Geology and Hydrogeology

By Donald S. Sweetkind, Wayne R. Belcher, Claudia C. Faunt, and
Christopher J. Potter

Chapter B of

Death Valley Regional Ground-Water Flow System, Nevada and California—Hydrogeologic Framework and Transient Ground-Water Flow Model

Edited by Wayne R. Belcher

Prepared in cooperation with the
U.S. Department of Energy
Office of Environmental Management, National Nuclear Security Administration, Nevada Site Office,
under Interagency Agreement DE–AI52–01NV13944, and
Office of Repository Development,
under Interagency Agreement DE–AI08–02RW12167

Scientific Investigations Report 2004–5205

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

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CHAPTER B. Geology and Hydrogeology

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Introduction

The geology of the Death Valley regional ground-water flow system (DVRFS) region, consisting of many types of rocks that have been subjected to a variety of structural disruptions, is stratigraphically and structurally complex. These rocks form a complex, three-dimensional (3D) framework that can be subdivided into aquifers and confining units on the basis of their ability to store and transmit water. The principal aquifer is a thick sequence of Paleozoic carbonate rock that extends throughout the subsurface of much of central and southeastern Nevada (Dettinger, 1989; Harrill and Prudic, 1998) and crops out in the eastern one-half of the DVRFS region (fig. B–1). Fractured Cenozoic volcanic rocks in the vicinity of the Nevada Test Site (NTS) and permeable Cenozoic basin fill throughout the DVRFS region (fig. B–1) locally are important aquifers that interact with the regional flow through the underlying Paleozoic carbonate rocks (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Harrill and others, 1988, sheet 2; Dettinger, 1989). Proterozoic to Early Cambrian metamorphic and siliciclastic rocks and Paleozoic siliciclastic rocks are the primary regional confining units; they are associated with abrupt changes in the potentiometric surface. Zeolitically altered and nonwelded tuffs within the Cenozoic volcanic rocks and fine-grained parts of the Cenozoic basin fill form locally important confining units (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975). Stratigraphic units in the DVRFS region are disrupted by large-magnitude offset thrust, strike-slip, and normal faults. Combinations of normal, reverse, and strike-slip faulting and folding episodes (Carr, 1984) have resulted in a complex distribution of rocks. Consequently, diverse rock types, ages, and deformational structures are juxtaposed, creating variable and complex subsurface conditions. These faults juxtapose units with different hydraulic properties that may disrupt regional flow paths. Broader zones of distributed deformation may enhance permeability through the creation of secondary (fracture) permeability (Carr, 1984). Understanding the ground-water flow system in Death Valley or in any area depends on understanding the geologic framework of the area, especially in stratigraphically and structurally complex areas.

More than 20 years of ground-water flow modeling of the DVRFS has produced a succession of models that represent the regional hydrogeologic framework and ground-water flow system. Different approaches were taken, however, in incorporating the geologic framework in the models with different geologic data sets or subsurface interpretations. In general, the models have used increasing levels of geologic detail, which has resulted in better model calibration. The increase in computing power and advances in modeling routines over time has allowed the incorporation of more geologic detail in framework and flow models. The data and descriptions presented in this chapter attempt to (1) integrate and resolve different geologic interpretations used in the two most recent regional flow models (IT Corporation, 1996a; D'Agnese and others, 1997; see discussion in Chapter A, this volume); and (2) incorporate abundant new data that were developed during or following the construction of the two models.

This chapter describes the geologic and hydrogeologic framework of the DVRFS region, summarizes the stratigraphic and structural settings, and discusses the major structures that affect ground-water flow. The hydrogeologic units and stratigraphic and structural data are discussed that are used as input for the 3D hydrogeologic framework model (HFM) (Chapter E, this volume) and used in the transient ground-water flow model (Chapter F, this volume).

Stratigraphic and Structural Setting

Stratigraphic Setting

In Late Proterozoic to Devonian time, the southwestern part of the United States was largely characterized by deposition of marine sedimentary rocks at the continental margin. The Paleozoic shelf province in the DVRFS region is bounded on the southeast by the westward limit of cratonal sections and on the northwest by facies transitions to rocks interpreted to have been deposited in deeper water (fig. B–1). In the DVRFS region, Late Proterozoic and Early Cambrian rocks form a westward-thickening wedge of predominantly quartzites and siltstones that record deposition on the early shelf edge of western North America (Stewart and Poole, 1974; Poole and others, 1992). These rocks are overlain by a thick succession of predominantly continental shelf-facies carbonate rocks deposited throughout most of the eastern and central parts of the DVRFS region during Paleozoic (Middle Cambrian through Devonian) time. These carbonate rocks and calcareous

