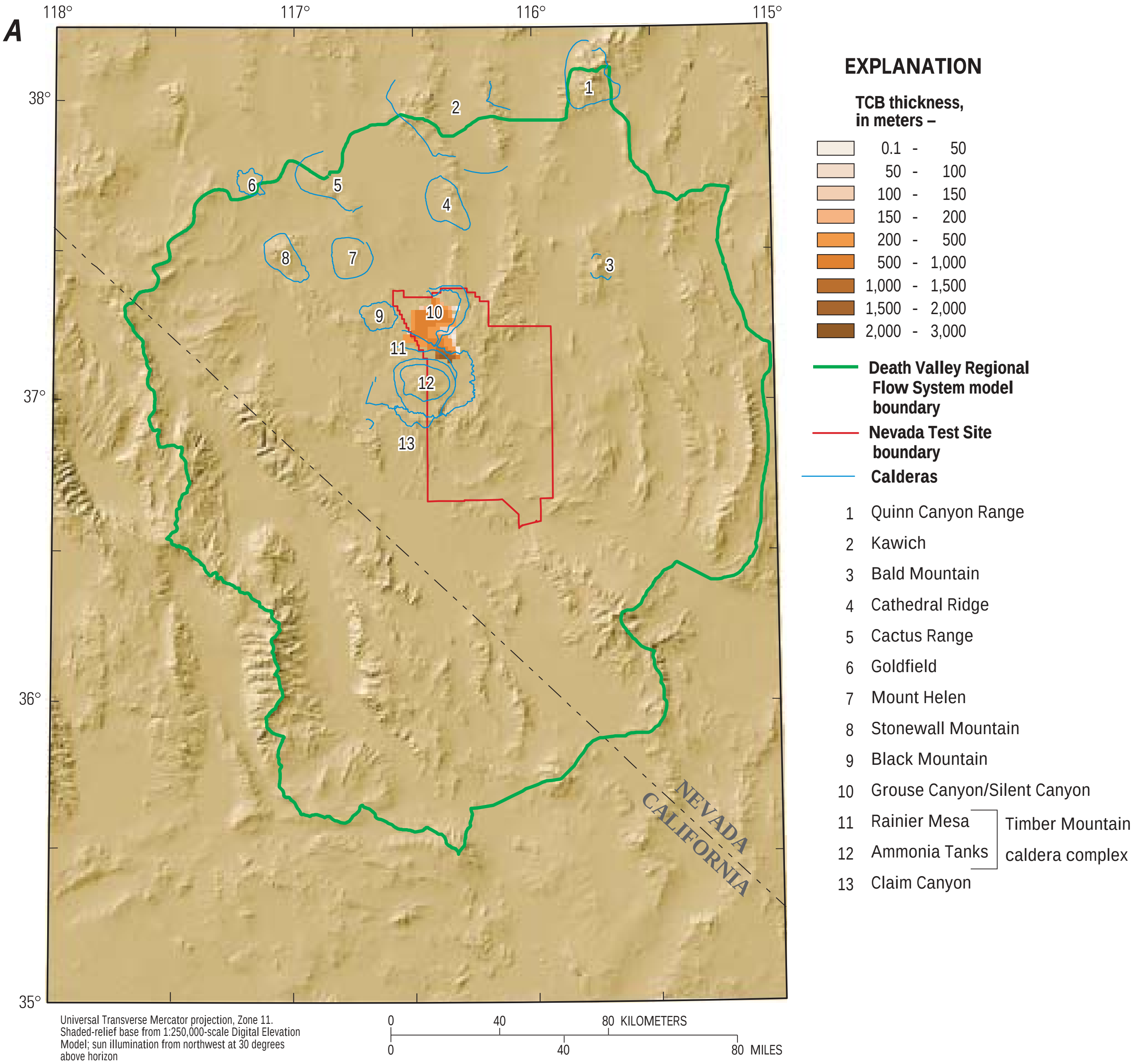

Figure 16. (***A***) Thickness of Bullfrog aquifer (TCB).

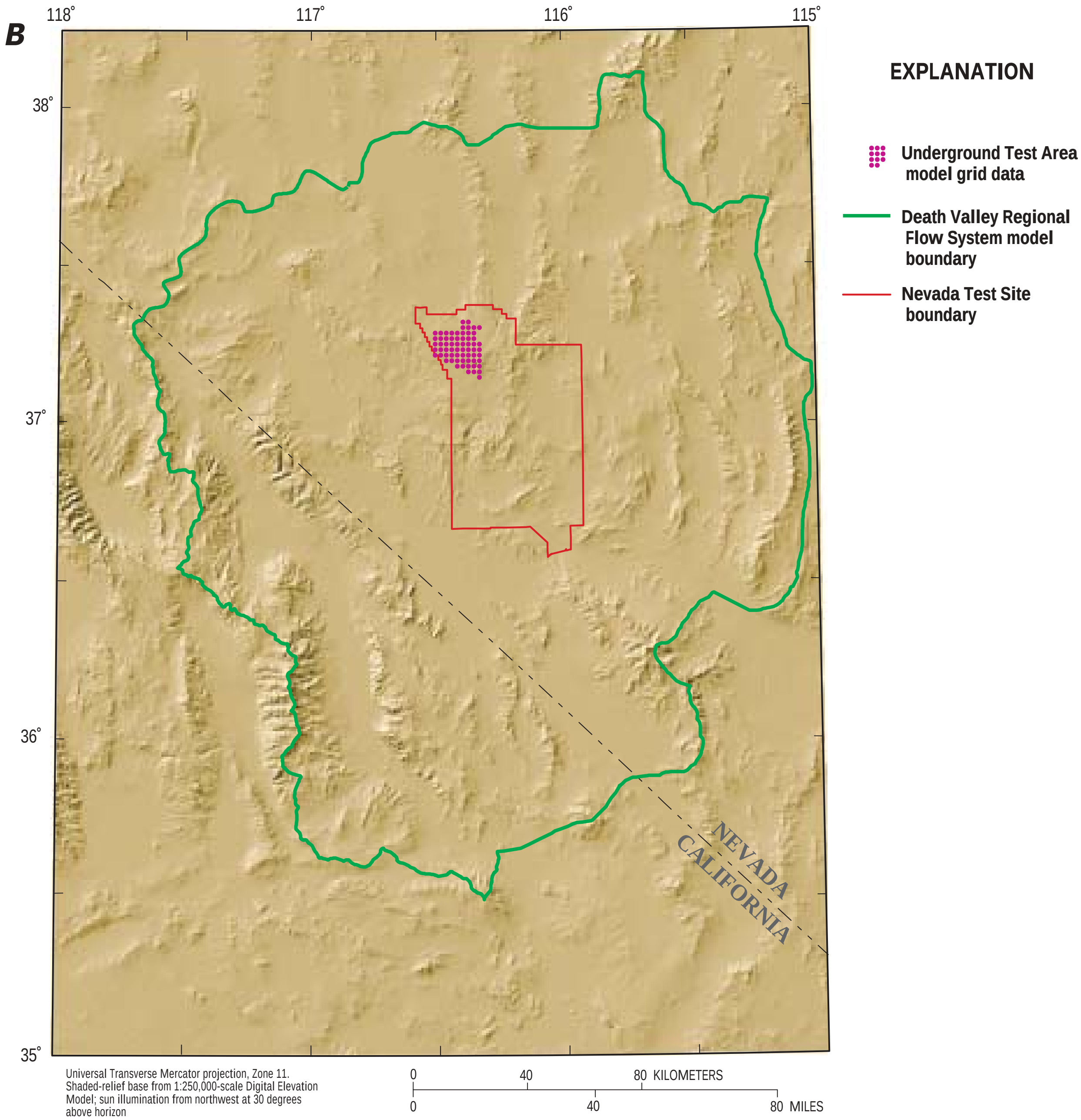

Figure 16–Continued. (***B***) Data sources used to construct gridded surface.

A

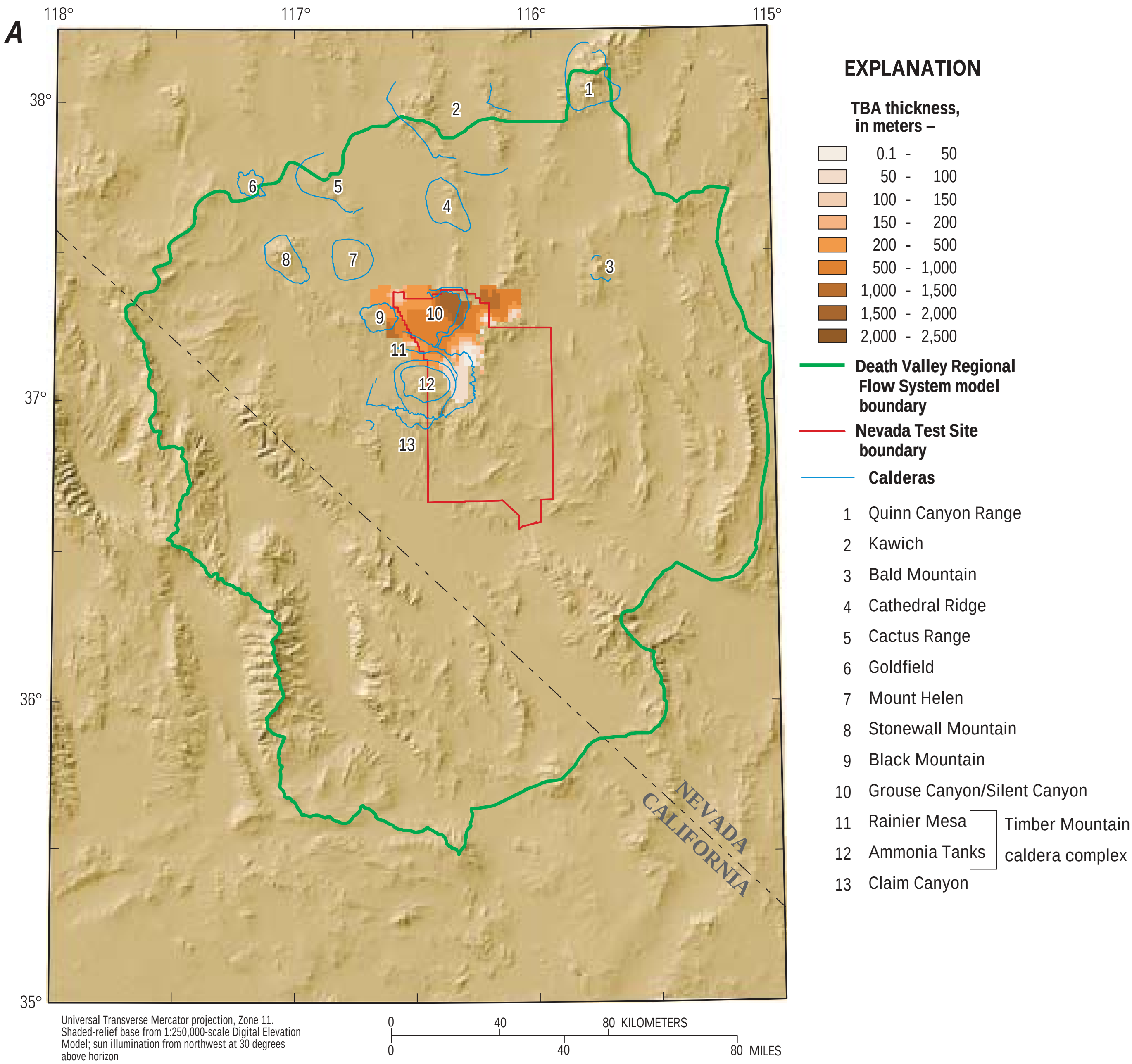

Figure 17. (*A*) Thickness of Belted Range aquifer (TBA).

B

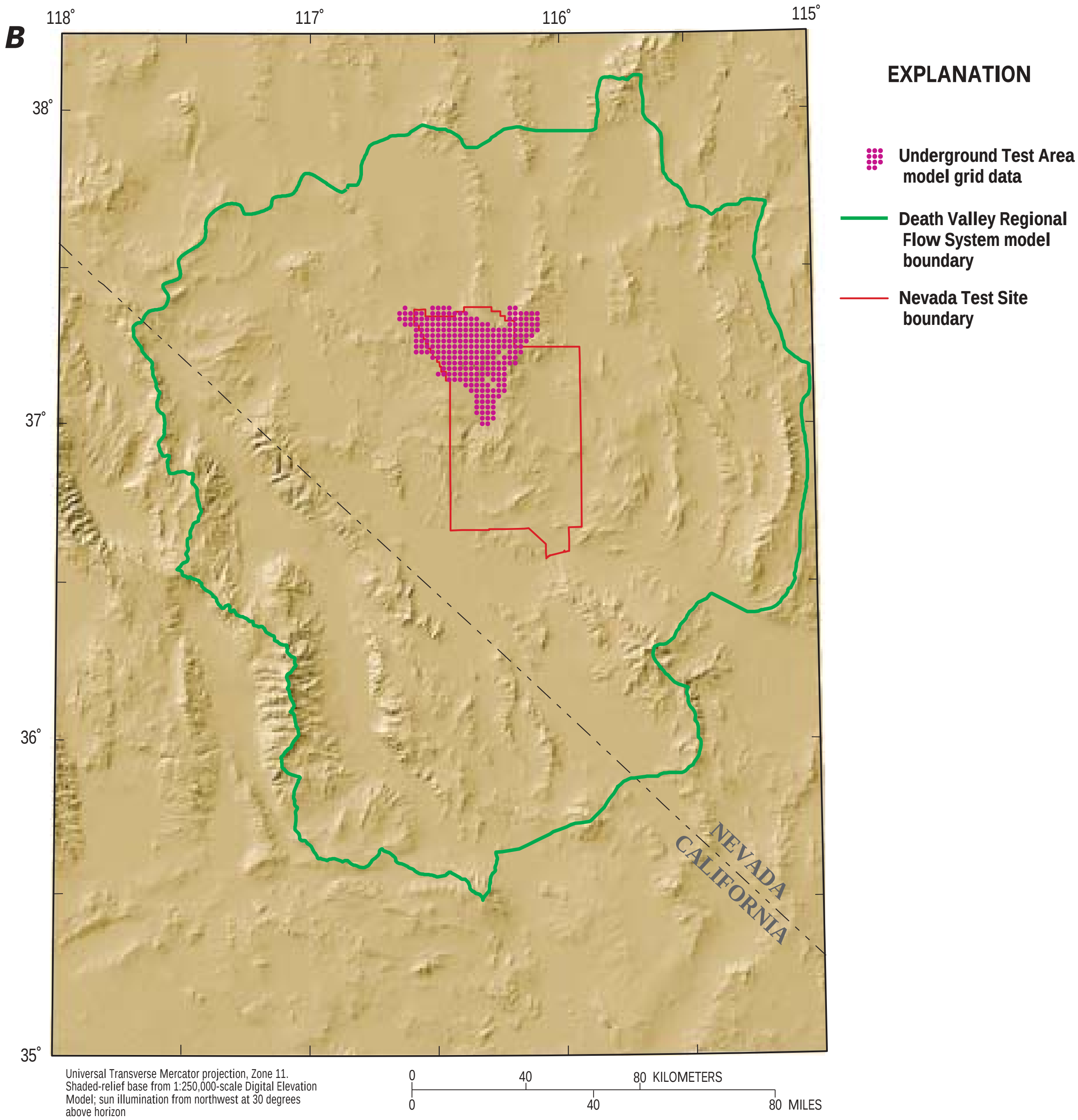

Figure 17–Continued. (***B***) Data sources used to construct gridded surface.

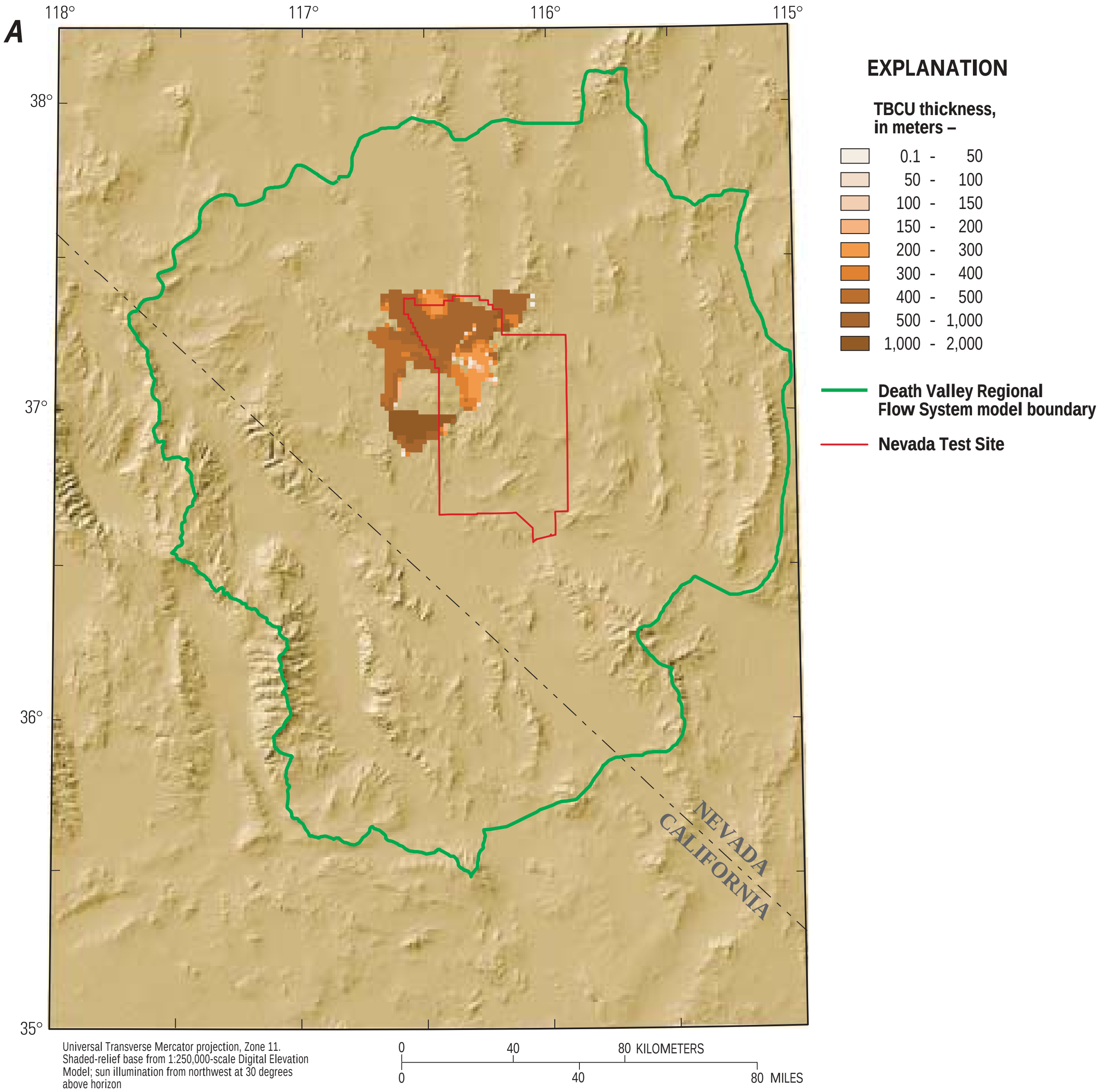

Figure 18. (*A*) Thickness of basal confining unit (TBCU).

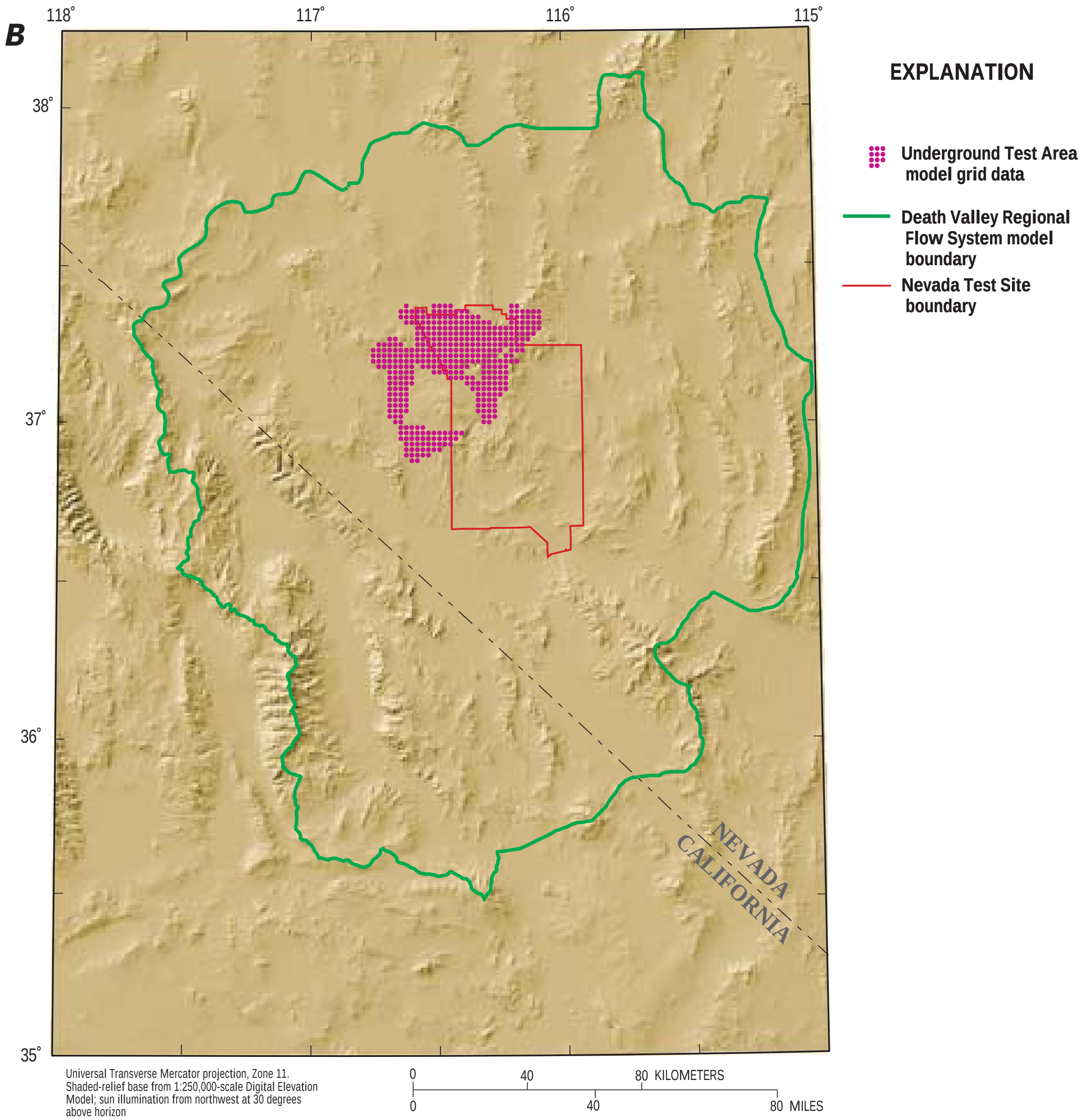

Figure 18–Continued. (***B***) Data sources used to construct gridded surface.