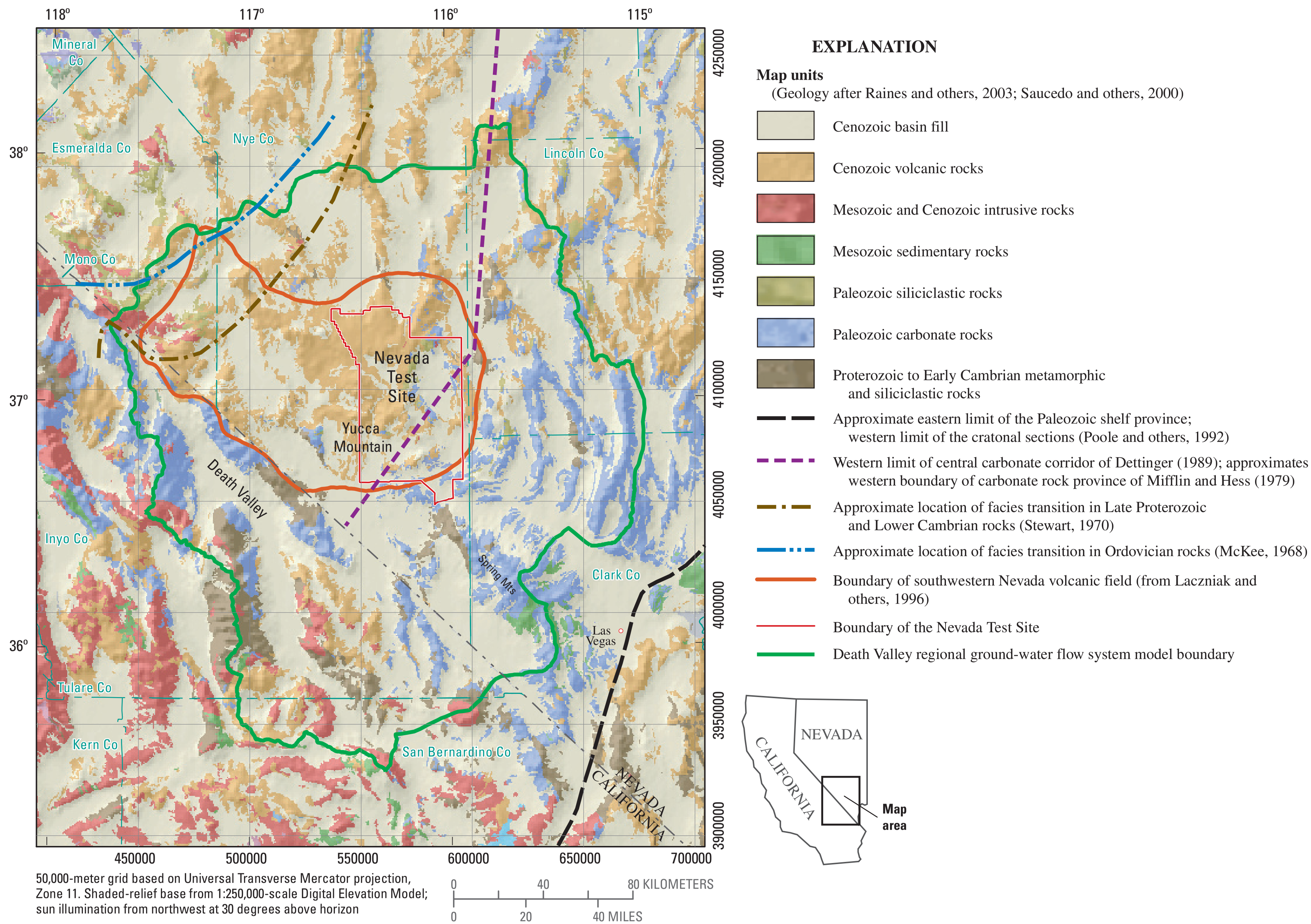


Figure B–1. Generalized geology within and surrounding the area of the Death Valley regional ground-water flow system.

shales form a westward-thickening carbonate- and clastic-rock section up to 4,500 m thick (Burchfiel, 1964) (fig. B–2). In the western and northwestern parts of the DVRFS region, Middle Cambrian through Devonian strata consist of slope-facies carbonate rocks intermixed with siliciclastic and volcanic rocks (Stewart, 1980). To the east of the DVRFS region, Middle Cambrian through Devonian strata form a relatively thin (hundreds of meters) cratonic sequence; to the west and northwest of the DVRFS region, these rocks represent deeper water facies (figs. B–1 and B–2). In the eastern and central parts of the DVRFS region, carbonate sedimentation was interrupted by two periods of siliciclastic rock deposition that resulted from periods of Paleozoic orogenesis.

In the vicinity of the NTS, deposition of marine carbonate rocks was interrupted during Late Devonian to Mississippian time (Poole and Sandberg, 1977; Poole, 1981; Trexler and others, 1996). Siliciclastic sediments were shed from uplifts to the north and west of the DVRFS region and deposited in a northeast-to-southwest-trending foreland basin. This basin dominantly consists of relatively low permeability argillites and shales and is now defined by the location of the Chainman Shale. Deposition of shelf-type carbonate rocks continued during Mississippian time in the southeastern part of the DVRFS region. By Pennsylvanian time, shallow marine carbonate rocks were deposited over much of the eastern and southern parts of the DVRFS region. During late Paleozoic and Mesozoic time, the Paleozoic stratigraphic sequence was deformed by regional thrust faulting (Armstrong, 1968; Barnes and Poole, 1968) of the older Late Proterozoic to Lower Cambrian siliciclastic section over the younger Paleozoic carbonate rock section.

Only minor amounts of Mesozoic sedimentary rocks are preserved in most of the DVRFS region (fig. B–1). Mesozoic cratonic sedimentary rocks are exposed east of the DVRFS region in the Las Vegas area and in the Spring Mountains; Mesozoic metasedimentary and metavolcanic rocks are sparsely exposed in the western part of the DVRFS region. Mesozoic plutonic rocks associated with the Sierra Nevada batholith are abundant immediately south and west of the DVRFS model area.

The distribution and character of Cenozoic volcanic and sedimentary rocks of the DVRFS region are influenced by two factors: (1) the general southward and westward sweep of volcanism across this area in Oligocene and Miocene time (fig. B–3) (Best and others, 1989; McKee, 1996; Dickinson, 2002); and (2) the timing, location, and magnitude of extension and the formation of basin-and-range topography. For the purposes of the regional ground-water flow model, the volcanic rocks of the region can be categorized into four groups: (1) Cenozoic volcanic centers and volcanic rocks north of the NTS, mostly older than volcanic rocks at the NTS (Ekren and others, 1971, 1977; Best and others, 1989; McKee, 1996); (2) the southwestern Nevada volcanic field (SWNVF), characterized in part by a thick section of regionally distributed welded tuffs that were derived from a central complex of nested calderas (Byers, Carr, Orkild, and others, 1976; Sawyer and others, 1994); (3) the central Death Valley volcanic field that is composed of a series of lava flows and nonwelded tuffs that were derived from localized volcanic centers rather than climactic caldera-forming eruptions (Wright and others, 1991); and (4) local, mostly younger extrusive rocks, both rhyolite flows and basaltic centers (fig. B–3). Eruptions of the SWNVF began about 16 Ma, peaked between 13.5 and 11 Ma, and then declined with time as the focus of volcanism migrated generally westward, largely moving out of the region about 5 Ma (fig. B–3).

Changes in sedimentation patterns of Cenozoic continental sedimentary rocks reflect the Cenozoic tectonic evolution of the DVRFS region. Relatively quiescent alluvial to lacustrine sedimentation of Oligocene to Early Miocene age gives way to post-Middle Miocene sedimentary rocks deposited in relatively small intermontane basins with local sediment sources as basin-range topography developed in the DVRFS region. Post-Miocene alluvial basins have progressively filled with as much as 1,500 m of coarse gravel and sand and locally fine-grained playa-lake deposits of silt and clay. In many basins, coarse synorogenic clastic sediments filled opening basins, later to be supplanted by alluvial fan, playa, and local channel deposits in Neogene time. Basin-range topography first developed in the DVRFS region from about 14 to about 12 Ma, and it is still actively evolving in the southwesternmost part of the region and to the west. Areas of thick Cenozoic rocks, both sedimentary and volcanic (fig. B–4), are interpreted on the basis of low-density gravity anomalies and depth-to-basement modeling (Jachens and Moring, 1990; Saltus and Jachens, 1995; Blakely and others, 1998, 1999, 2001).