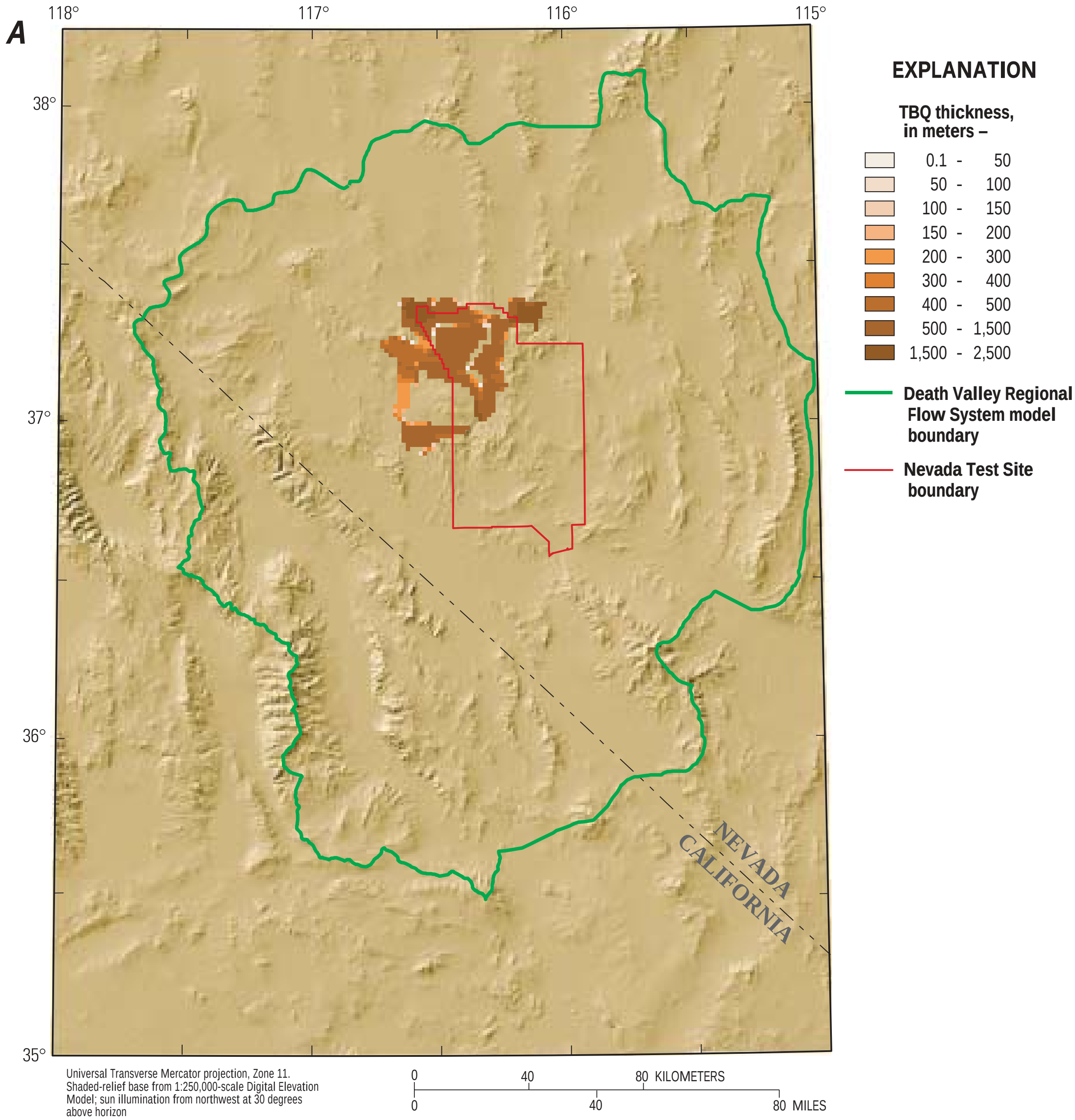

Figure 19. (***A***) Thickness of basal aquifer (TBQ).

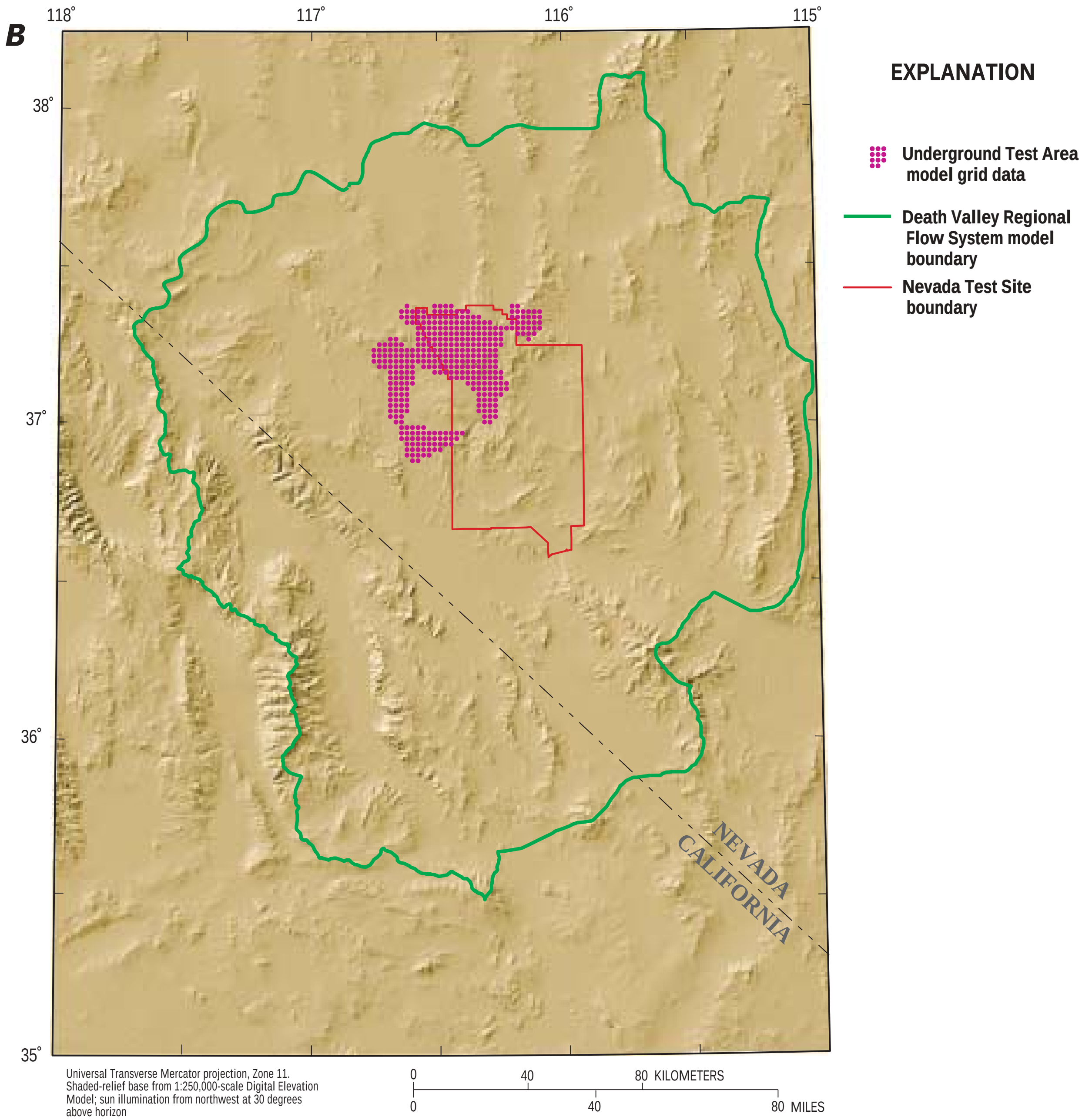

Figure 19–Continued. (***B***) Data sources used to construct gridded surface.

(U.S. Department of Energy, 1997) consolidated sedimentary rocks of Tertiary age present in the vicinity of the NTS into the volcanic confining units (see table 3). The TSDVS unit is represented by the gridded interpretations of the UGTA Phase I geologic model with cross-section interpretations from Grose and Smith (1989) to extend the Death Valley section across the entire width of Death Valley.

At Bat Mountain in the southern Funeral Mountains, the TSDVS directly overlies the lower carbonate aquifer and has a maximum thickness of 2,600 m with the flow model area of the HFM in southern Death Valley. In the Black Mountains and the Greenwater Range, unit TSDVS directly overlies the Proterozoic basement and(or) Tertiary granites. The TSDVS, along with the LCCU and local intrusives, forms a barrier to southwestward ground-water flow into Death Valley, effective south of the Funeral Mountains (fig. 1).

Mesozoic Volcaniclastic and Sedimentary Rocks (Mvs)

The rocks of Mesozoic age (Mvs) are predominantly continental fluvial, lacustrine, and eolian deposits and clastic and carbonate sedimentary rocks in the eastern part of the region, as well as Mesozoic-aged volcanic rocks in the southwest part of the region. These rocks form outcrops on the sides of the Spring Mountains where they have been overridden by thrust faulting. The Aztec Sandstone, present in the lower plate of the Keystone thrust, acts primarily as an aquifer, whereas other Mesozoic-aged sedimentary units, such as the Chinle and the Moenkopi Formations, can act as confining units. Where intensively faulted, these rocks can be highly permeable and locally may form significant aquifers (Bedinger and others, 1989b); however, they are not widespread. Limited sections of the Mesozoic volcanic rocks are also found in the southwestern part of the Death Valley region (Bedinger and others, 1989a). The Mvs primarily exists in the Spring Mountains and in the southwestern part of the Death Valley region and has a maximum thickness of 1,300 m in the flow model area of the HFM south of the Owlshead Mountains (fig. 1). Mvs depicted at the NTS (fig. 21*A*) was derived from outcrop representations from Faunt and others (1997).

Upper Carbonate Aquifer (UCA)

The upper carbonate aquifer (UCA) consists of limestone, dolomite, and calcareous shales of Paleozoic age that are stratigraphically above the Eleana Formation and Chainman Shale (which form the upper clastic confining unit; see following section) and large-scale thrusted carbonate units primarily in the upper plate of the CP thrust in the Calico Hills (Cole and Cashman, 1999). These thrusted units include all Pennsylvanian strata, plus Mississippian strata that do not include the Eleana Formation and the Chainman Shale. Where they are not separated by the Eleana Formation and Chainman Shale, the Pennsylvanian and Mississippian carbonates are included in the lower carbonate aquifer. The UCA unit includes Pennsylvanian and Mississippian-aged carbonates above the Eleana Formation and Chainman Shale, as well as older carbonates traditionally assigned to the lower carbonate aquifer contained in the CP thrust (Laczniak and others, 1996). The gridded interpretations from the UGTA Phase I geologic model (U.S. Department of Energy, 1997), supplemented by lithologic borehole data, were used to model the upper surface of the UCA.

The UCA exists primarily in the area of Yucca Flat and has a maximum thickness of 900 m in the area of the HFM near Calico Hills (fig. 22). In western Yucca Flat, several isolated, mostly buried erosional remnants of Devonian and older carbonates overlie the upper clastic confining unit. These carbonates have been interpreted to be remnants of the CP thrust sheet, which is thought to have been emplaced over the upper clastic confining unit from the east, rooted in Yucca Flat (Caskey and Schweickert, 1992). Pennsylvanian carbonate rocks, which outcrop at Syncline Ridge of western Yucca Flat, are contained within the UCA.

Upper Clastic Confining Unit (UCCU)

The upper clastic confining unit (UCCU) is composed essentially of the Eleana Formation, along with the Chainman Shale (Laczniak and others, 1996). The Eleana Formation, composed mostly of relatively impermeable argillites and shales, forms a locally important clastic confining unit. The argillites and shales tend to deform plastically, probably by shearing and tight folding. Thus, open fractures are unlikely to occur at depth in this formation. The Eleana Formation is thousands of meters thick (Winograd and Thordarson, 1975, p. C43). The extent of this unit is thought to coincide with many large hydraulic gradients in the region (Fridrich and others, 1994). For example, large hydraulic gradients in the area of Yucca Flat are attributed to the low transmissivity values of the Eleana Formation (D'Agnese and others, 1997). The gridded interpretations from the UGTA Phase I geologic model (U.S. Department of Energy, 1997), supplemented with outcrop and lithologic borehole data, were used to model the top surface of the UCCU.

In the NTS area, the UCCU stratigraphically and hydraulically separates the regional carbonate aquifer into upper and lower carbonate aquifers beneath Yucca Flat and northern Jackass Flats and has a maximum thickness of 4,300 m in the flow model area of the HFM near Oasis Valley (fig. 1). The Chainman Shale of the UCCU overlies the lower carbonate aquifer both in the subsurface and in outcrop in the western part of Yucca Flat (U.S. Department of Energy, 1997).

Lower Carbonate Aquifer (LCA)

The lower carbonate aquifer (LCA) is the most important regional aquifer because of its distribution and large hydraulic conductivity. Limestone, dolomite, and calcareous shales of Paleozoic age underlie many valleys and crop out along the flanks of and throughout some mountains. The geologic units included in the LCA include all Devonian-, Silurian-, and Ordovician-aged strata, plus the Cambrian Nopah Formation, the Bonanza King Formation, and the upper two-thirds of the Carrara Formation (Laczniak and others, 1996). Also included in the LCA are Pennsylvanian and Mississippian carbonates where the UCCU does not separate the Paleozoic carbonates into an upper and lower aquifer. These carbonate rocks cover an extensive part of the area around Death Valley, extending to the north and the east. They are commonly interbedded with siltstones and shales and locally interrupted by volcanic intrusions in the north. These carbonates, which have an aggregate thickness of about 8,000 m, are generally the most permeable rocks in the area (Bedinger and others, 1989b, p. A17). Where hydraulically connected, they provide an avenue for interbasinal flow (D'Agnese and others, 1997). In general, the LCA is thin or missing on the structural highs and is thickest in the structural lows of the lower clastic confining unit. The LCA has a maximum thickness of 6,100 m in the flow model area of the HFM in the Timpahute Range (figs. 24 to 28). While the LCA crops out extensively in the ranges, it can be covered by basin-fill sediments in the valleys.

Most of the springs in the area are associated with the carbonate rocks. Intergranular flow is not significant in these rocks; the large transmissivity is primarily due to fractures and solution channels (Winograd and Thordarson, 1975). Hydraulic tests of carbonate-rock aquifers throughout eastern and southern Nevada indicate that faults can increase the carbonate-rock transmissivity by factors of 25 or more (Dettinger, 1989).

Thrusted LCA complicates the flow patterns in the ground-water system, and where repeated stratigraphic section occurs, thrusted LCA is modeled as separate units. The area between the southern Funeral Mountains and the Spring Mountains contains separately defined thrust-fault areas in which the lower clastic confining unit overlies the LCA. These thrust zones trend generally east-northeast and represent the Schwaub Peak, Specter Range, and the Wheeler Pass thrusts. LCA units in these thrusts are included in both the lower and upper plates of these thrust systems (LCA_T1 (fig. 25) and LCA_T2 (fig. 26), respectively). Other hydrologically significant thrusts in the region include the Lee Canyon thrust in the Spring Mountains (LCA_LC (fig. 27) and the Gass Peak thrust in the Sheep Range (LCA_GP [fig. 28]). The Belted Range thrust is represented implicitly in the LCA as a thickened section.

In the Yucca Mountain area, the LCA is covered by volcanic rocks (VA and VCU) leaving high uncertainty about how much LCA exists under the volcanic cover. Well UE–25 p#1 near Yucca Mountain penetrates the LCA. A single small outcrop of Devonian carbonate is exposed on the west end of the Black Mountain caldera (LCA also crops out on Bare Mountain, the Striped Hills, and the Specter Range). This outcrop indicates that most of the LCA thickness might underlie the volcanic rocks, barring unknown structural complications. Based on the UGTA Phase I geologic model (U.S. Department of Energy, 1997), the LCA was incorporated in the model west of the Pahute Mesa caldera complex, north of Oasis Valley. If the LCA does exist inside the calderas, it is probably highly altered by the intrusive and extrusive geologic processes. The continuity of the LCA in the northwestern part of the HFM is highly uncertain.

The base of the LCA is exposed along with the LCCU in the structural uplift in the northern Halfpint Range on the east side of Yucca Flat. The LCA dips westward from the uplift into Yucca Flat. It is interpreted in the UGTA Phase I geologic model

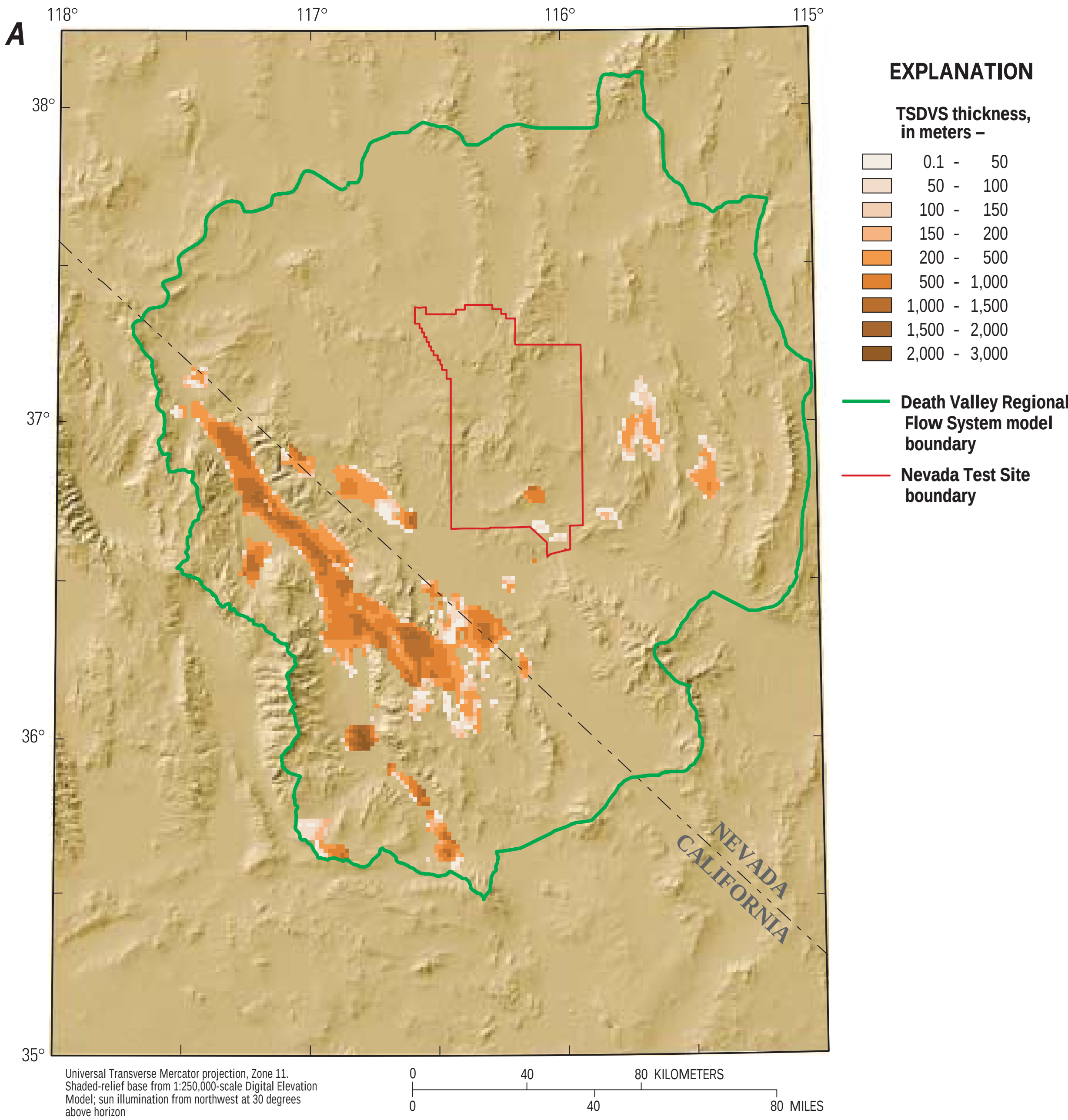

Figure 20. (*A*) Thickness of Tertiary sediments/Death Valley section (TSDVS).

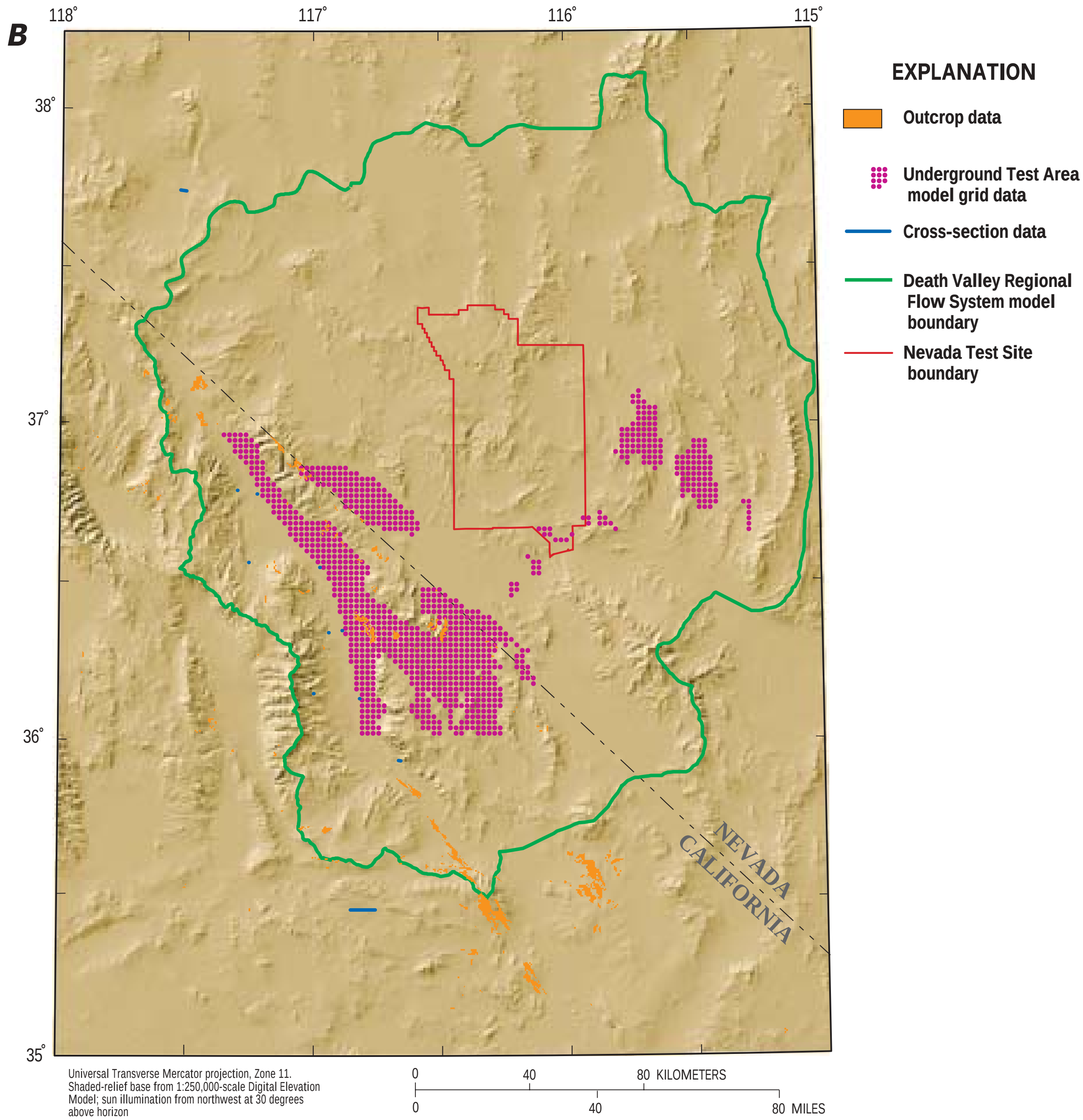

Figure 20–Continued. (***B***) Data sources used to construct gridded surface.