More detailed stratigraphic descriptions are found in geologic compilations of the DVRFS region or parts of the region by Wahl and others (1997), Slate and others (2000), and Workman, Menges, Page, Taylor, and others (2002).

Structural Setting

The oldest deformation of hydrologic significance in the DVRFS region was the formation of regional thrust belts in late Paleozoic and Mesozoic time. Thrust faults are exposed in mountain ranges throughout the central and southern parts of the DVRFS region, from the Pahranagat Range, Sheep Range, and Spring Mountains on the east to the Funeral, Grapevine, and Cottonwood Mountains on the west (fig. B–5; see also map compilations of Workman, Menges, Page, Taylor, and others, 2002, and Workman, Menges, Page, Ekren, and others, 2002, and references cited therein). The northern part of the DVRFS region is largely covered by volcanic rocks and Cenozoic sediments, making the projection of thrusts northward uncertain.

Individual thrust faults that are exposed in separated range blocks have been interpreted to be regionally continuous Paleozoic and Mesozoic structures that were disrupted by Cenozoic extensional and strike-slip faulting (Armstrong, 1968; Barnes and Poole, 1968; Longwell, 1974; Stewart, 1988; Wernicke and others, 1988; Caskey and Schweickert, 1992; Snow, 1992; Serpa and Pavlis, 1996; Cole and Cashman, 1999;

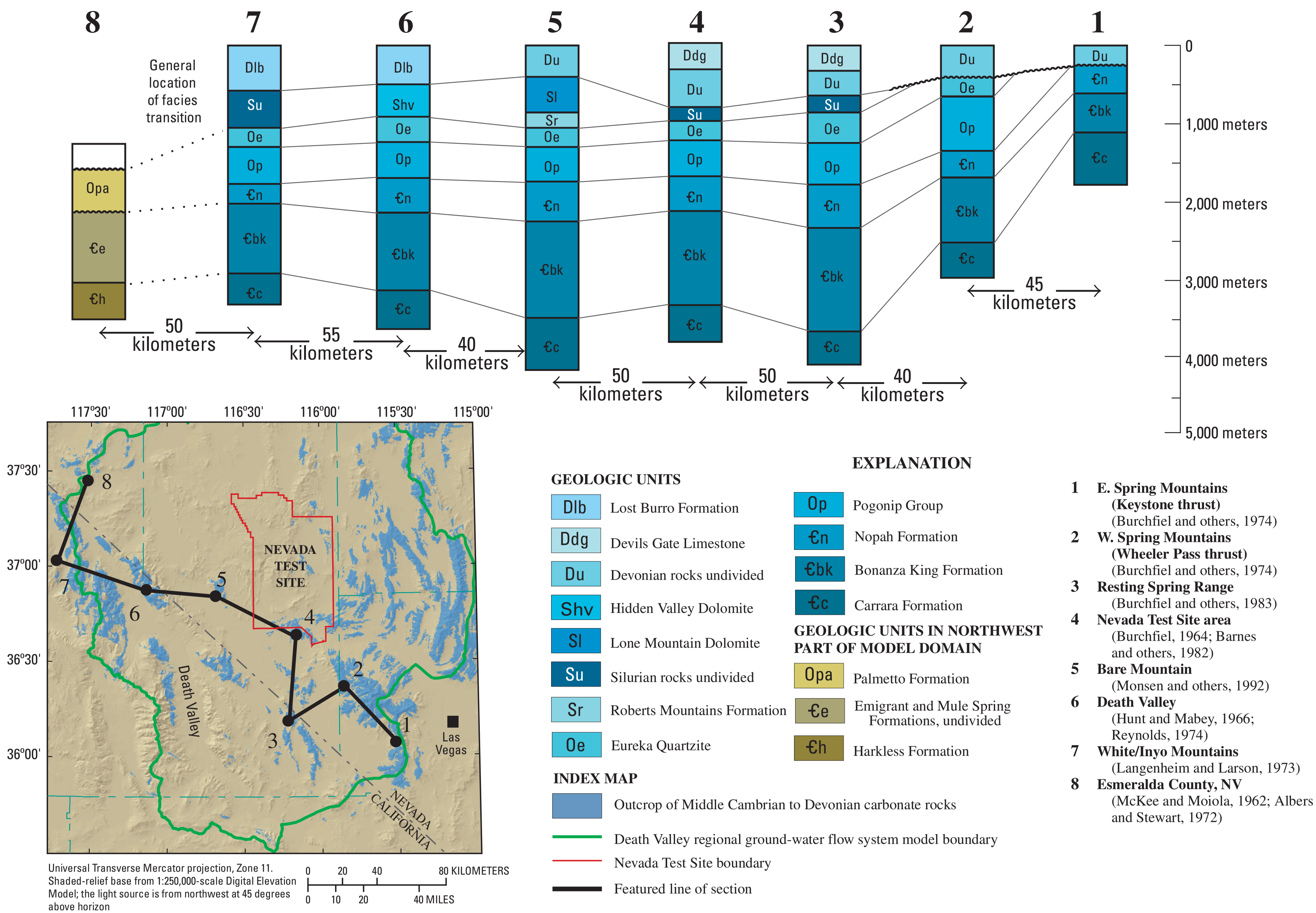
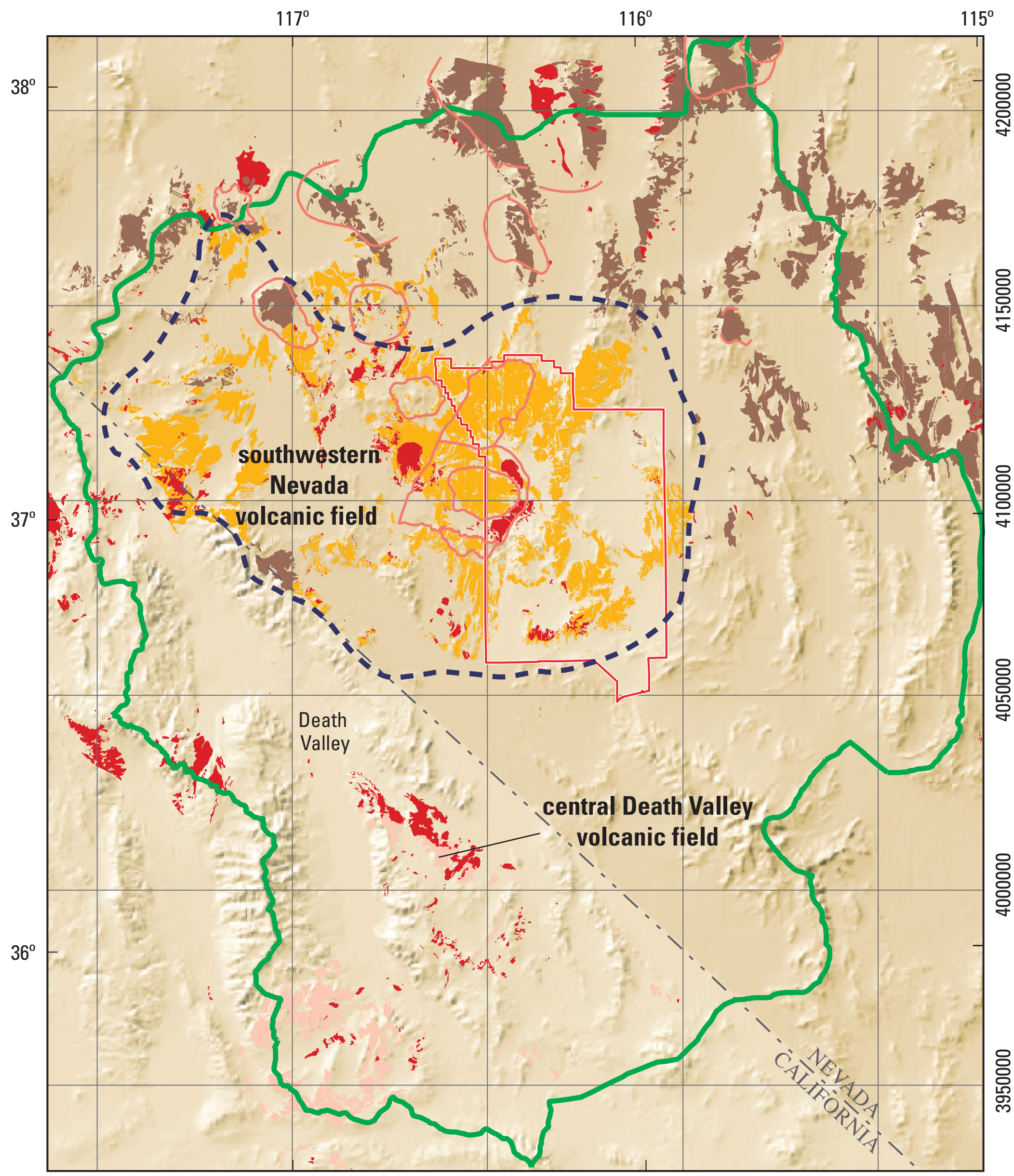


Figure B–2. Stratigraphic diagram of Paleozoic carbonate-rock units.