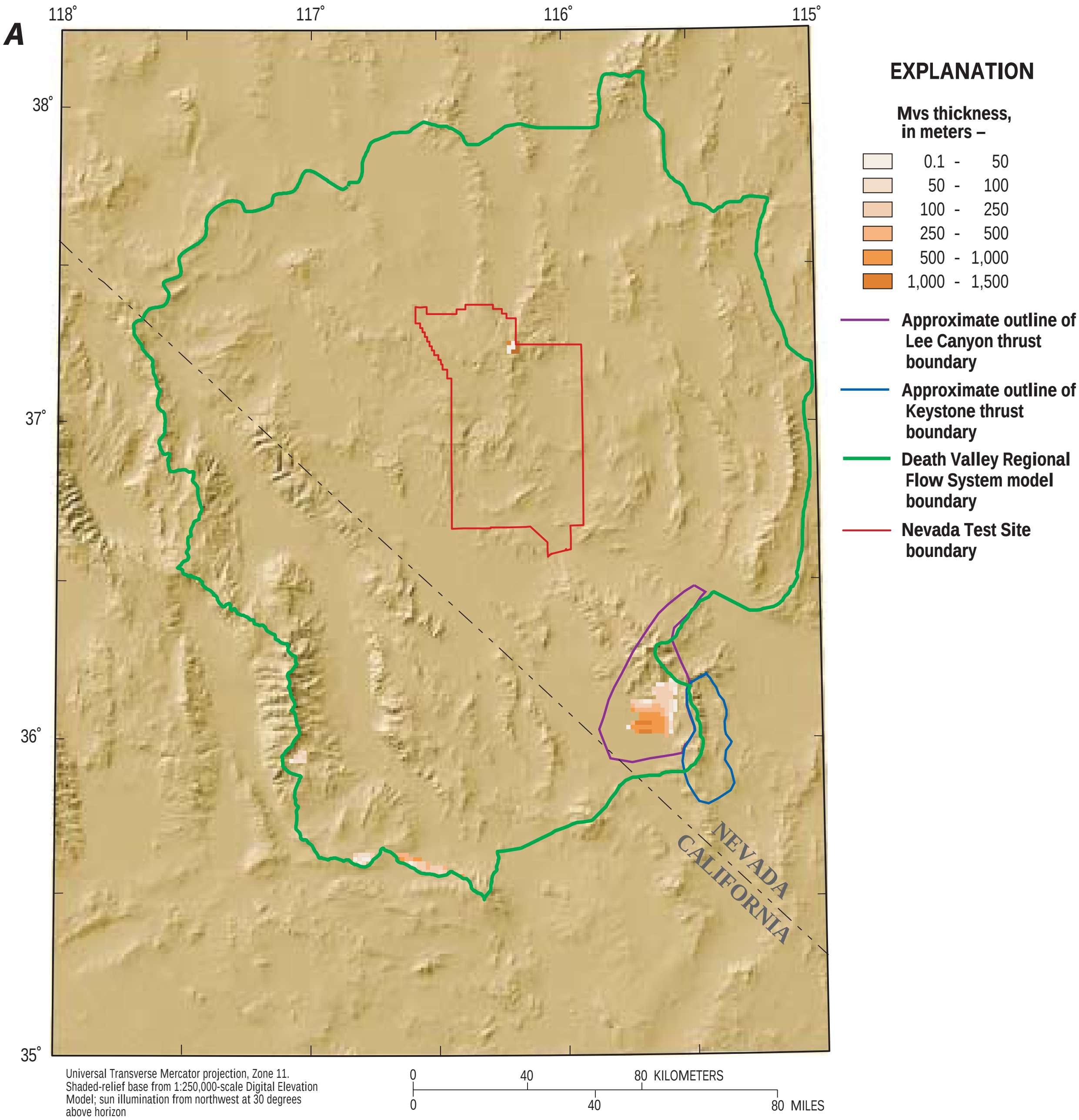

Figure 21. (***A***) Thickness of Mesozoic volcaniclastic and sedimentary rocks (Mvs) including Lee Canyon (Mvs_LC) and Keystone (Mvs_KS) thrusts.

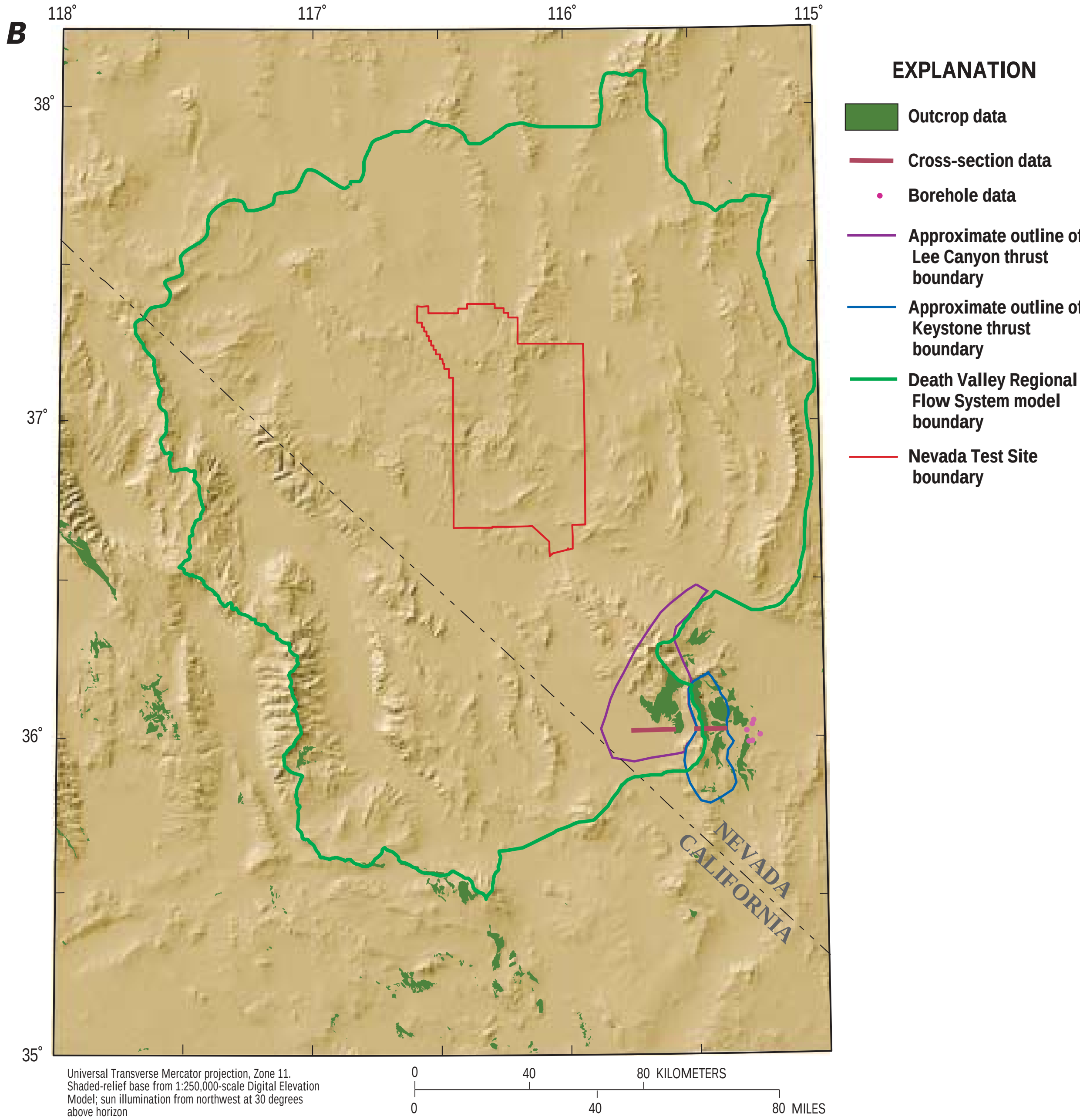

Figure 21–Continued. (***B***) Data sources used to construct gridded surface.

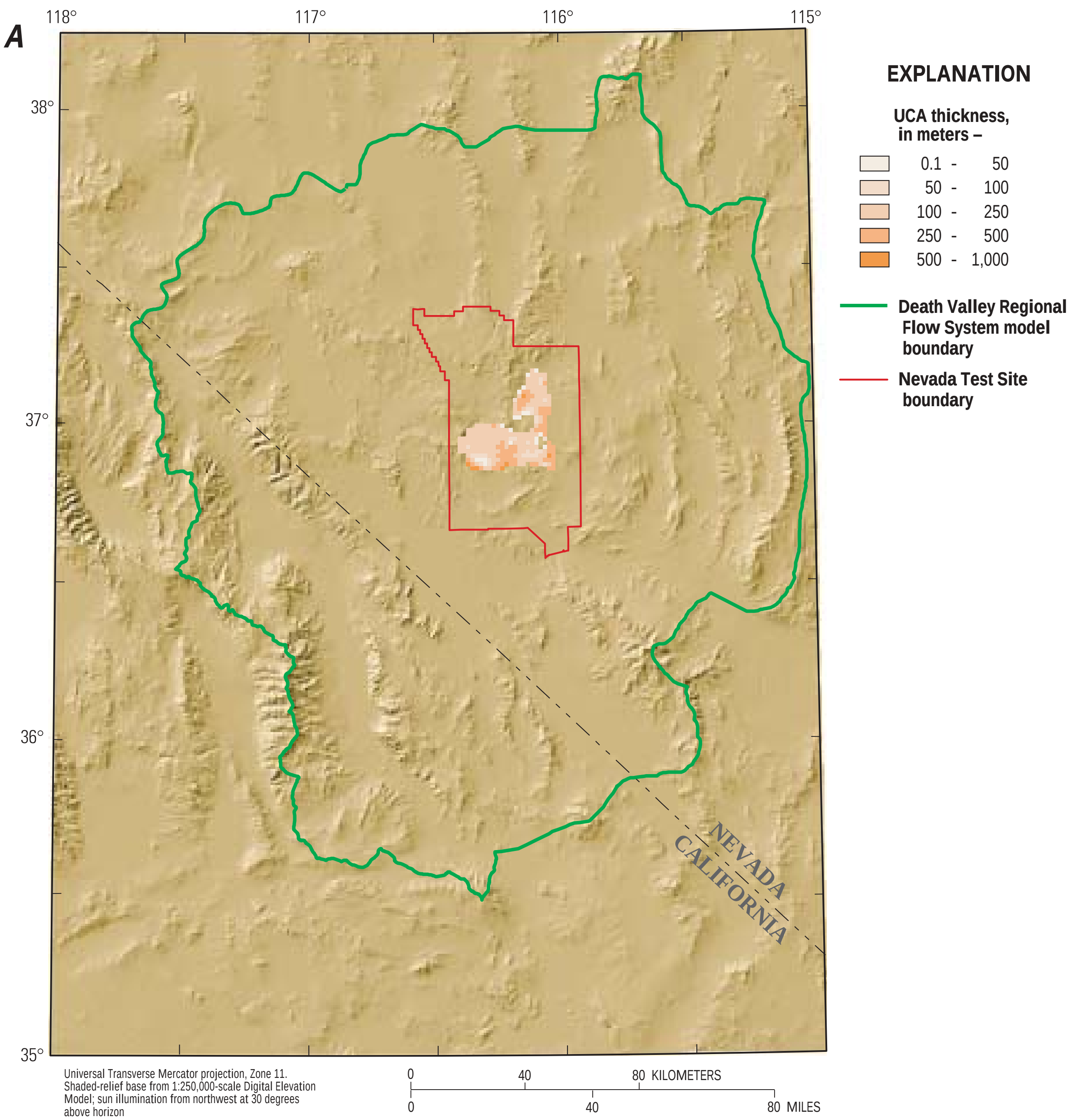

Figure 22. (***A***) Thickness of upper carbonate aquifer (UCA).

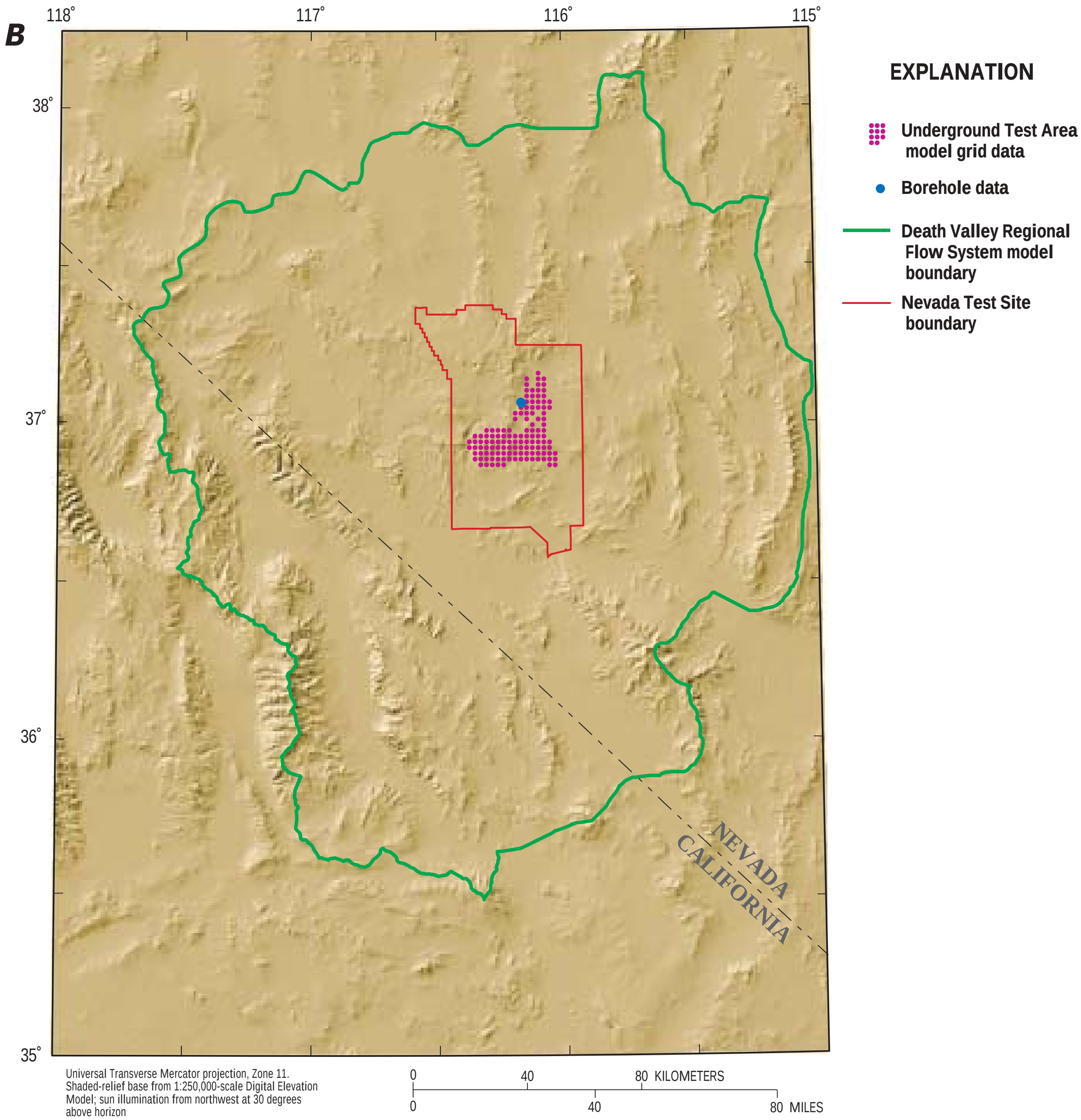

Figure 22–Continued. (***B***) Data sources used to construct gridded surface.

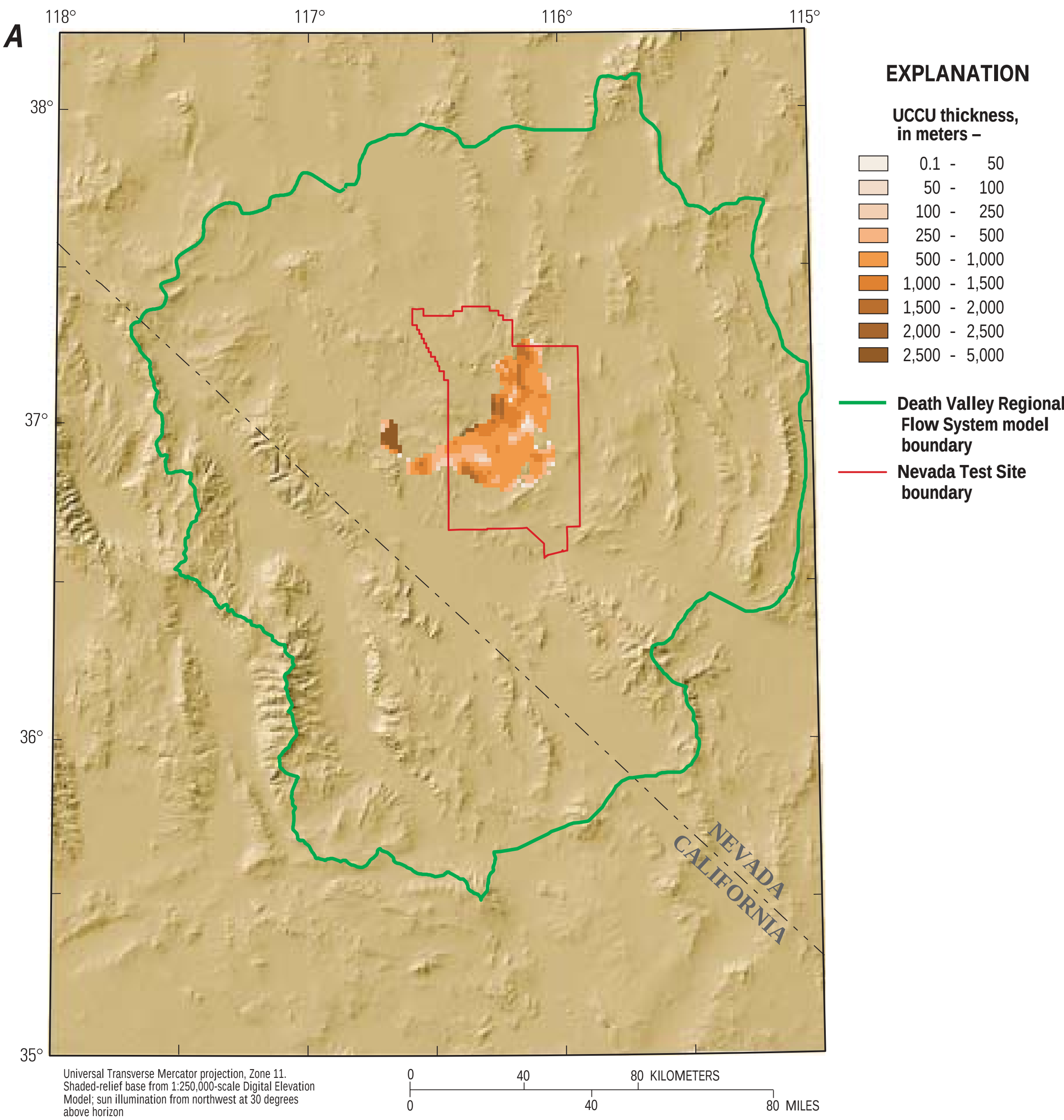

Figure 23. (***A***) Thickness of upper clastic confining unit (UCCU).

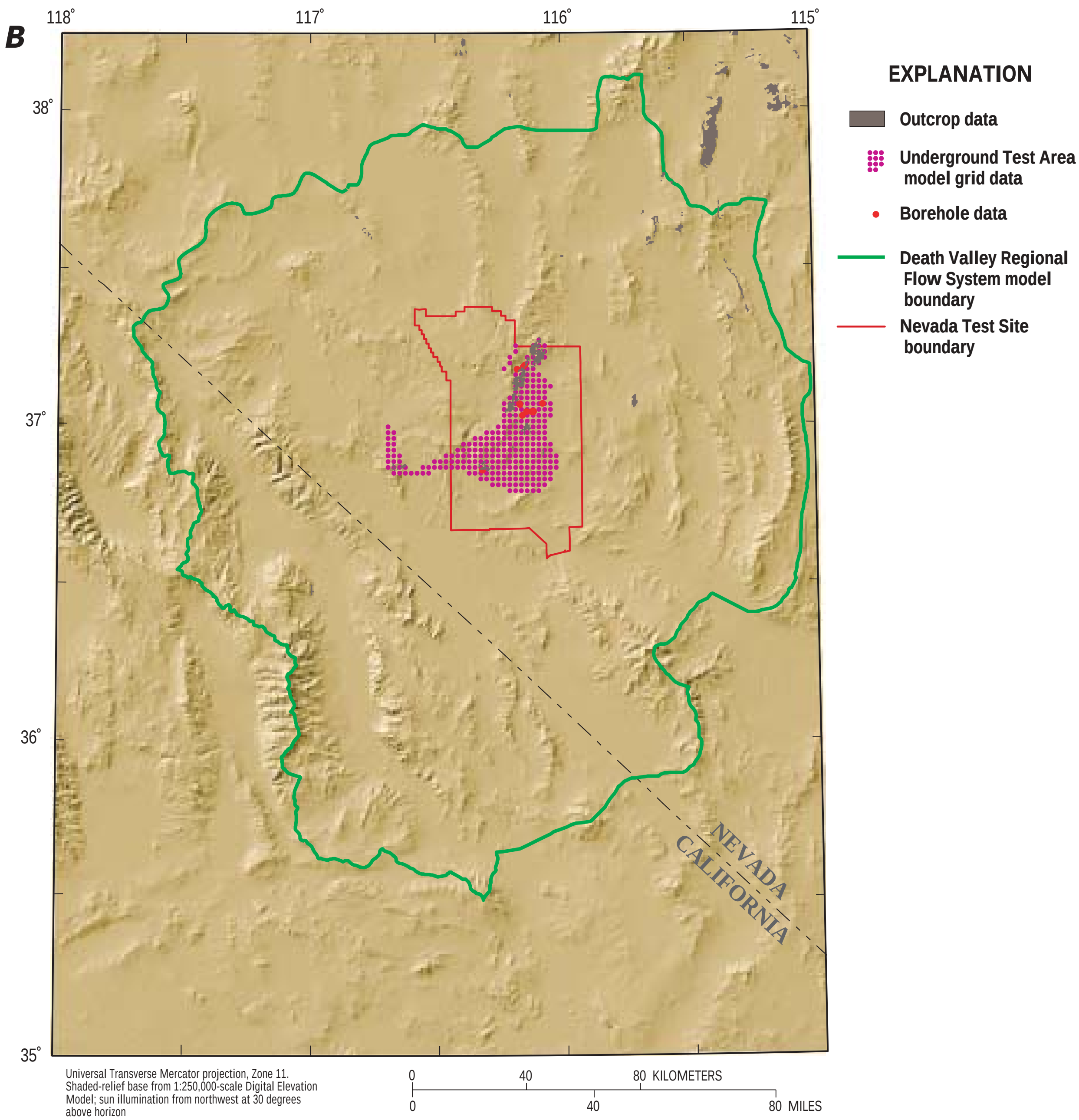

Figure 23–Continued. (***B***) Data sources used to construct gridded surface.

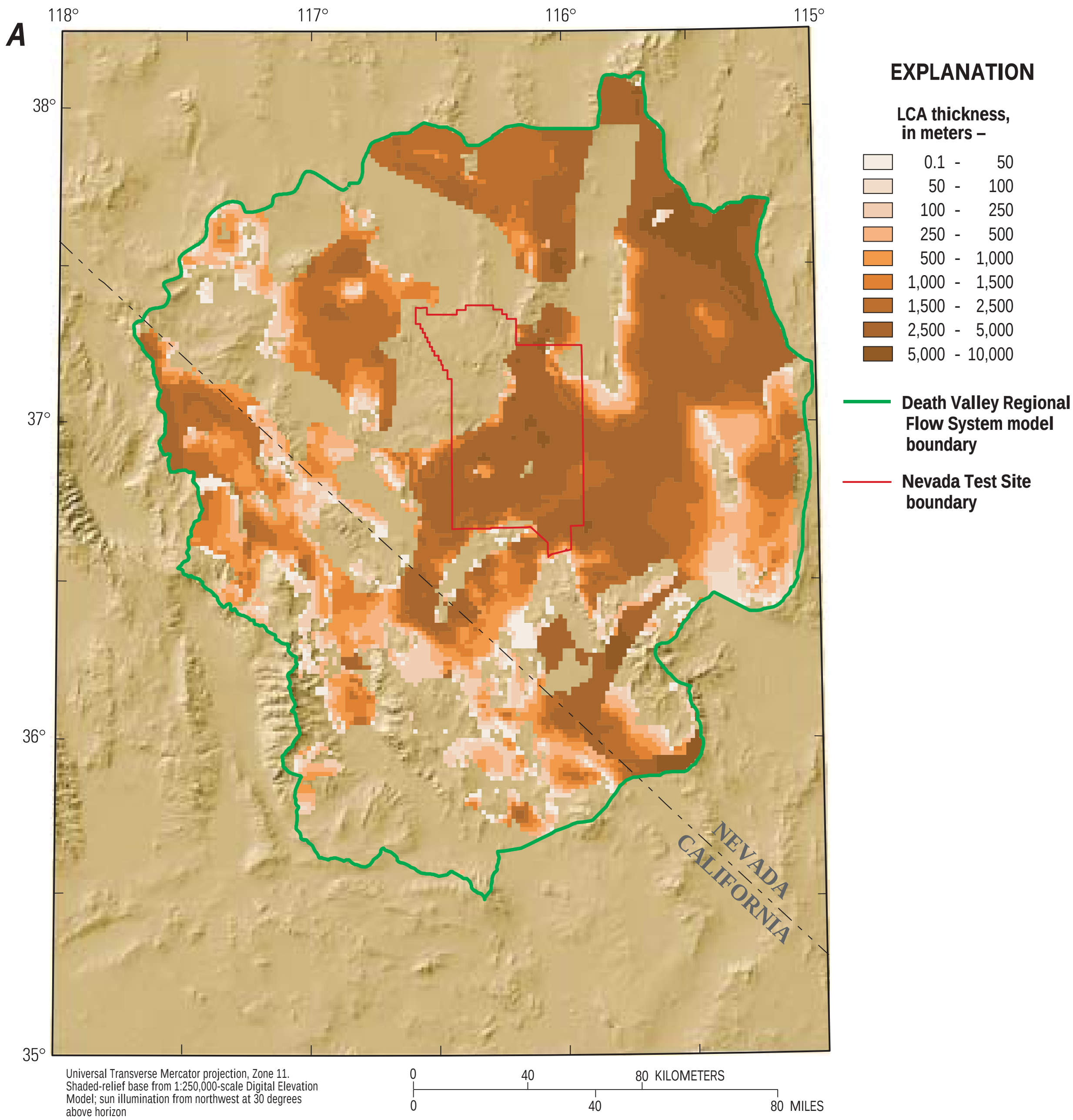

Figure 24. (*A*) Thickness of lower carbonate aquifer (LCA).

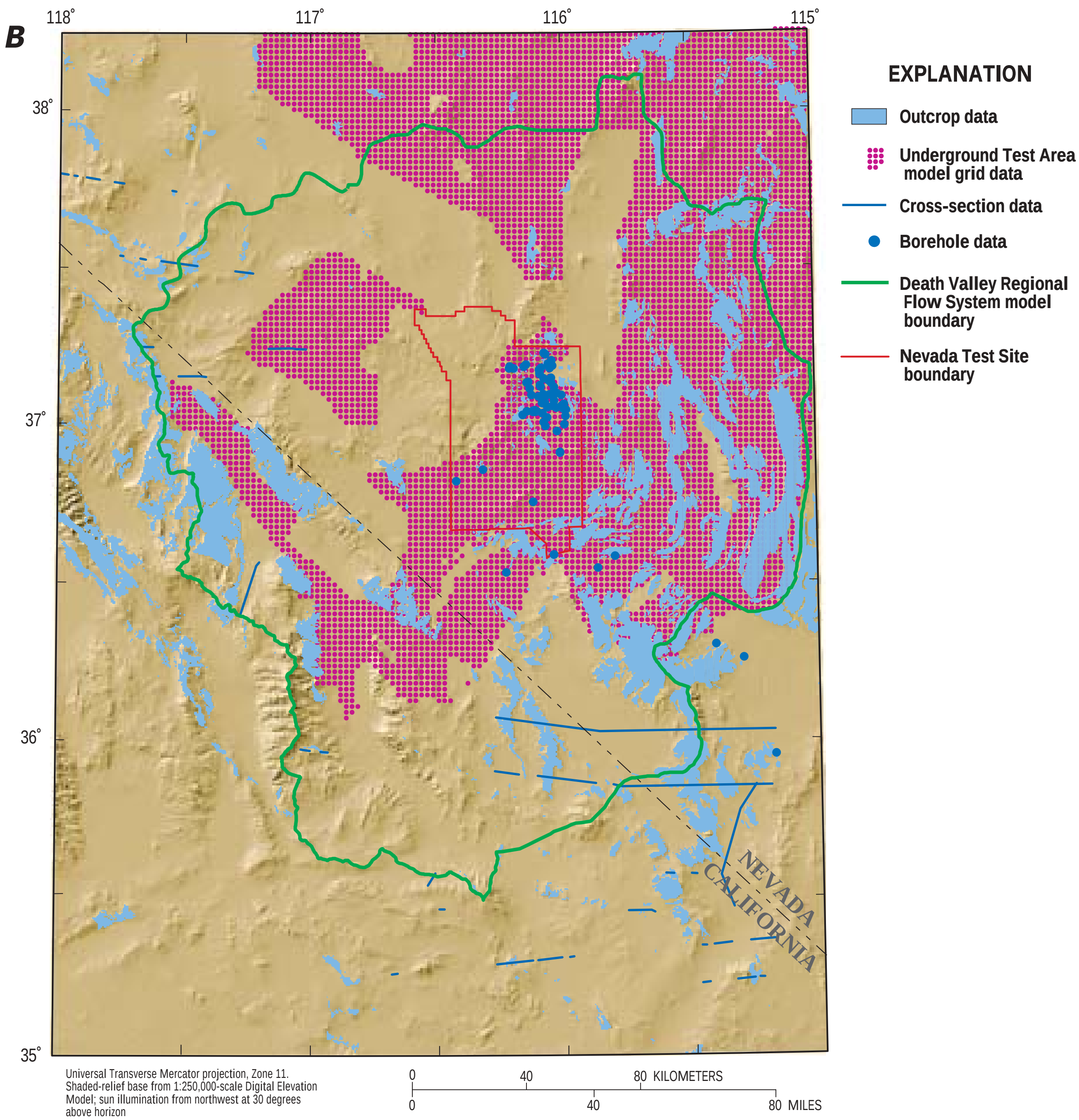

Figure 24–Continued. (***B***) Data sources used to construct gridded surface.

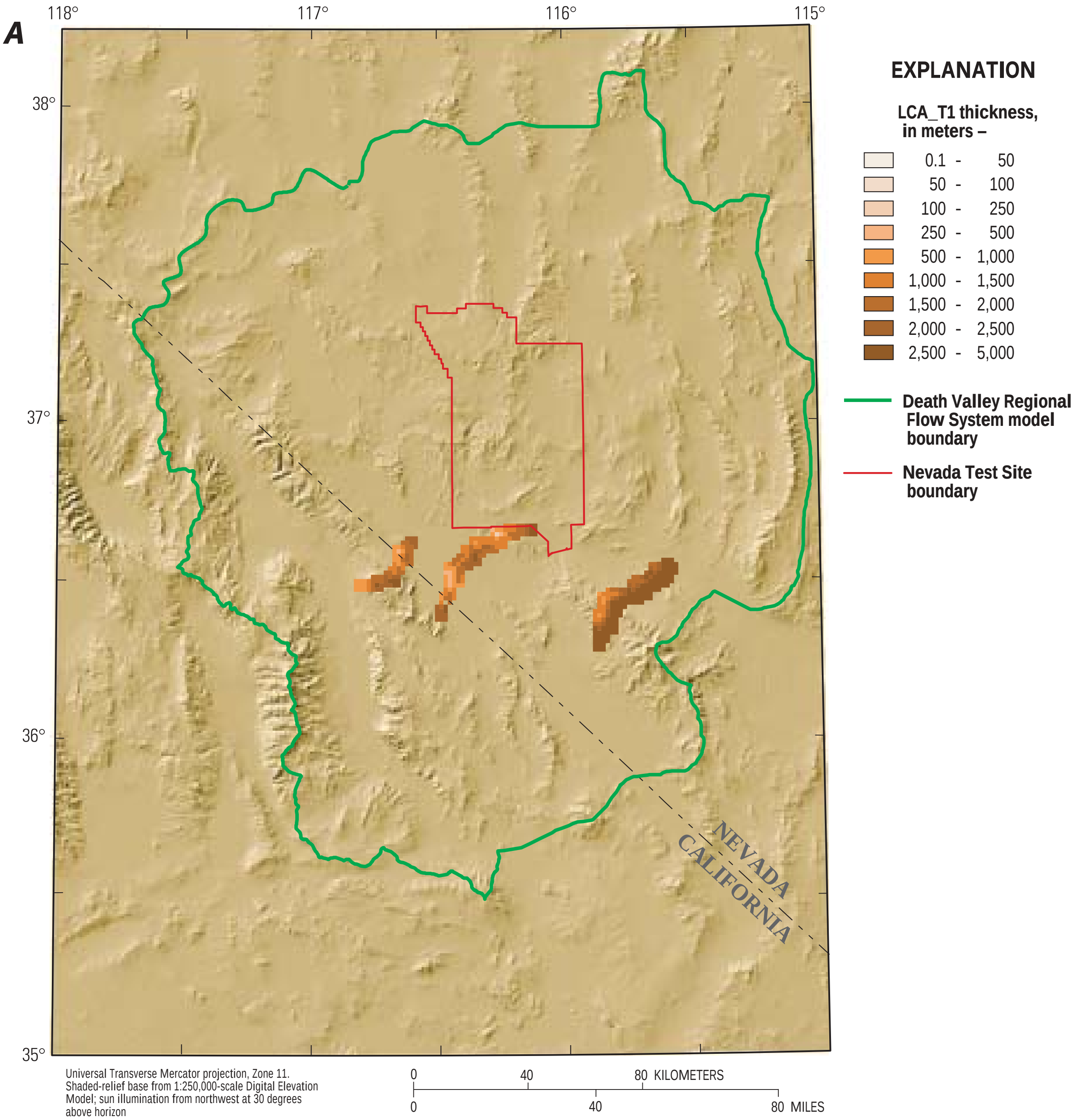

Figure 25. (***A***) Thickness of lower carbonate aquifer–Schwaub Peak, Specter Range, and Wheeler Pass lower thrust plate (LCA_T1).

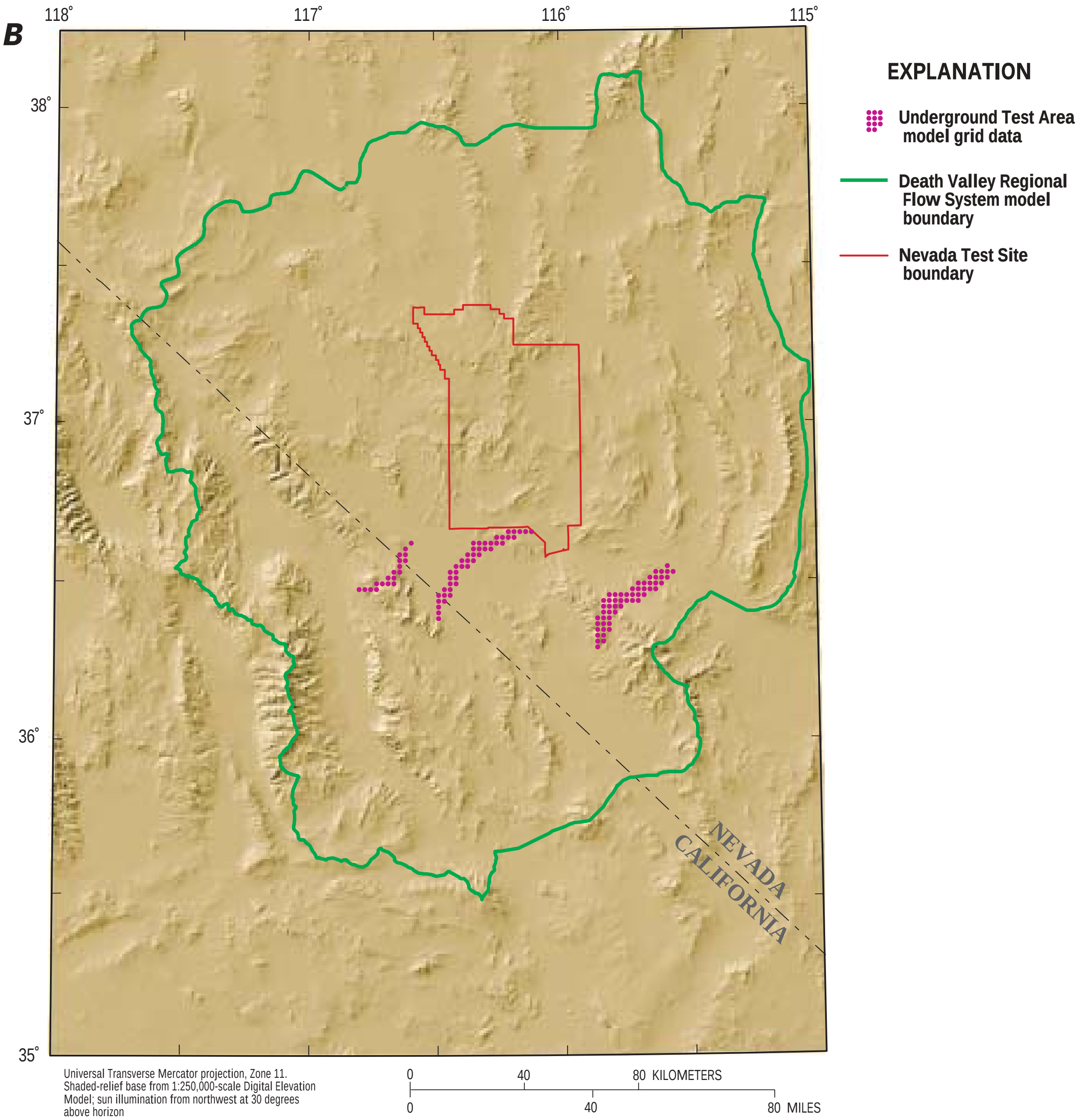

Figure 25–Continued. (***B***) Data sources used to construct gridded surface.

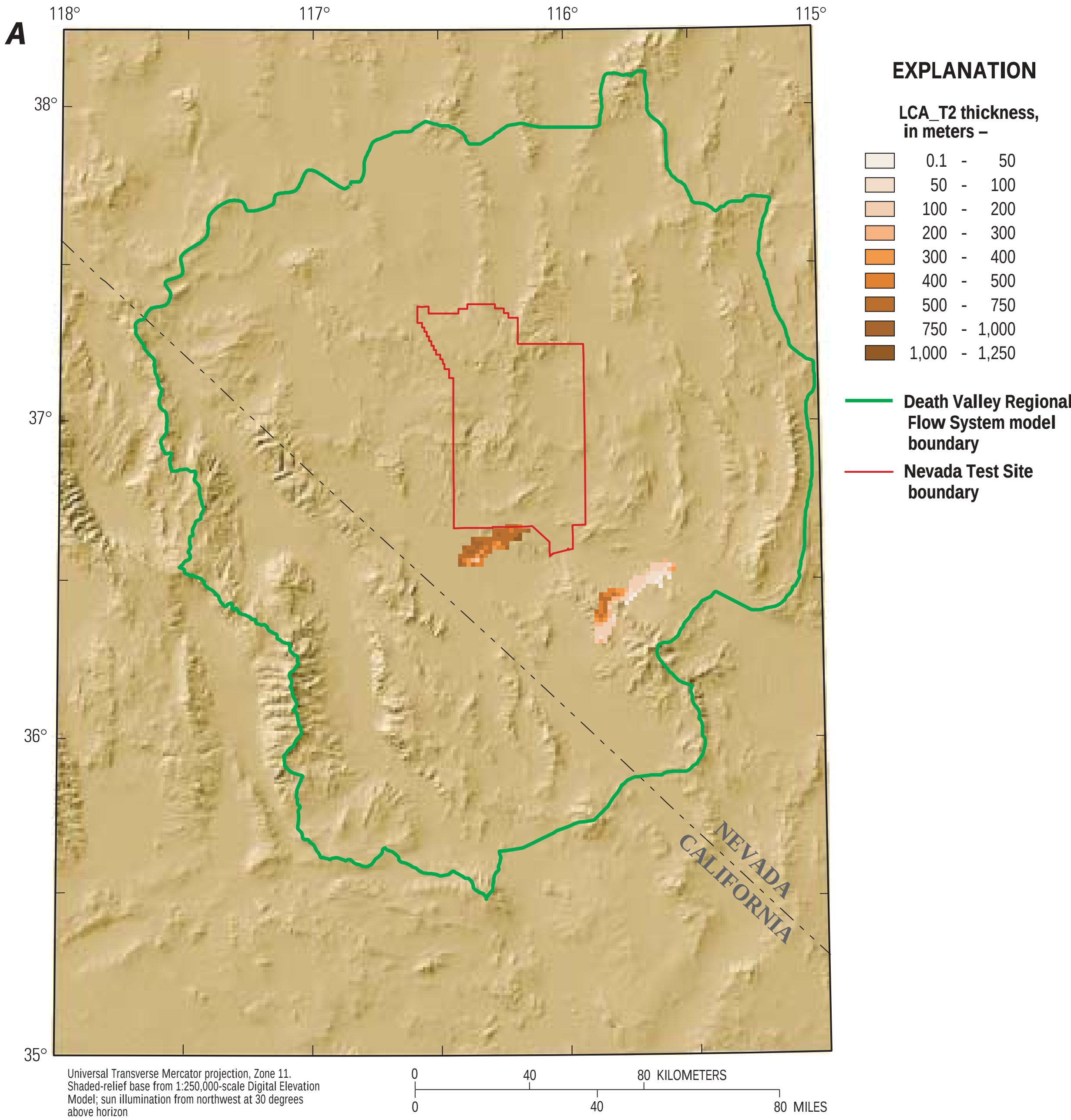

Figure 26. (***A***) Thickness of lower carbonate aquifer—Schwaub Peak, Specter Range, and Wheeler Pass upper thrust plate (LCA_T2).

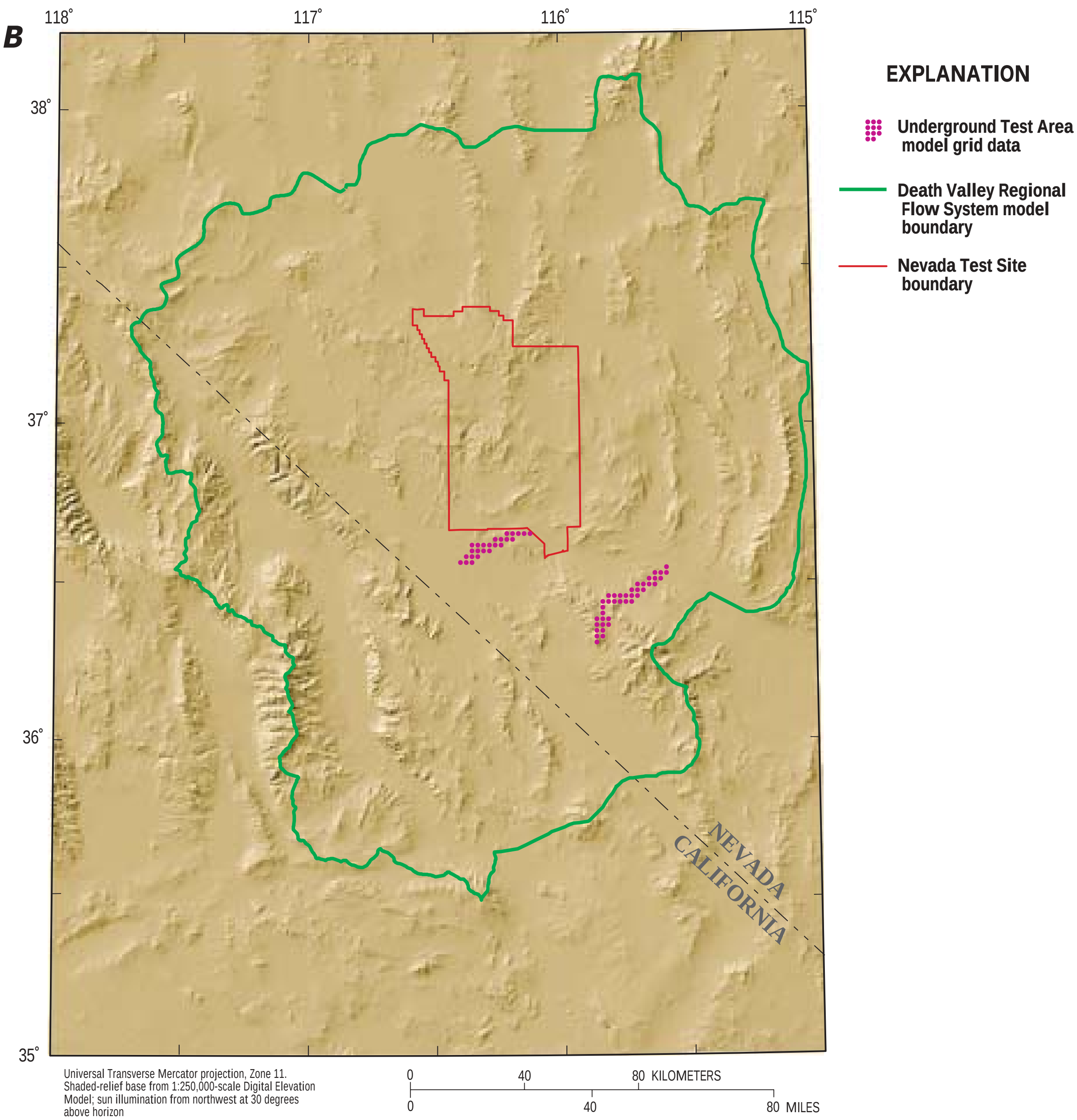

Figure 26–Continued. (***B***) Data sources used to construct gridded surface.