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

0 40 80 KILOMETERS
0 20 40 MILES

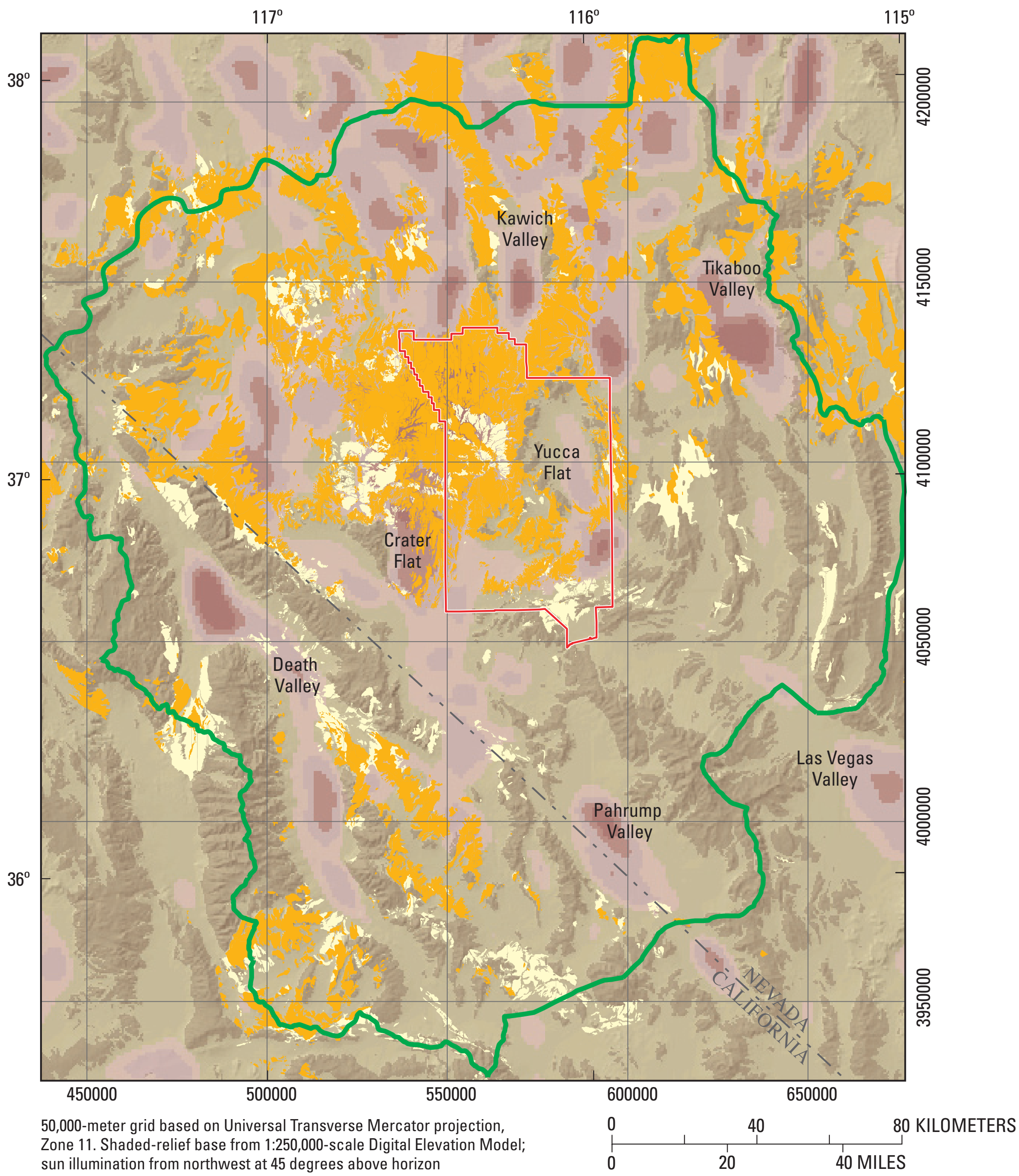
EXPLANATION

Map units
(from Workman, Menges, Page, Taylor and others, 2002)

- Quaternary and Tertiary basaltic volcanic rocks (11 Ma and younger)
- Tertiary volcanic rocks of the central Death Valley volcanic field (14 to 5 Ma)
- Tertiary volcanic rocks of the southwestern Nevada volcanic field (15 to 7.5 Ma)
- Oligocene-Early Miocene tuffs erupted prior to southwestern Nevada volcanic field (27 to 17 Ma)

- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary
- Boundary of southwestern Nevada volcanic field (from Laczniak and others, 1996)
- Caldera boundary (from Workman, Menges, Page, Ekren, and others, 2002)

Figure B–3. Volcanic features of the Death Valley regional ground-water flow system region.