A

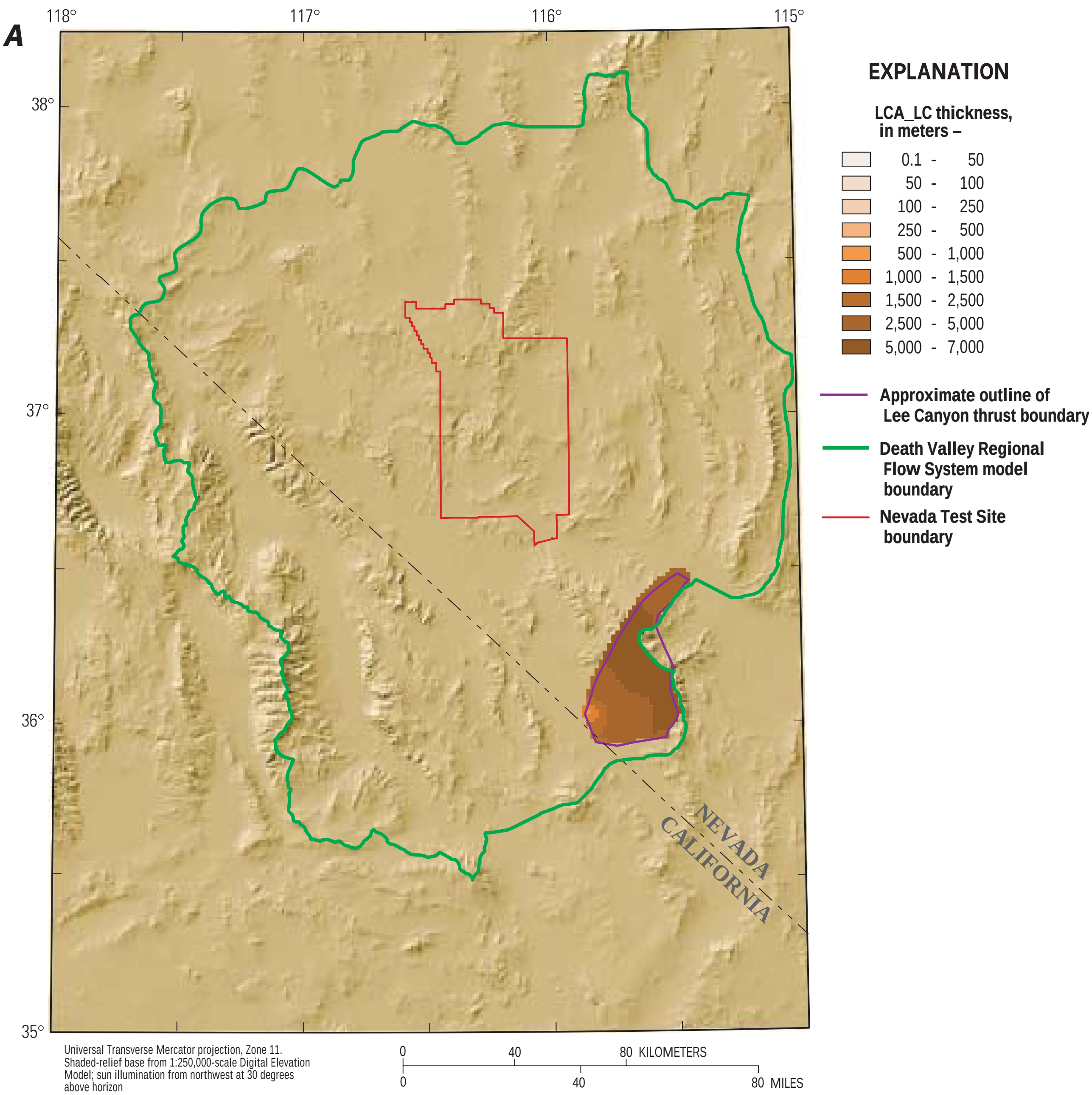

Figure 27. (***A***) Thickness of lower carbonate aquifer—Lee Canyon thrust (LCA_LC).

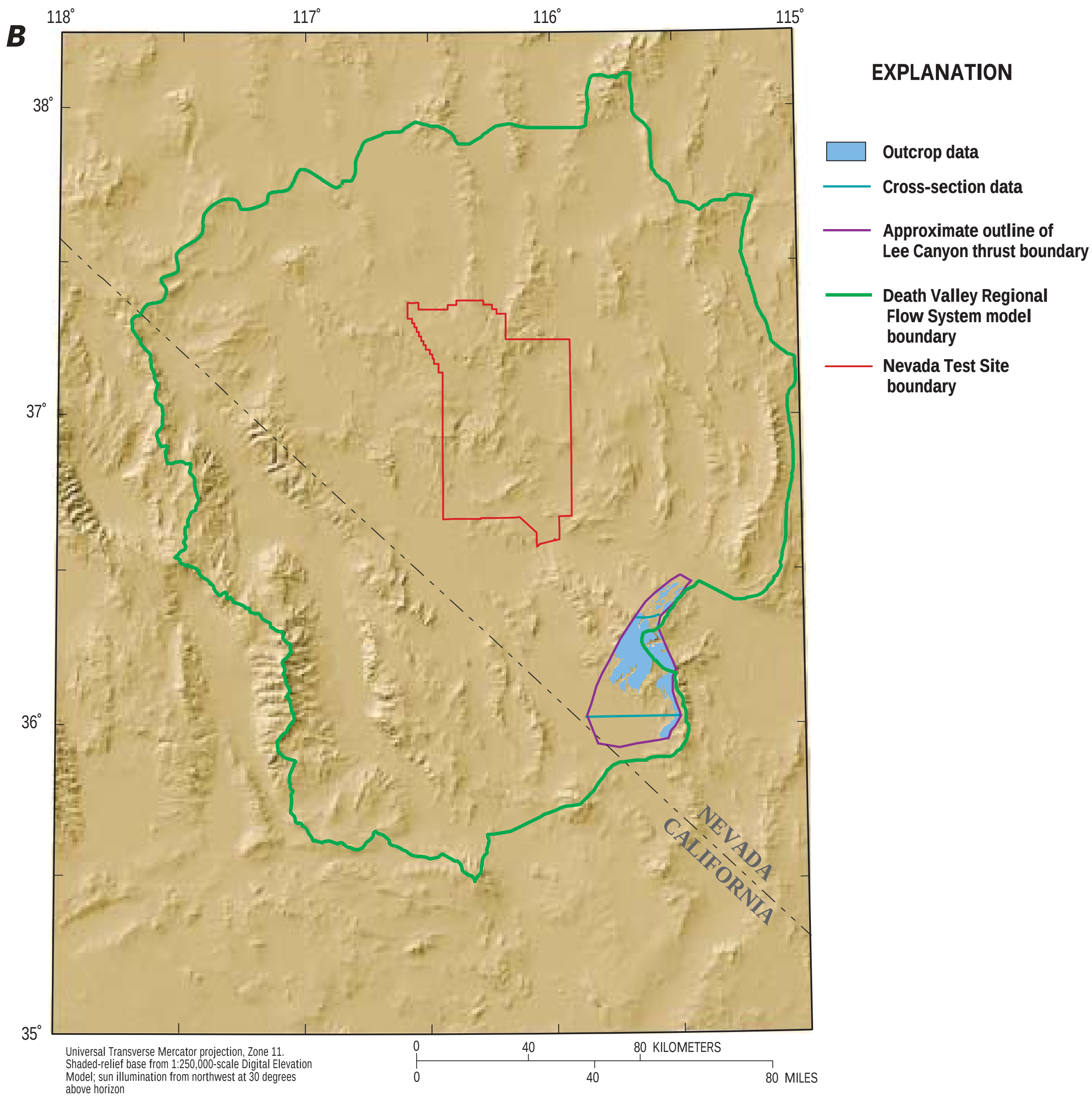

Figure 27–Continued. (***B***) Data sources used to construct gridded surface.

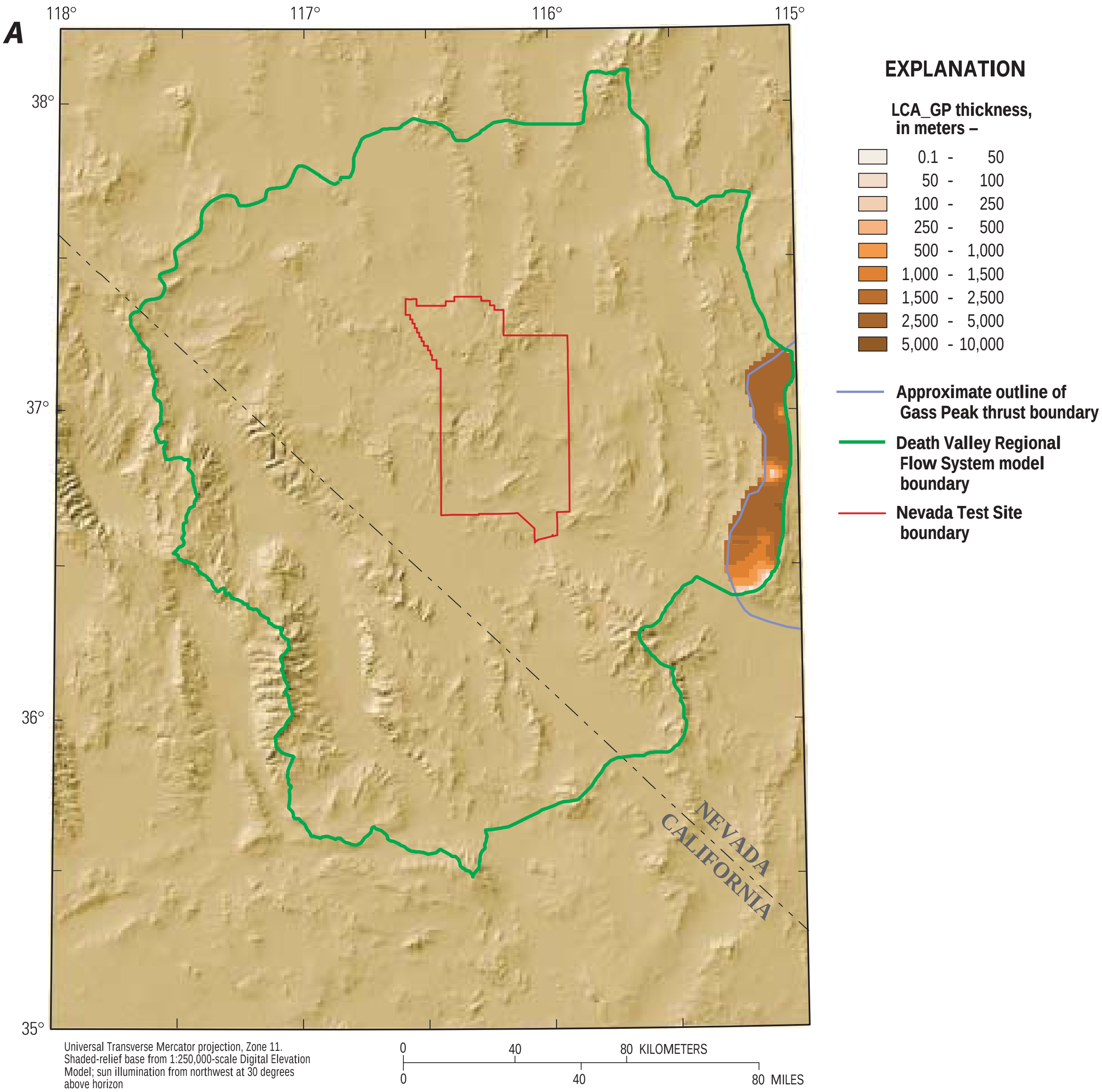

Figure 28. (***A***) Thickness of lower carbonate aquifer—Gass Peak thrust (LCA_GP).

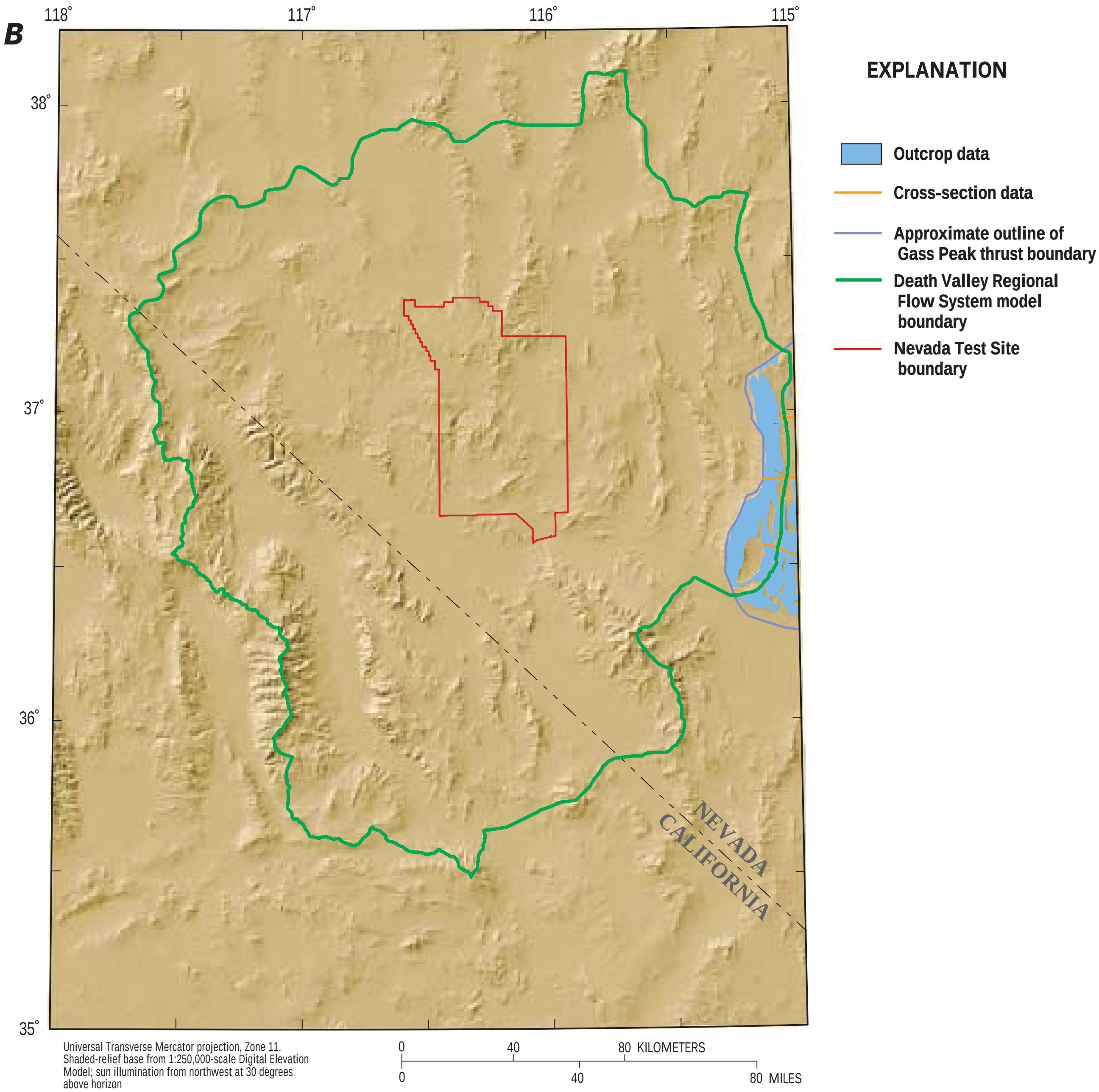

Figure 28–Continued. (***B***) Data sources used to construct gridded surface.

(U.S. Department of Energy, 1997) that the entire Paleozoic section is present in the subsurface beneath Yucca Flat, is tilted to the west, and is erosionally truncated from top to bottom beneath the volcanic cover such that the LCA thins from west to east. In central Yucca Flat where the Chainman Shale (UCCU) occurs, the full thickness of LCA at 4,400 m should occur underneath and is presented as such (U.S. Department of Energy, 1997).

In the vicinity of Cactus Flat, northwest of the NTS, the UGTA Phase I geologic model interpretation (U.S. Department of Energy, 1997) includes no LCA in the subsurface due to erosion. Instead, a thick section of volcanic rocks covers the surrounding area. LCA occurs both north and south of the Cactus Flat area. IT Corporation (U.S. Department of Energy, 1997) indicates that it is more reasonable to assume that LCA exists beneath the Cactus Range due to the sporadic presence of Mississippian-aged sedimentary rocks in the Cactus Range, but did not model this in the UGTA Phase I geologic model. IT Corporation indicates the importance of this alternative interpretation by indicating that such an interpretation would allow the LCA beneath the Cactus Range to be a hydraulic corridor for regional flow from the northern part of the region around the western edge of the NTS (U.S. Department of Energy, 1997). The LCA present south of the Cactus Range ends southward in an erosional truncation against the lower clastic confining unit where it has been uplifted by the Belted Range thrust system at Bare Mountain.

In the eastern side of the model area, the LCA has been tectonically thickened by thrust faulting to an interpreted 7,500 meters thick. A thick section of LCA is preserved in the down-dropped, east side of the Bare Mountain fault (U.S. Department of Energy, 1997). The LCA thins toward the west as it laps onto structural highs on the Halfpint/Groom Ranges uplift. This westward thinning is due to both erosion and original deposition. The LCA is up to 5,400 m (about 17,700 ft) thick east of the Halfpint-Grant Ranges uplift. The increased thickness is due to structural duplexing on Mesozoic-aged thrusts (U.S. Department of Energy, 1997).

From approximately the middle of the northern part of the model area, a west-to-east shale/carbonate facies change progressively increases the relative amount of shale in the LCA. The boundary between the lower clastic confining unit and the LCA boundary is time-transgressive and climbs through the Paleozoic section with shale increasing in the lower part. The LCA becomes increasingly shaly toward the northwestern side of the model area (U.S. Department of Energy, 1997).

Lower Clastic Confining Unit (LCCU)

Late Proterozoic to early Paleozoic siltstone, quartzite, shale, sandstone, and some metamorphic rocks form clastic confining units, designated as the lower clastic confining unit (LCCU) although it may locally be considered as an aquifer due to fracturing in some areas. The LCCU includes the lower one-third of the Lower Cambrian Carrara Formation, the Lower Cambrian Zabriskie Quartzite, the Lower Cambrian to Late Proterozoic Wood Canyon Formation, and all Late Proterozoic-aged clastic units, as well as the predominantly clastic facies of the Cambrian and Ordovician rocks in the Esmeralda County area (U.S. Department of Energy, 1997). The structural position of the LCCU has controlled its altitude and the amount of LCA preserved on top of it. Structural highs of LCCU may direct ground-water flow around those features (U.S. Department of Energy, 1997). Regionally, these rocks vary in aggregate thickness with a maximum thickness of about 3,500 m. These rocks permit negligible interstitial ground-water movement but frequently are highly fractured and locally brecciated (Winograd and Thordarson, 1975). At shallow depths, the fractures and breccias can be conduits to flow, converting the clastic rocks into locally important shallow aquifers (D'Agnese and others, 1997).

Clastic rocks in the region differ hydrologically from carbonate rocks in two important ways. First, secondary porosity rarely develops along bedding planes in any of the clastic rocks because of the low solubility of their constituents, which include quartz, mica, and clay minerals. Second, the clastic rocks deform more plastically than the carbonates and, as a result, fractures may become sealed or isolated during deformation (Winograd and Thordarson, 1975). In these rocks, the fractures may be sealed by continued deformation caused by the same process that formed them or by later plastic deformation. Open fractures in interbedded competent rocks may be sealed by plastic deformation of the less competent interbedded strata (Winograd and Thordarson, 1975).

The LCCU is a major confining unit in the region and, along with the pCgm, represents the hydraulic basement for the HFM, having a maximum thickness of 6,100 m in the flow model area of the HFM in the Groom Range (figs. 29–32). This thickness may be greater because the base of the HFM is set at 4,000 m below sea level. The holes in the surface presented in figure 29*A* are areas where the gridded surface altitudes are less than 4,000 m below sea level, intrusive bodies penetrate the unit, or where the Precambrian granite and metamorphic rock unit is present.

East of the Bare Mountain Fault, the LCCU is down-dropped by this fault. West of the Bare Mountain Fault, the LCCU crops out in the Funeral Mountains. The western arm of the Amargosa alluvial basin is interpreted to be shallow and to be floored by structurally high LCCU and a relatively thin veneer of Tertiary sediments beneath the alluvium. The LCCU is exposed at the surface northwest of Yucca Flat in the Eleana Range (U.S. Department of Energy, 1997).

West of the Silent Canyon caldera complex, the LCCU is exposed along the western boundary of the model area. The LCCU crops out locally in the San Antonio Mountains and in a large area on the western side of the model area south of the San Antonio Mountains (fig. 1). On the east side of the HFM, the LCCU is structurally high in a long, north-south-trending uplift that extends from the Halfpint Range to the Groom Range (U.S. Department of Energy, 1997). LCCU is interpreted in the UGTA Phase I geologic model (U.S. Department of Energy, 1997) to be present in a position beneath Emigrant Valley between the Belted Range and the Groom Range. As presented in the UGTA Phase I geologic model (U.S. Department of Energy, 1997), the LCA was completely eroded from the LCCU before deposition of the volcanic rocks in Emigrant Valley.

The LCCU contains thrusts of this unit from the Belted Range thrust system, which strikes southwestward from Rainier Mesa. It has been interpreted to connect with a thrust at Bare Mountain where the same structural relations are displayed (Caskey and Schweickert, 1992; Cole and Cashman, 1999), and this interpretation was made in the UGTA Phase I geologic model (U.S. Department of Energy, 1997). In the southern NTS, this thrust system would lie to the north of a UCCU exposure in Calico Hills. The Belted Range thrust is represented as a thickened zone of LCCU.

In the framework model, the LCCU also is present explicitly as four explicitly thrusted units—the combined upper and lower plates of the Specter Range and Wheeler Pass thrust (LCCU_T1 (fig. 30) and LCCU_T2 (fig. 31), respectively) in the Amargosa Desert area and the Gass Peak thrust (LCCU_GP [fig. 32]) in the Sheep Range. The Belted Range thrust system (represented implicitly as thickened sections in the framework model) is one of the most prominent hydrogeologic features in the area of investigation. The thrust juxtaposes two regionally important confining units (LCCU and UCCU) and, therefore, can be a significant barrier to ground-water flow. It is apparent that few major Tertiary extensional faults cross the thrust system to disrupt this barrier. The one exception is the Bare Mountain Fault, which has positioned the Crater Flat basin across this feature (U.S. Department of Energy, 1997).