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 45 degrees above horizon

EXPLANATION

Map units
(from Workman, Menges, Page, Taylor, and others, 2002)

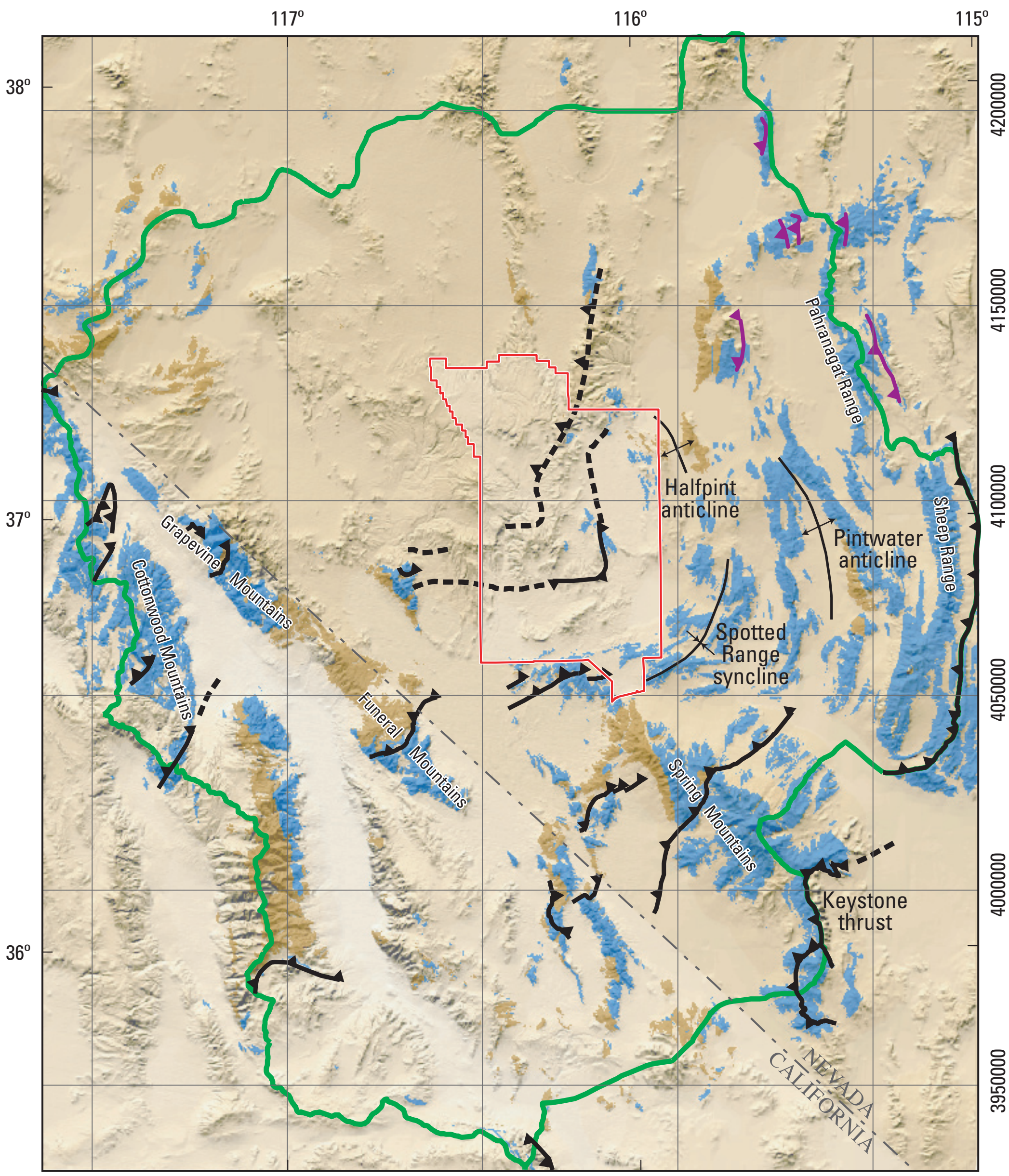
- Cenozoic sedimentary rocks
- Cenozoic volcanic rocks
- Pre-Cenozoic bedrock

Modeled thickness of Cenozoic rocks from gravity data
(from Blakely and others, 2001)

- 500–1,000 meters
- 1,000–2,000 meters
- 2,000–3,000 meters
- >3,000 meters

- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary

Figure B–4. Basins of the Death Valley regional ground-water flow system region.