Precambrian Granites and Metamorphic Rocks (pCgm)

Crystalline metamorphic and igneous rocks of Middle Proterozoic age and metamorphosed Late Proterozoic sedimentary rocks (pCgm) are widespread throughout the southern part of the region, cropping out in many mountain ranges and underlying most of the area at depth (Bedinger and others, 1989a). Hydrologically, this unit behaves similarly to the other crystalline rocks (such as the intrusive bodies) in the Death Valley region. Ground water is thought to exist only locally in these crystalline bodies where the rock is fractured. Because the fractures are poorly connected, these rocks act mostly as confining units or barriers to flow (D'Agnese and others, 1997).

The UGTA Phase I geologic model combined the foliated Middle Proterozoic metamorphic rocks (pCgm) and the metamorphosed clastic rocks (LCCU) into a single LCCU basement unit (U.S. Department of Energy, 1997). Because of the possible different hydrologic character of these two rock groups, the pCgm was separated from the clastic LCCU. Map and cross-section data used to produce the HFM described in D'Agnese and others (1997) were used to create a pCgm gridded surface interpretation. This surface was then mathematically applied to separate out the LCCU from the basement unit in the UGTA Phase I geologic model. All altitudes from the UGTA Phase I LCCU unit above the pCgm surface were assigned as being part of the LCCU horizon surface.

The pCgm forms the base of the HFM, the ultimate basement of the region. Because these rocks are cratonic rocks, they should occur everywhere beneath the model (fig. 33), except possibly beneath the

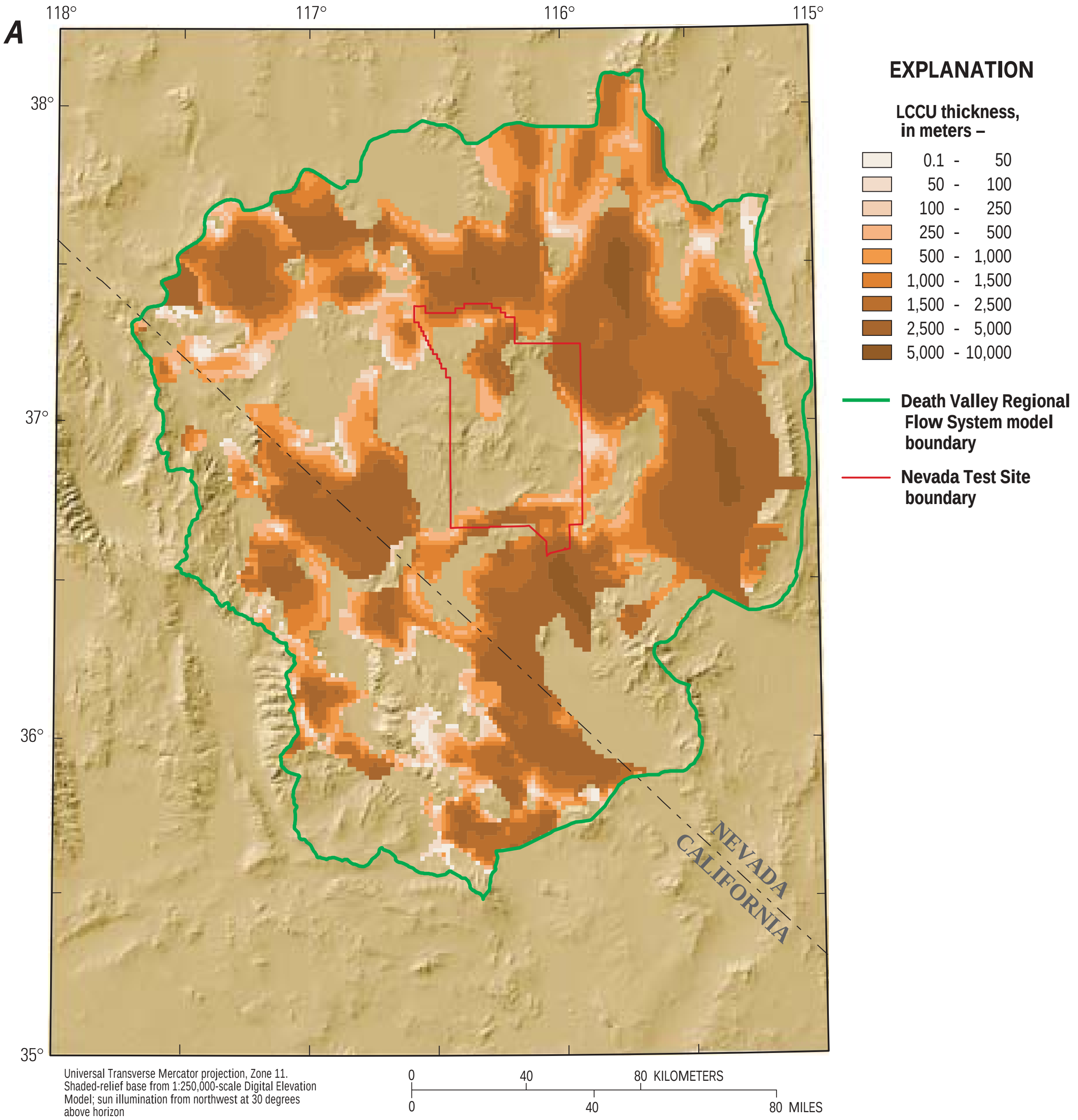

Figure 29. (*A*) Thickness of lower clastic confining unit (LCCU).

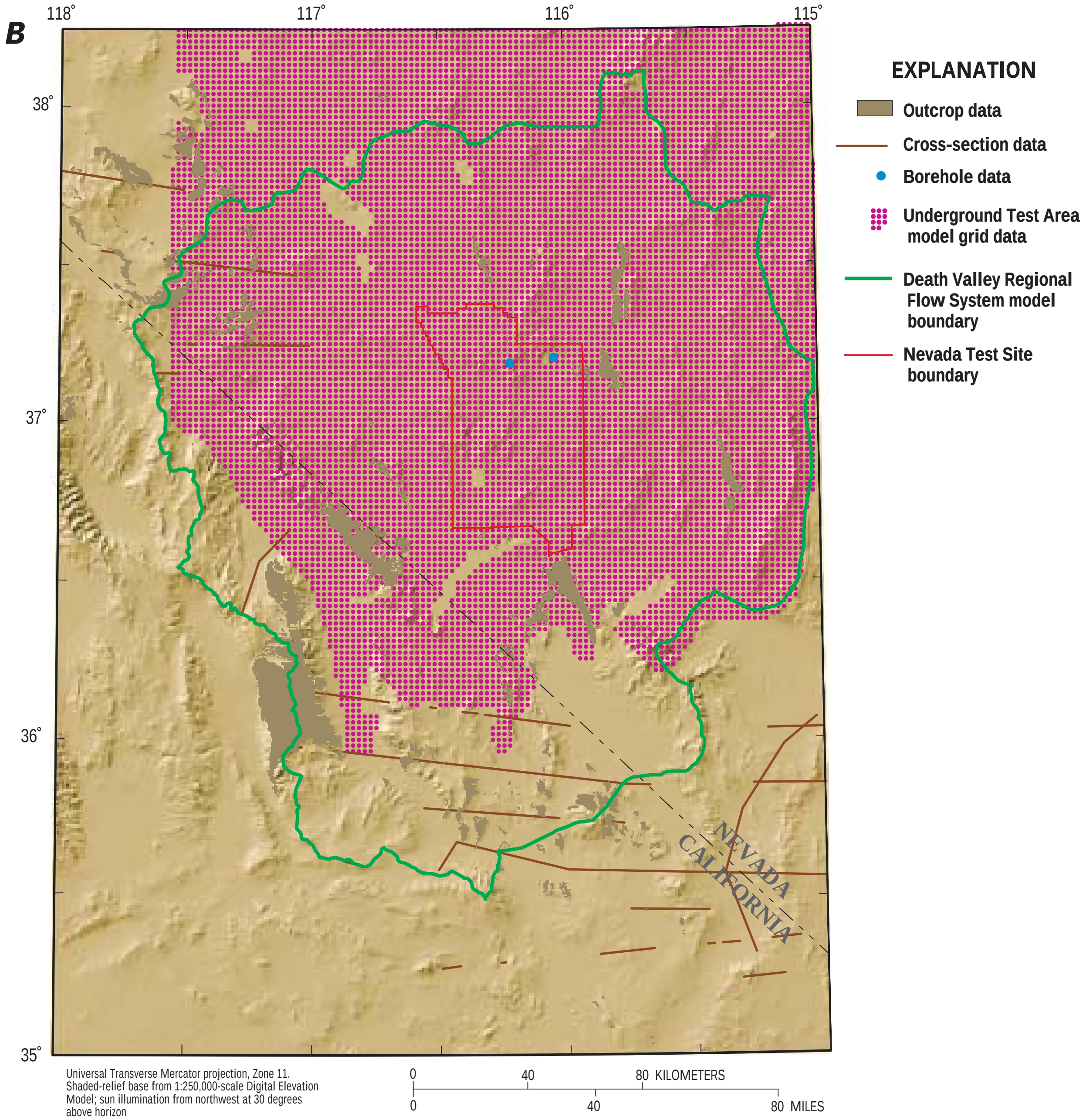

Figure 29–Continued. (***B***) Data sources used to construct gridded surface.

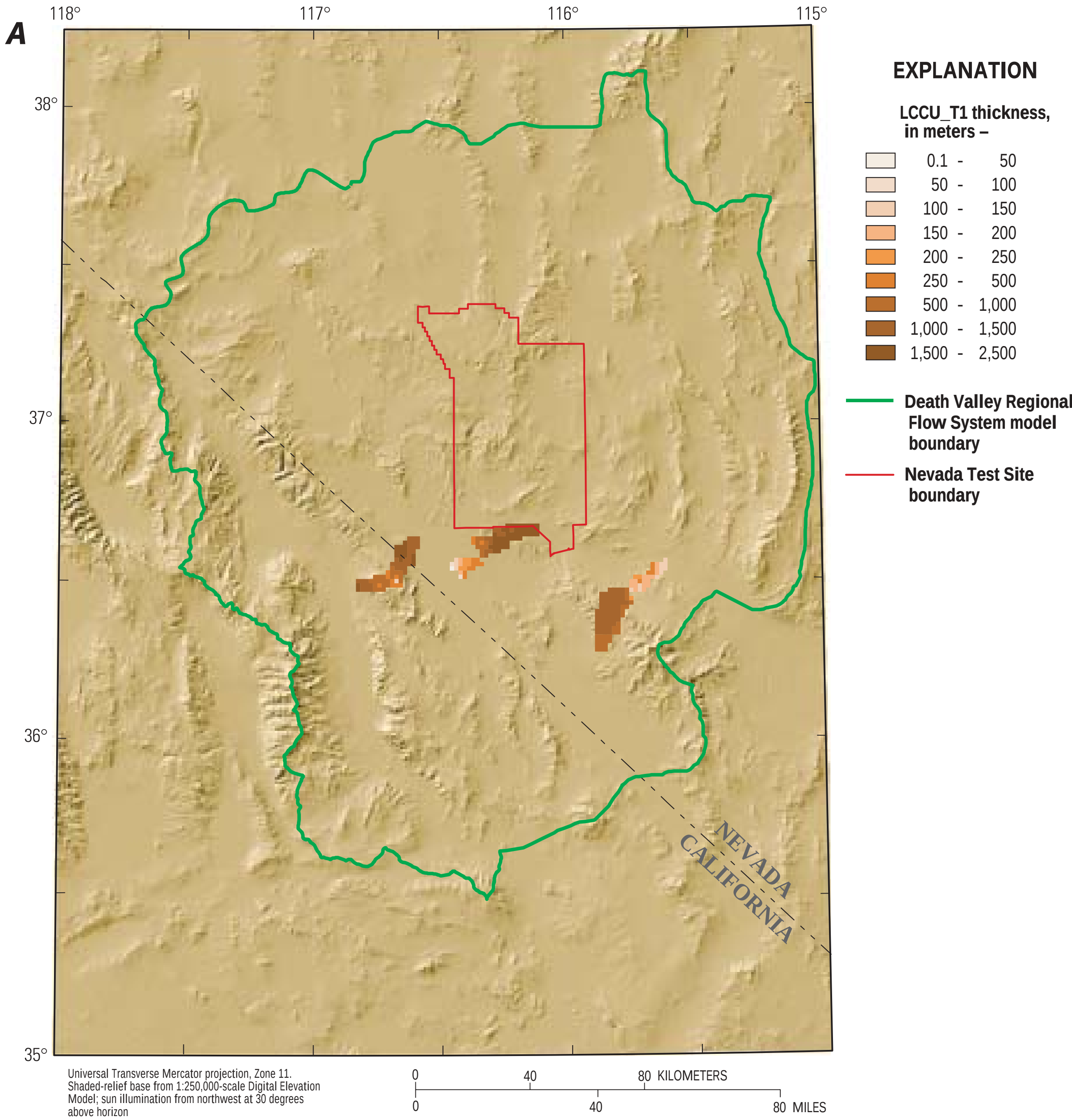

Figure 30. (***A***) Thickness of lower clastic confining unit—Schwaub Peak, Specter Range, and Wheeler Pass lower thrust plate (LCCU_T1).

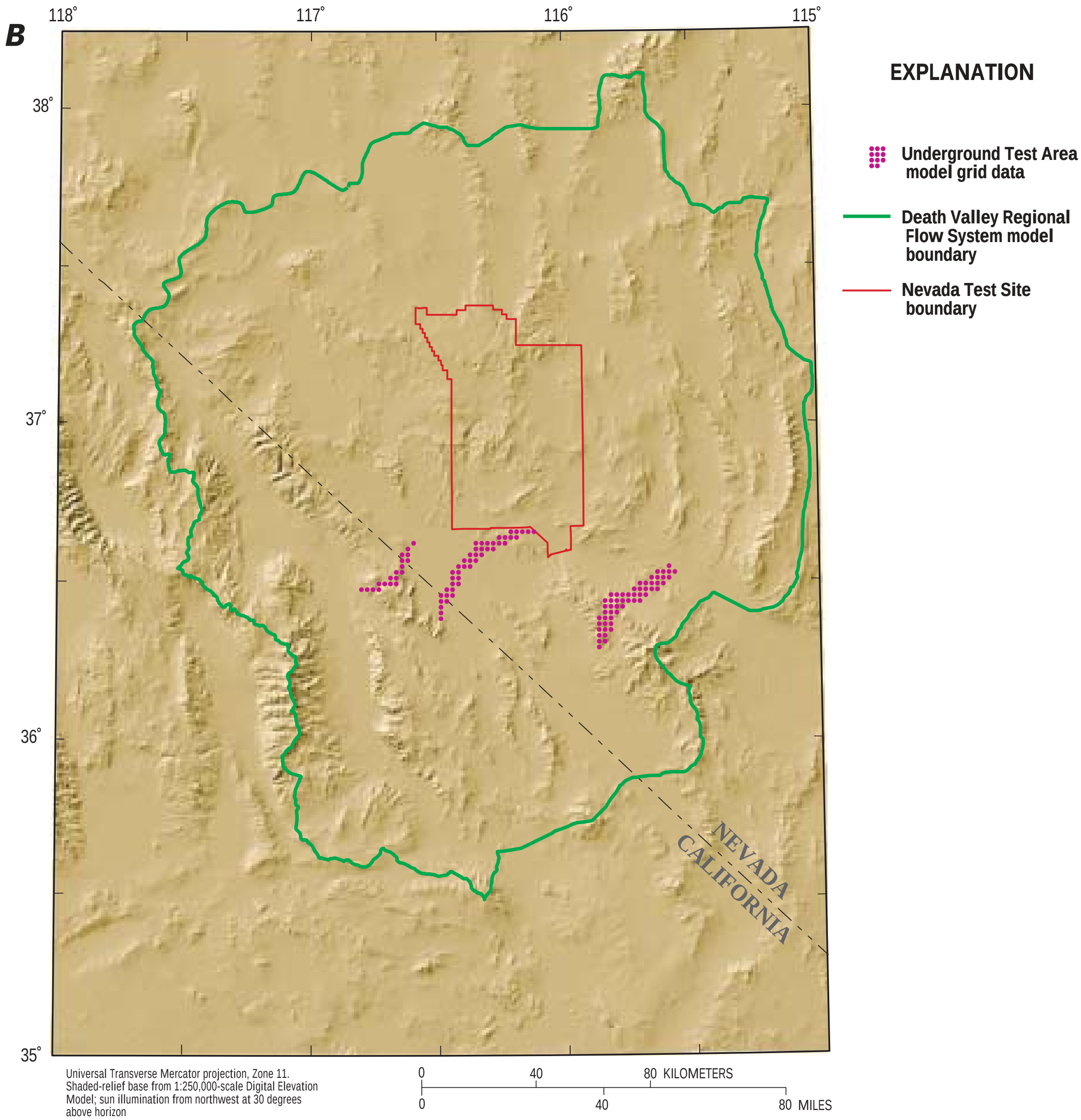

Figure 30–Continued. (***B***) Data sources used to construct gridded surface.

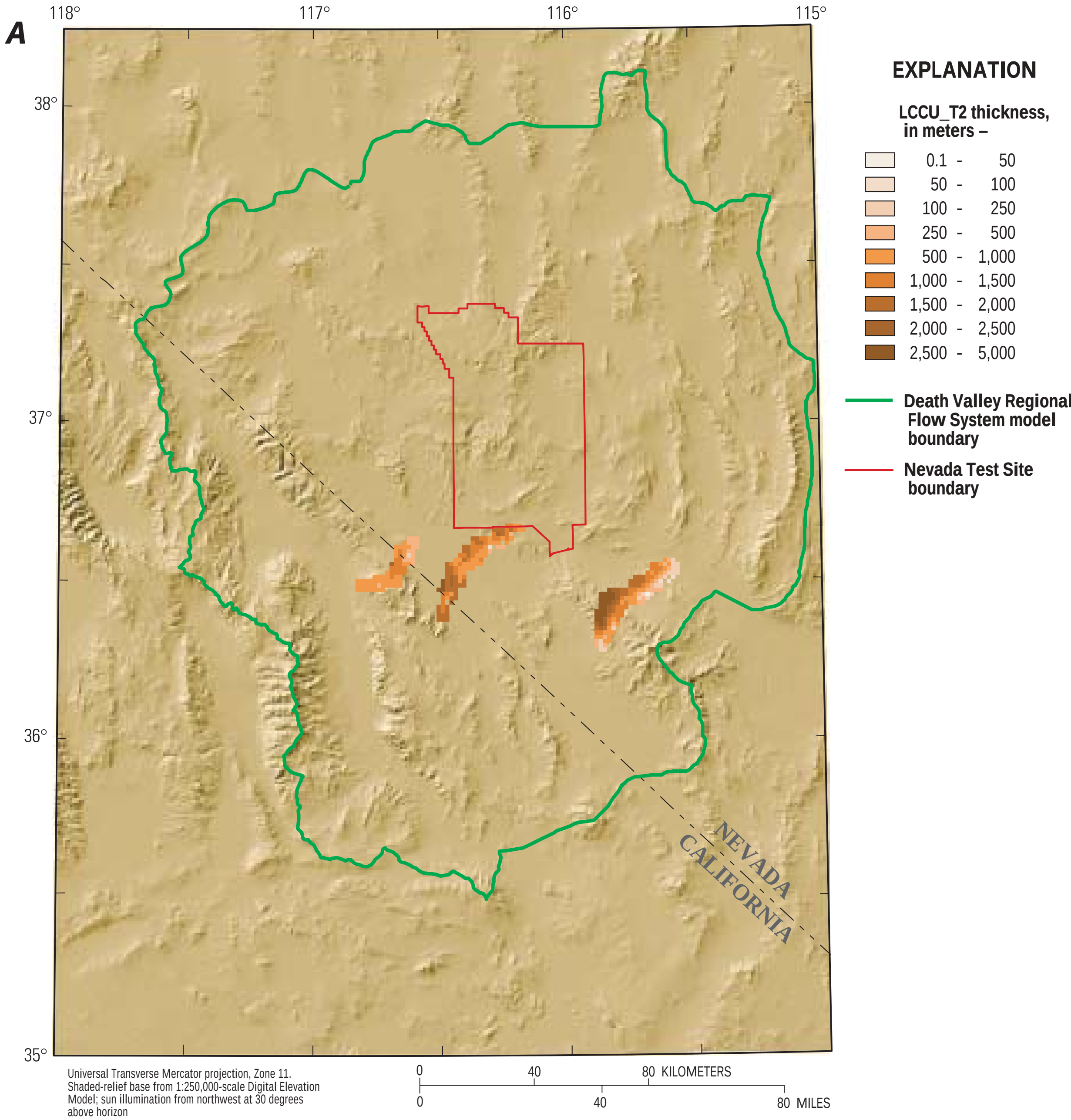

Figure 31. (***A***) Thickness of lower clastic confining unit—Schwaub Peak, Specter Range, and Wheeler Pass upper thrust plate (LCCU_T2).

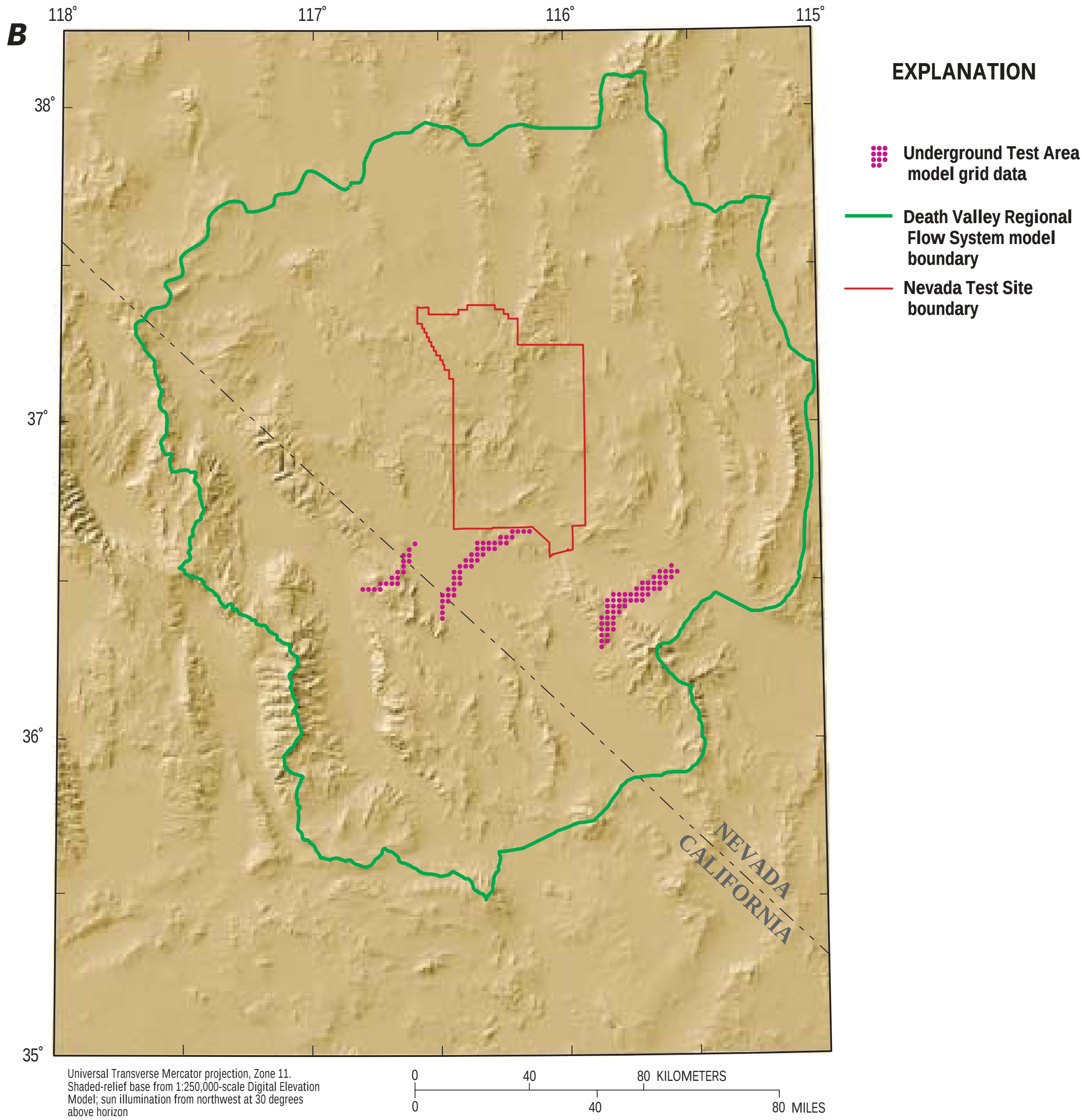

Figure 31–Continued. (***B***) Data sources used to construct gridded surface.

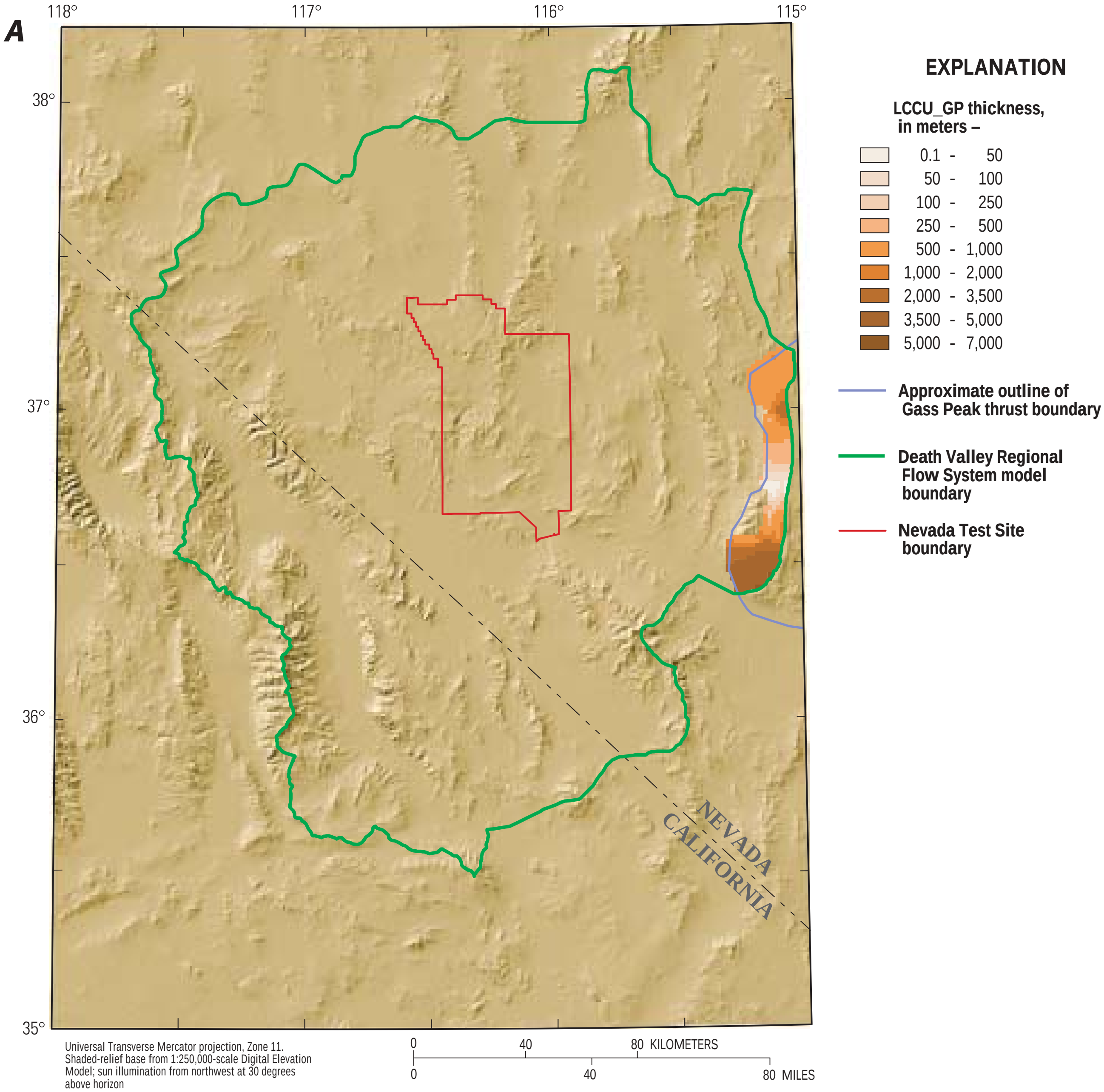

Figure 32. (***A***) Thickness of lower clastic confining unit—Gass Peak thrust (LCCU-GP).

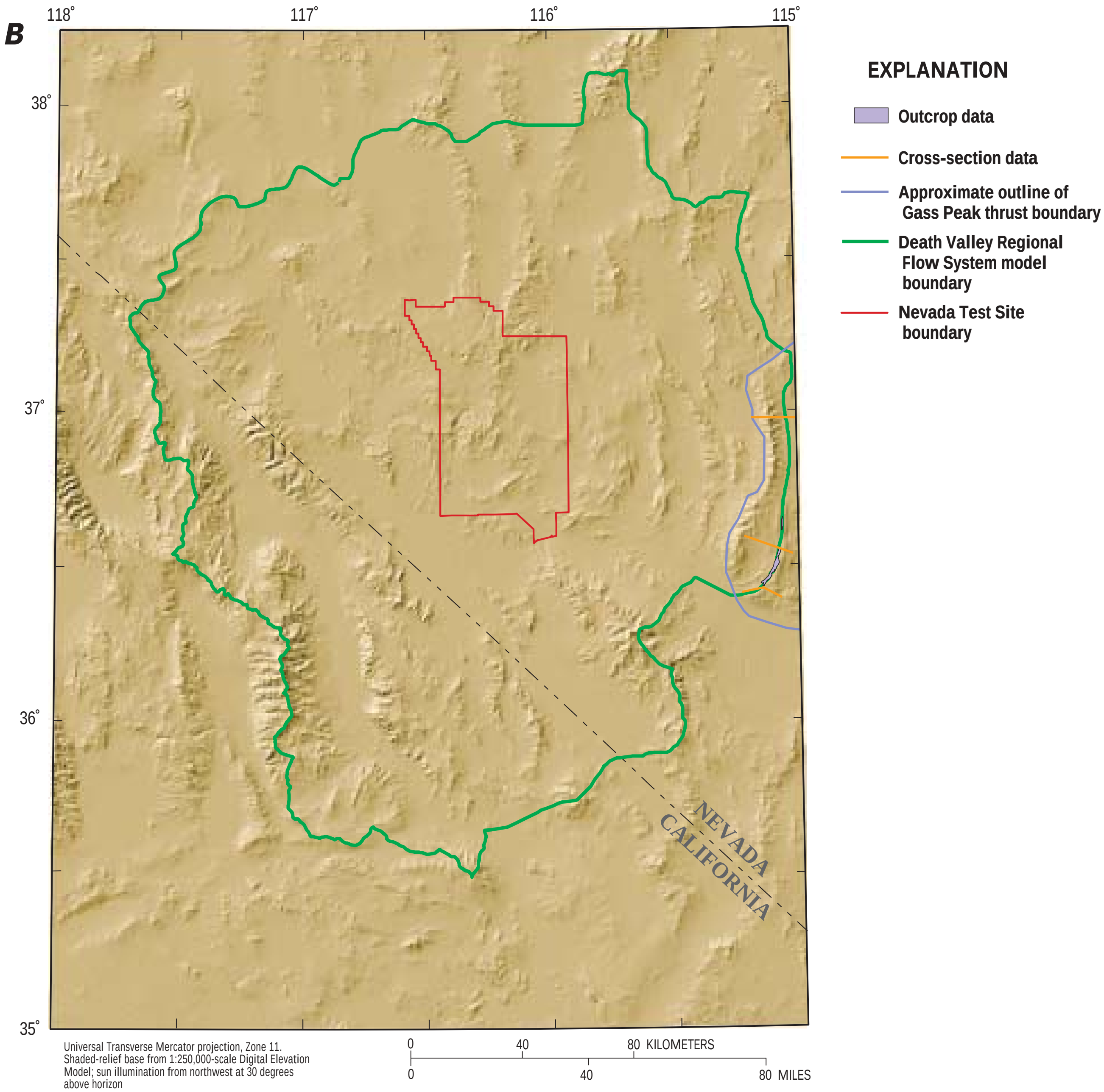

Figure 32–Continued. (***B***) Data sources used to construct gridded surface.

calderas. They have a maximum thickness of 5,600 m in the flow model area of the HFM in the southern Panamint Range (fig. 33*A*). The HFM only extends to 4,000 m below sea level and often truncates this unit. The pCgm probably does not exist beneath the calderas at Timber Mountain and Pahute Mesa depicted in the framework model. The upwelling magma and volcanic activity during the Cenozoic most probably completely destroyed or completely altered the character of the country rocks. The caldera rocks probably merge into the cratonic rocks at depth, at least with respect to hydrogeologic properties, becoming relatively impermeable and indistinguishable from the cratonic rocks. The holes in the surface presented in figure 33*A* represent areas where the surface altitudes are less than 4,000 m below sea level (the base of the HFM) or where intrusive bodies penetrate the unit.

Tertiary-Jurassic Intrusives (TJi)

Crystalline granitic rocks of Mesozoic and Tertiary age (TJi) are widespread throughout the southern part of the region and occur as isolated plutonic bodies in the northern part of the framework model (fig. 34*A*). They crop out in many mountain ranges and underlie most of the southern part of the region at depth (Bedinger and others, 1989a). Ground water is thought to occur in these crystalline rocks only where they are fractured. Because these fractures are poorly connected, these units act mostly as confining units or barriers to flow.

The unit has a maximum thickness of 6,500 m in the flow area of the HFM in the southern Panamint Range (fig. 34). This thickness is limited by the lower boundary of the HFM at 4,000 m below sea level. Intrusive rocks crop out in the Panamint Range, Black Mountains, Owlshead Mountains, Kingston Range, Avawatz Mountains, Granite Mountains, and Soda Mountains. Several intrusions occur in the northern one-third of the model area. The intrusive bodies that occur in the framework model area are treated as vertical-sided blocks cutting through all layers in the HFM.

APPLICATION OF THREE-DIMENSIONAL FRAMEWORK MODEL

Evaluating the Model

The 3D framework was evaluated once it was constructed. These evaluations consisted of visual inspection of the gridded surfaces and various mathematical manipulations of the grids to assess extent and thickness of the hydrogeologic units. The model was sliced vertically along the grid cells corresponding to a series of north-south and east-west cross sections, creating a fence diagram. These slices were then displayed and could be rotated and viewed from any desired orientation (fig. 35). In addition, surfaces of the altitude of each hydrogeologic unit were also constructed. The displays along these sections and the surfaces represent the contents of the 3D geocellular model and reflect all of the processing steps. Thickness grids also were constructed to examine for potential areas of geologic unreasonableness. Gridded surfaces of the altitudes also were compared to the input data used to construct the grids to assess the accuracy of the gridding processes. Comparing the gridded surfaces with those from the UGTA Phase I geologic model and the YMP hydrogeologic framework model provided a suitable method of evaluating the fidelity of the framework model representation. Where necessary, gridding was revised using different gridding algorithm settings to produce a closer match to known geologic conditions or manually edited to reflect professional judgment.

The YMP hydrogeologic framework model (D'Agnese and others, 1997) and the UGTA Phase I geologic model (U.S. Department of Energy, 1997) were both evaluated to assess how well each model represented the subsurface hydrogeologic interpretation each was intended to model. The hydrogeologic framework model described in this report was also evaluated for how well it represented the subsurface hydrogeologic interpretation. Reasonably good agreement between the framework model and the two previous framework models (D'Agnese and others, 1997; U.S. Department of Energy, 1997) was found. The model sections retain the basic lithology and geometrical characteristics needed for the numerical ground-water flow modeling.

Discrepancies can be seen on some of the model surface. The gridding algorithm tends to extrapolate grids one grid cell beyond the limits of the data. Coupling this with the tendency of SGM to extrapolate grids one cell farther than necessary at onlapping

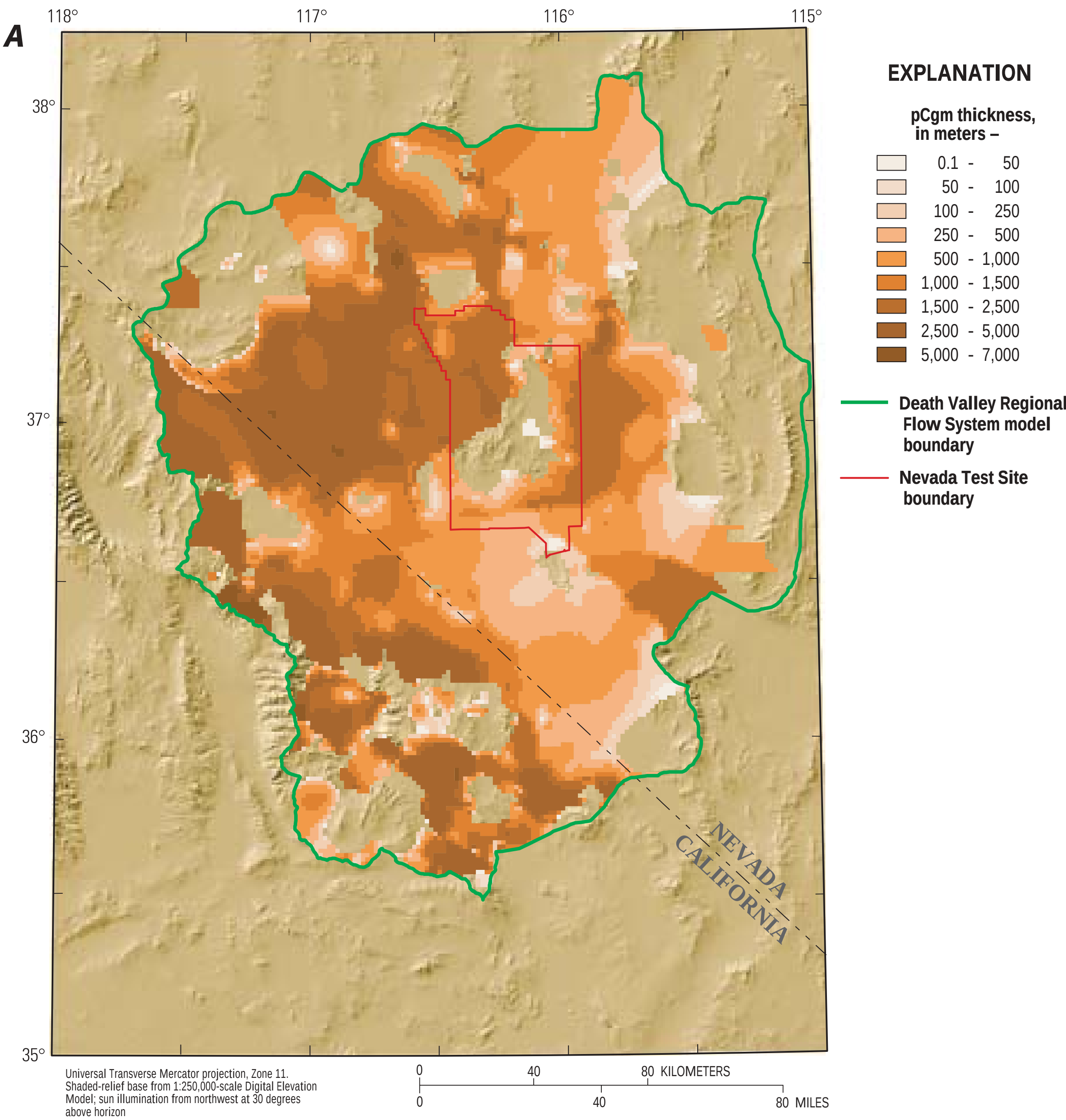

Figure 33. (***A***) Thickness of Precambrian granite and metamorphic rocks (pCgm).

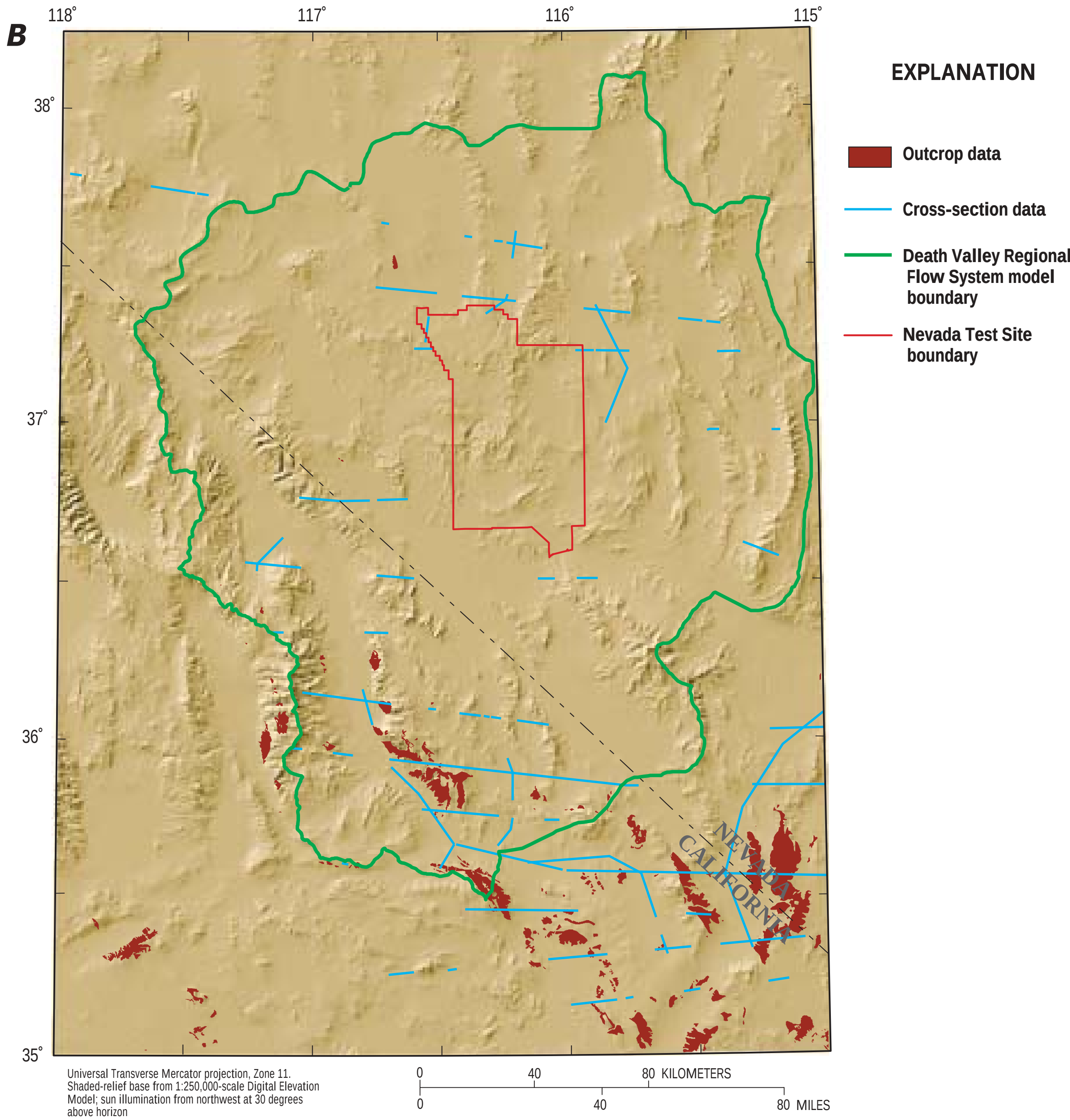

Figure 33–Continued. (***B***) Data sources used to construct gridded surface.

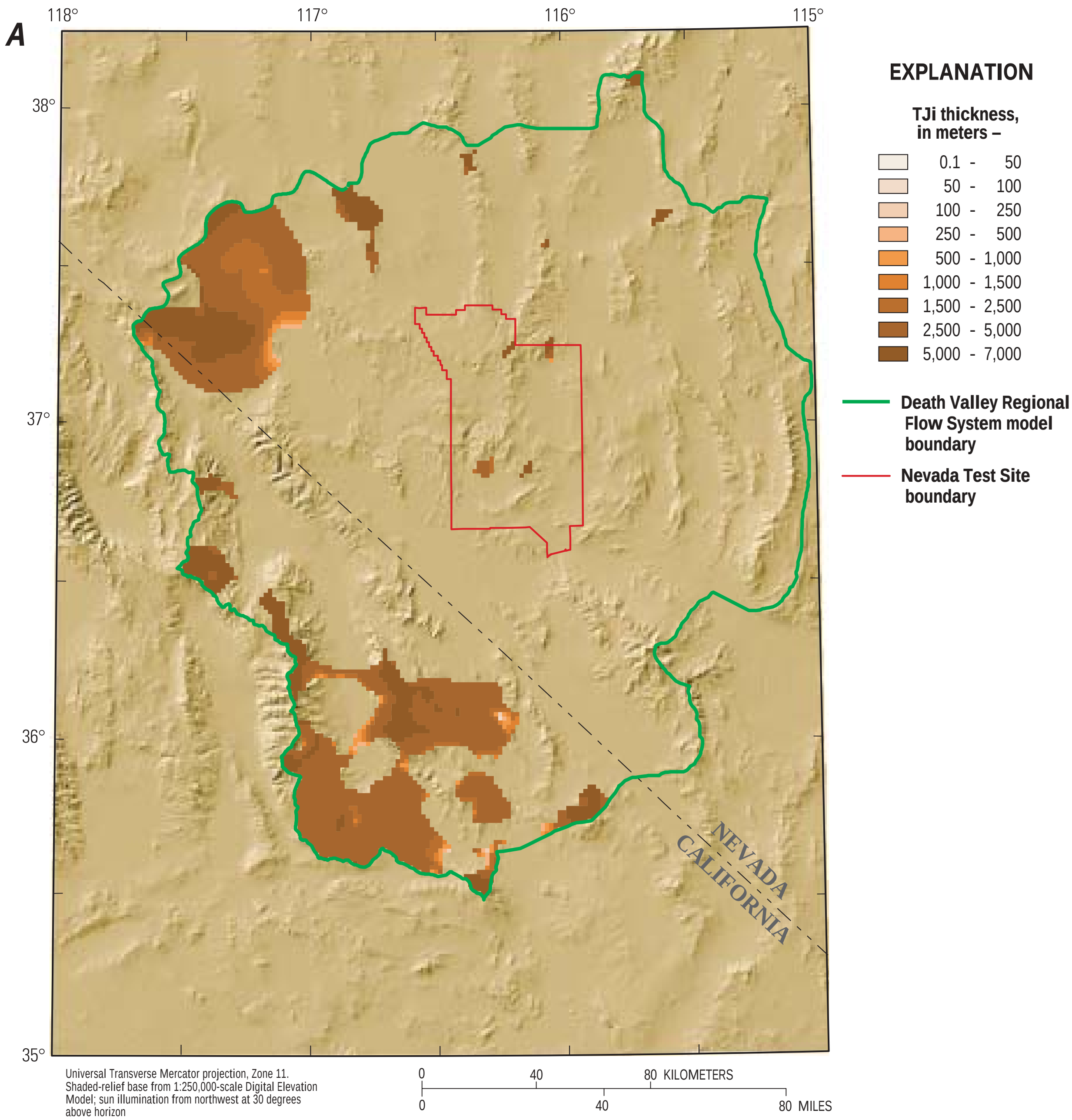

Figure 34. (*A*) Thickness of Tertiary-Jurassic intrusives (TJi).

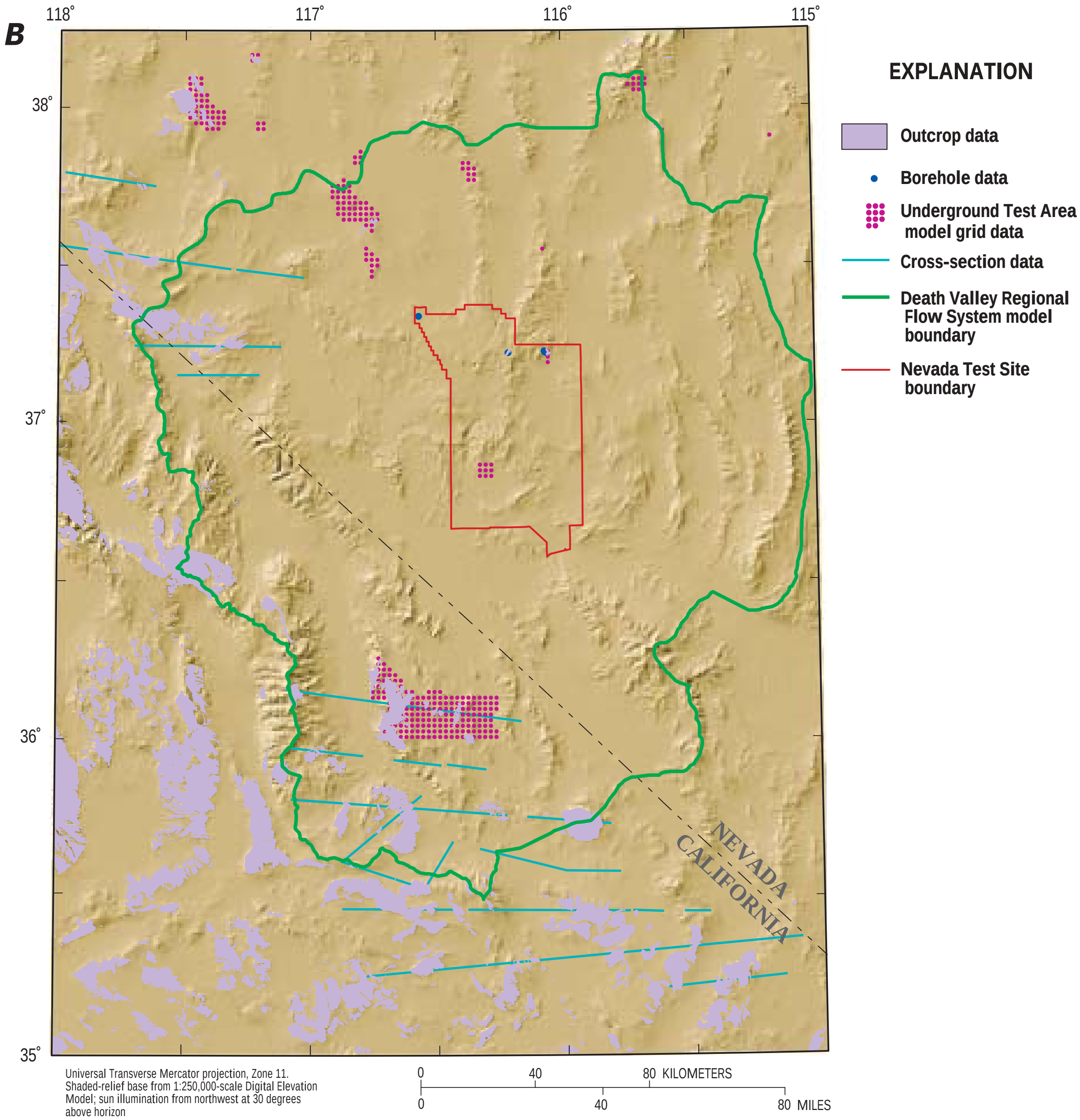

Figure 34–Continued. (***B***) Data sources used to construct gridded surface.

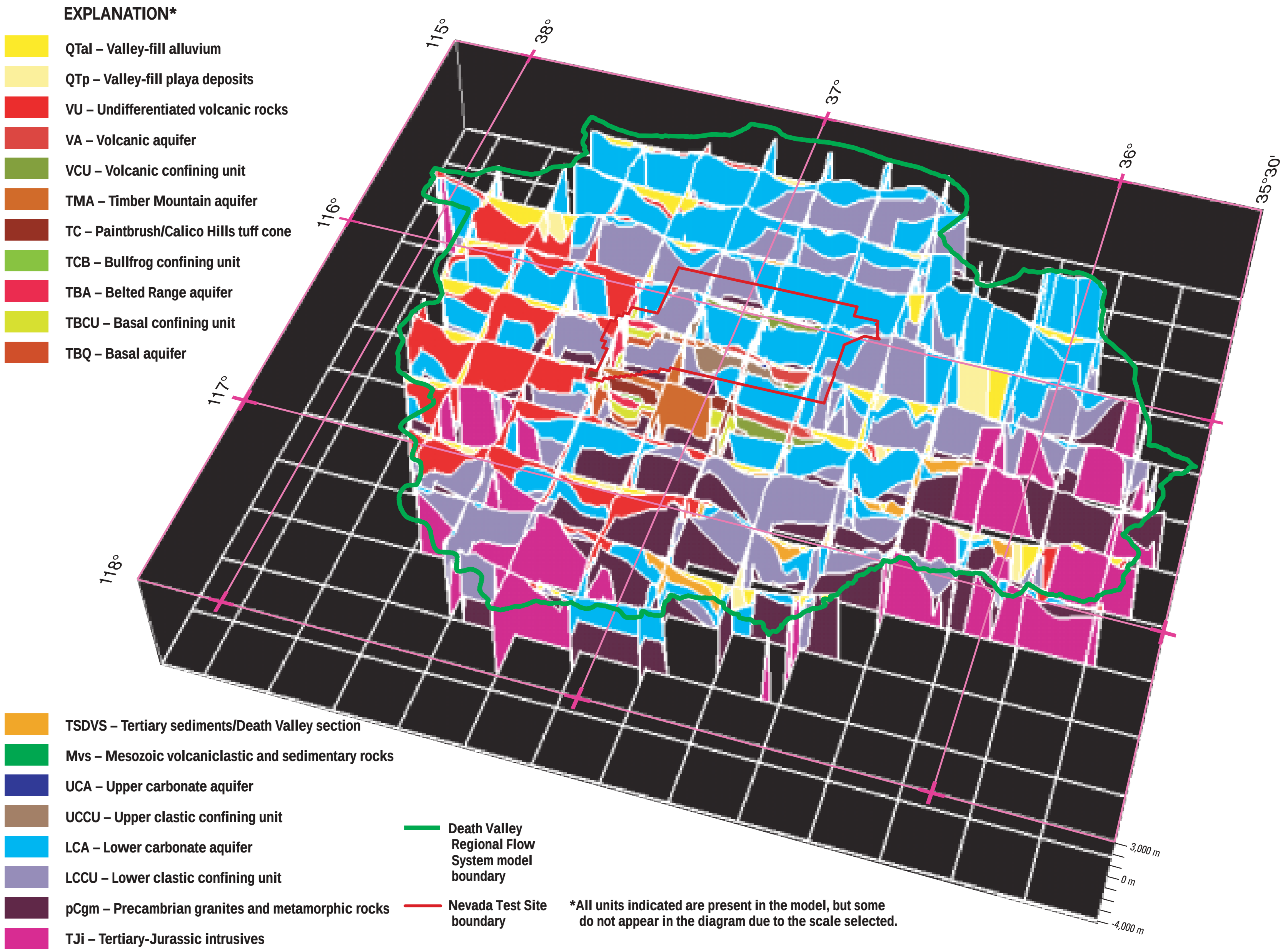

Figure 35. Oblique perspective view of three-dimensional hydrogeologic framework model showing the distribution of the hydrogeologic units using a series of north-south- and east-west-oriented cross-sectional slices.

edges creates a larger surface distribution of the shallow alluvial units that tend to extend too far up the hill slopes. The effect is enhanced because of the fairly coarse (1,500 m) grid cell dimensions. As mentioned previously, this is especially evident in the QTal surface. Because these extended surfaces are thin and are largely above the saturated zone, no significant error is introduced into the assessment of hydraulic properties for the flow model.

The flow modeling process also provided a mechanism to evaluate the HFM. These analyses were used in conjunction with independent hydrogeologic data to modify and improve the existing conceptual model, observation data sets, and weighting. No modifications were made simply to improve model fit; supporting independent hydrogeologic criteria were also needed before modifications were made.

Here is a listing of the modifications made during the flow model calibration process:

1. Because of the relatively smoothed nature of the UGTA Phase I gridded interpretation, the resulting surfaces did not correspond to topography very well. Because of this lack of matching outcrop data, UGTA Phase I gridded interpretations were not used for the QTal and QTp units—only mapped outcrop data were used.
2. In the Stewart Valley area, LCA altitudes were too high, removing QTal and QTp that should be present. The LCA altitudes were lowered to correspond to the top of Paleozoic rocks as depicted in Blakely and others (1999).
3. TJi grids in the area of Tecopah, California and Stewart Valley were overextrapolated from the data used to produce the gridded interpretation. The TJi grid in these areas was modified to conform more to the extent of the TJi depicted on the mapped outcrop data and the UGTA Phase I gridded interpretations.
4. A possible overrepresentation of pCgm in the HFM was compensated by reconstructing the LCCU and the pCgm gridded interpretations using the procedure described in the “Precambrian Granites and Metamorphic Rock (pCgm)” section.

Attribution of Model Cells

The SGM software allows each cell to have multiple attributes. The software automatically assigned basic attributes to each cell to define its row, column, sequence, layer, depth, and altitude. The cells were further attributed to define their hydrogeologic units and the top and bottom of the hydrogeologic unit. Additional attributes, such as zones with similar hydrologic properties, can also be added into the data base.

SUMMARY

A 3D digital hydrogeologic framework model was constructed to develop a 3D interpretation of the regional hydrogeology of the Death Valley regional ground-water flow system. The framework model documented in this report represents a combination of two existing regional framework models (U.S. Department of Energy, 1997; D'Agnese and others, 1997). The 3D digital hydrogeologic framework model provides a description of the geometry and geologic composition of the materials that control the regional ground-water flow system. It serves as an important information source for the numerical ground-water flow model being developed for the Death Valley regional ground-water flow system. Four primary data sources were used to develop the 3D hydrogeologic framework model: geologic maps, geologic cross sections, borehole information sites, and grids from the UGTA Phase I geologic model. The geologic maps, cross sections, and borehole information were classified into hydrogeologic units. Fourteen regional interpretive geologic cross sections (reflecting a consistent interpretation of regional structural style), approximately 700 pieces of borehole information, and gridded surfaces from the UGTA Phase I model provided the subsurface control for the framework model. The hydrogeologic framework model estimated a total of 28 hydrogeologic units, including repeated units from thrust faults.

The HFM defines regional-scale geology and structures to a depth of 4,000 m below sea level. The model has 1,500-m horizontal resolution and variable vertical thickness within the hydrogeologic units. Gridded interpretations from the UGTA Phase I geologic model were used as the core of the HFM. These grids were supplemented by geologic map, cross sections, and lithologic borehole data to give greater detail in the interior part of the model and to extend the model beyond the bounds of the UGTA Phase I geologic model. Although thousands of faults have been mapped in the region, only 300 were used for offsetting units in the final 3D model definition.

Because the geology of the Death Valley region is structurally complex, any conceptualization of the subsurface geometry and hydrologic properties contains great uncertainties. In general, uncertainty in subsurface interpretations increases with distance from outcrops, boreholes, and, to a degree, geologic interpretations (such as cross sections). The greatest density of subsurface data exists near Yucca Mountain and the NTS weapons testing areas such as Yucca Flat and Pahute Mesa. Most boreholes outside these areas only penetrate the alluvium. During the course of ground-water flow model calibration, it was noted that in some locations, the HFM did not allow for adequate simulations. In such locations, the HFM was examined and revisions were made accordingly, if appropriate.

REFERENCES CITED

Anderman, E.R., and Hill, M.C., 2000, MODFLOW–2000, The U.S. Geological Survey modular ground-water flow model—Documentation of the hydrogeologic-unit flow (HUF) package: U.S. Geological Survey Open-File Report 00–342, 89 p.

Bedinger, M.S., Langer, W.H., and Reed, J.E., 1989a, Ground-water hydrology, *in* Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., Studies of geology and hydrology in the Basin and Range Province, Southwestern United States, for isolation of high-level radioactive waste—Characterization of the Death Valley region, Nevada and California: U.S. Geological Survey Professional Paper 1370–F, p. 28–35.

Bedinger, M.S., Langer, W.H., and Reed, 1989b, Hydraulic properties of rocks in the Basin and Range Province, *in* Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B., Reed, J.E., and Brady, B.T., eds., Studies of geology and hydrology in the Basin and Range Province, Southwestern United States, for isolation of high-level radioactive waste—Basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370–A, p. 16–18.

Blakely, R.J., Jachens, R.C., Calzia, J.P., and Langenheim, V.E., 1999, Cenozoic basins of the Death Valley extended terrain as reflected in regional-scale gravity anomalies, *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic basins of the Death Valley region: Boulder, Colo., Geological Society of America Special Paper 333, p. 1–16.

Burchfiel, B.C., and Davis, G.A., 1981, Mojave desert and environs, *in* Ernst, W.G., ed., The geotectonic development of California, Rubey volome: Englewood Cliffs, New Jersey, Prentice-Hall, p. 217–252.

Byers, F.M., Jr., Carr, W.J., Orkild, P.P., Quinlivan, W.D., and Sargent, K.A., 1976, Volcanic suites and related cauldrons of the Timber Mountain-Oasis Valley caldera complex, southern Nevada: U.S. Geological Survey Professional Paper 919, 70 p.

Carr, W.J., 1984, Regional structural setting of Yucca Mountain, southwestern Nevada, and late Cenozoic rates of tectonic activity in part of the southwestern Great Basin, Nevada and California: U.S. Geological Survey Open-File Report 84–854, 109 p.

Carr, W.J., 1990, Styles of extension in the Nevada Test Site region, southern Walker Lane Belt—An integration of volcano-tectonic and detachment fault models, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Boulder, Colo., Geological Society of America, Memoir 176, chap. 13, p. 283–303.

Caskey, S.J. and Schweickert, R.A., 1992, Mesozoic Deformation in the Nevada Test Site and vicinity—Framework of the Cordilleran Fold and Thrust Belt and Tertiary extension north of Las Vegas Valley: Tectonics v. 11, no. 6, p. 1314–1331.

Cole, J.C., and Cashman, P.H., 1999, Structural relationships of pre-Tertiary rocks in the Nevada Test Site region, southern Nevada: U.S. Geological Survey Professional Paper 1607, 39 p.

D'Agnese, F.A., Faunt, C.C., Turner, A.K., and Hill, M.C., 1997, Hydrogeologic evaluation and numerical simulation of the Death Valley regional ground-water flow system, Nevada, and California: U.S. Geological Survey Water-Resources Investigations Report 96–4300, 124 p.

Denny, C.S., and Drewes, Harold, 1965, Geology of the Ash Meadows quadrangle, Nevada-California: U.S. Geological Survey Bulletin 1181–L, 56 p.

Dettinger, M.D., 1989, Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development, summary of findings, 1985–88—Program for the study and testing of carbonate-rock aquifers in eastern and southern Nevada: Carson City, Nev., State of Nevada, Summary Report no. 1, 37 p.

Dickinson, W.R., and Snyder, W.S., 1979, Geometry of triple junctions related to the San Andreas transform: Journal of Geophysical Research, v. 84, p. 561–572.

Downey, J.S., Kolm, K.E., and Gutentag, E.D., 1990, Selection of geohydrologic boundaries for ground-water flow models, Yucca Mountain, Nevada: Tucson, University of Arizona, Proceedings of Waste Management 90, v. 2, p. 725–734.

Faunt, C.C., 1994, Characterization of the three-dimensional hydrogeologic framework of the Death Valley region, Nevada and California: Golden, Colorado School of Mines, Ph.D. dissertation, 235 p.

Faunt, C.C., D'Agnese, F.A., and Turner, A.K., 1997, A hydrogeologic map of the Death Valley region, Nevada and California—Developed using GIS techniques: U.S. Geological Survey Water-Resources Investigations Report 95–4016, 18 p., 1 plate.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Company, Inc., 534 p.

Ferguson, J.F., Cogbill, A.H., and Warren, R.G., 1994, A geophysical-geological transect of the Silent Canyon Caldera Complex, Pahute Mesa, Nevada: Journal of Geophysical Research, v. 99, no. 33, p. 4323–4339.

Fridrich, C.J., Dudley, W. W., Jr., and Stuckless, J. S., 1994, Hydrogeologic analysis of the saturated-zone ground-water system, under Yucca Mountain, Nevada: Journal of Hydrology, v. 154 no. 1–4, p. 133–168.

Grose, T.L., 1983, Thirty-two geologic cross sections, Clark, Esmeralda, Lincoln, Mineral and Nye Counties, Nevada and adjacent areas in California: Nevada Bureau of Mines and Geology Open-File Report 83–13, 32 plates with text descriptions, scale 1:250,000.

Grose, T.L., and Smith, G.I., 1989, Geology, *in* Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., Studies of geology and hydrology in the Basin and Range Province, Southwestern United States, for isolation of high-level radioactive waste: U.S. Geological Survey Professional Paper 1370–F, p. 5–19.

Harbaugh, J.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW–2000, The U.S. Geological Survey's modular ground-water flow model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Hill, M.C., 1992, A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91–484, 358 p.

Jennings, C.W., 1961, Geologic map of California—Kingman sheet: California Division of Mines and Geology, scale 1:250,000.

Jennings, C.W., Burnett, J.L., and Troxel, B.W., 1962, Geologic map of California—Trona sheet: California Division of Mines and Geology, scale 1:250,000.

Laczniak, R.A., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96–4109, 59 p.

Locke, Augustus, Billingsley, P.R., and Mayo, E.B., 1940, Sierra Nevada tectonic patterns: Geological Society of America Bulletin, v. 51, p. 513–540.

Longwell, C.R., 1960, Possible explanation of diverse structural patterns in southern Nevada: American Journal of Science, v. 258-A, p. 192-203.

McAllister, J.F., 1970, Geology of the Furnace Creek Borate Area, Death Valley, Inyo County, California: California Division of Mines and Geology, Map Sheet 14, scale 1:24,000.

McAllister, J.F., 1973, Geologic map and sections of the Amargosa Valley borate area—Southeast continuation of the Furnace Creek area—Inyo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–782, scale 1:24,000.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 576 p.

McKee, E.H., Hildenbrand, T.G., Anderson, M.L., Rowley, P.D., and Sawyer, D.A., 1999, The Silent Canyon Caldera Complex—A three-dimensional model based on drill-hole stratigraphy and gravity inversion: U.S. Geological Survey Open-File Report 99–555, accessed November 14, 2001 at URL http://geopubs.wr.usgs.gov/open-file/of99-555/, 79 p.

Mifflin, M.D., 1988, Region 5, Great Basin, *in* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, Colo., Geological Society of America, The geology of North America, v. O–2, p. 69–78.

Peterson, F.F., 1981, Landforms of the Basin and Range province defined for soil survey: Reno, Nev., Max C. Fleischmann College of Agriculture, University of Nevada, Reno, Nev., Agricultural Bulletin No. 28, 53 p.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent States: U.S. Geological Survey Hydrologic Investigations Atlas 694–A, 1 sheet.

Potter, C.J., Sweetkind, D.S., Dickerson, R.P., and Killgore, M.L., 2002, Hydrostructural maps of the Death Valley regional flow system, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2372, 2 pl., scale 1:350,000, pamphlet text,12 p.

Sawyer, D.A., Fleck, R.J., Lanphere, M.A., Warren, R.G., Broxton, D.E., and Hudson, M.R., 1994, Episodic caldera volcanism in the Miocene southwestern Nevada volcanic field—Revised stratigraphic framework, $^{40}Ar/^{39}Ar$ geochronology, and implications for magmatism and extension: Geological Society of America Bulletin, v. 106, no. 10, p. 1304–1318.

Stewart, J.H., 1971, Basin and range structure—A system of horsts and grabens produced by steep-sided extension: Geological Society of America Bulletin, v. 82, no. 4, p. 1019-1044.

Stewart, J.H., 1978, Basin and range structure in North America—A review, *in* Smith R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics in the western Cordillera: Geological Society of America Memoir 152, p. 1–31.

Stewart, J.H., 1980, Geology of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.

Stewart, J.H., 1988, Tectonics of the Walker Lane Belt, western Great Basin—Mesozoic and Cenozoic deformation in a zone of shear, *in* Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States, Rubey volume: Englewood Cliffs, New Jersey, Prentice Hall, p. 683–713.

Stewart, J.H., and Carlson, J.E., 1978, Geologic map of Nevada: U.S. Geological Survey Map, scale 1:500,000, 2 sheets.

Strand, R.G., 1967, Geologic map of California—Mariposa sheet: California Division of Mines and Geology, scale 1:250,000.

Streitz, Robert, and Stinson, M.C., 1974, Geologic map of California—Death Valley sheet: California Division of Mines and Geology, scale 1:250,000.

U.S. Department of Energy, 1997, Regional groundwater flow and tritium transport modeling and risk assessment of the Underground Test Area, Nevada Test Site, Nevada: U.S. Department of Energy Report DOE/NV–477 (Underground Test Area subproject, Phase I data analysis task, vol. 1, Regional geologic model data documentation package, ITLV/10972-181), various pagination.

Waddell, R.K., 1982, Two-dimensional, steady-state model of ground-water flow, Nevada Test Site and vicinity, Nevada-California: U.S. Geological Survey Water-Resources Investigations Report 82–4085, 72 p.

Warren, R.G., Cole, G.L., and Walther, Douglas, 2000, Structural block model for the three-dimensional geology of the southwestern Nevada volcanic field: Los Alamos National Laboratory Report LA–UT–00–5866, unpaginated.

Wernicke, B.P., Axen, G.J., and Snow, J.K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757.

Winograd, I.J., and Pearson, F.J., Jr., 1976, Major carbon-14 anomaly in a regional carbonate aquifer—Possible evidence for mega scale channeling, south-central Great Basin: Water Resources Research, v. 12, no. 6, p. 1125–1143.

Winograd, I.J., and Thordarson, William, 1975, Hydrologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712C, p. C1–C126.