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

0 40 80 KILOMETERS
0 20 40 MILES

EXPLANATION

Map units
(from Workman, Menges, Page, Taylor, and others, 2002)

- Paleozoic carbonate rocks
- Late Proterozoic to Cambrian siliciclastic rocks

- Thrust, dashed where inferred, arrow on upper plate (from Potter, Sweetkind, and others, 2002)
- Thrust (from Workman, Menges, Page, Taylor and others, 2002)
- Anticlinal axis
- Synclinal axis
- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary

Figure B–5. Thrust faults of the Death Valley regional ground-water flow system region.

Snow and Wernicke, 2000). Individual thrusts and folds have been correlated throughout the DVRFS region on the basis of stratigraphic throw, sense of vergence, relative position, spacing, and style (Burchfiel and others, 1983; Wernicke and others, 1988, Snow and Wernicke, 1989; Snow, 1992; Caskey and Schweickert, 1992; Serpa and Pavlis, 1996). Regardless of specific correlation, mapped thrusts have been projected beneath Cenozoic cover on the basis of regional geologic relations and available outcrop and borehole control (Wernicke and others, 1988; Snow and Wernicke, 1989; Cole, 1997; Cole and Cashman, 1999; Potter, Sweetkind, and others, 2002).

Associated with the Paleozoic and Mesozoic regional thrusting are regional thrust-related folds (fig. B–5). West of the Sheep Range, the Pintwater anticline (Longwell and others, 1965) and the Spotted Range syncline (Barnes and others, 1982) are a regional, north-trending fold pair. Proterozoic and Paleozoic rocks in the eastern part of the NTS area are exposed in the Halfpint anticline, which has a core of Late Proterozoic siliciclastic rocks (Cole, 1997).

Cenozoic deformation of the region is characterized by a variety of structural patterns that overlap in space and time: (1) basin-range extension, (2) local extreme extension along detachment faults that currently have gentle dips, (3) development of discrete strike-slip faults and transtensional basins in the Walker Lane belt, and (4) Cenozoic volcanism that both preceded and accompanied regional extension. The magnitude of late Cenozoic extensional deformation varied spatially in the Death Valley region, with greatly extended domains alternating with lesser extended domains (Wernicke and others, 1984; Guth, 1981; Wernicke, 1992) (fig. B–6). In the northern part of the DVRFS region, late Cenozoic extensional deformation was dominated by movement along north- to northeast-striking normal faults related to development of the characteristic basin and range structure and associated topography of the southern Great Basin (Stewart, 1980). There, the north-south-trending basins such as Tikaboo Valley and Kawich Valley generally have asymmetric cross sections, with dominant normal faults producing a half-graben geometry. These normal faults generally dip 50° to 65° and have as much as 3,000 m of displacement. Gravity data (Healey and others, 1981) indicate that some of the larger faults are concealed beneath surficial deposits in the basins between the exposed range-front faults.

In the southern part of the DVRFS region, extension is spatially variable but in general of greater magnitude than in the northern part of the DVRFS region (fig. B–6). Tracts of east-dipping, rotated range blocks are bounded by west-side-down normal faults that are inferred to flatten and converge at depth into a deep detachment zone (Guth, 1981, 1990; Wernicke and others, 1984). In other parts of the DVRFS region, such as at Yucca Mountain, closely spaced north-striking normal faults apparently do not merge into a gently dipping detachment at depth (Brocher and others, 1998). Local large-magnitude extension is expressed as detachment-related core complexes. In these areas, gently to moderately dipping, large-offset extensional detachment faults expose broadly domed metamorphic complexes in the lower plates of the faults. The upper plates commonly are highly extended and tilted along normal faults that merge into the detachment faults. Although these detachment faults generally have gentle dips, the fault surfaces locally have dips of 50° to 60°. Strike-slip faults of both northwest and northeast strike may have transferred extensional strain between individual extensional domains (Wernicke and others, 1984).

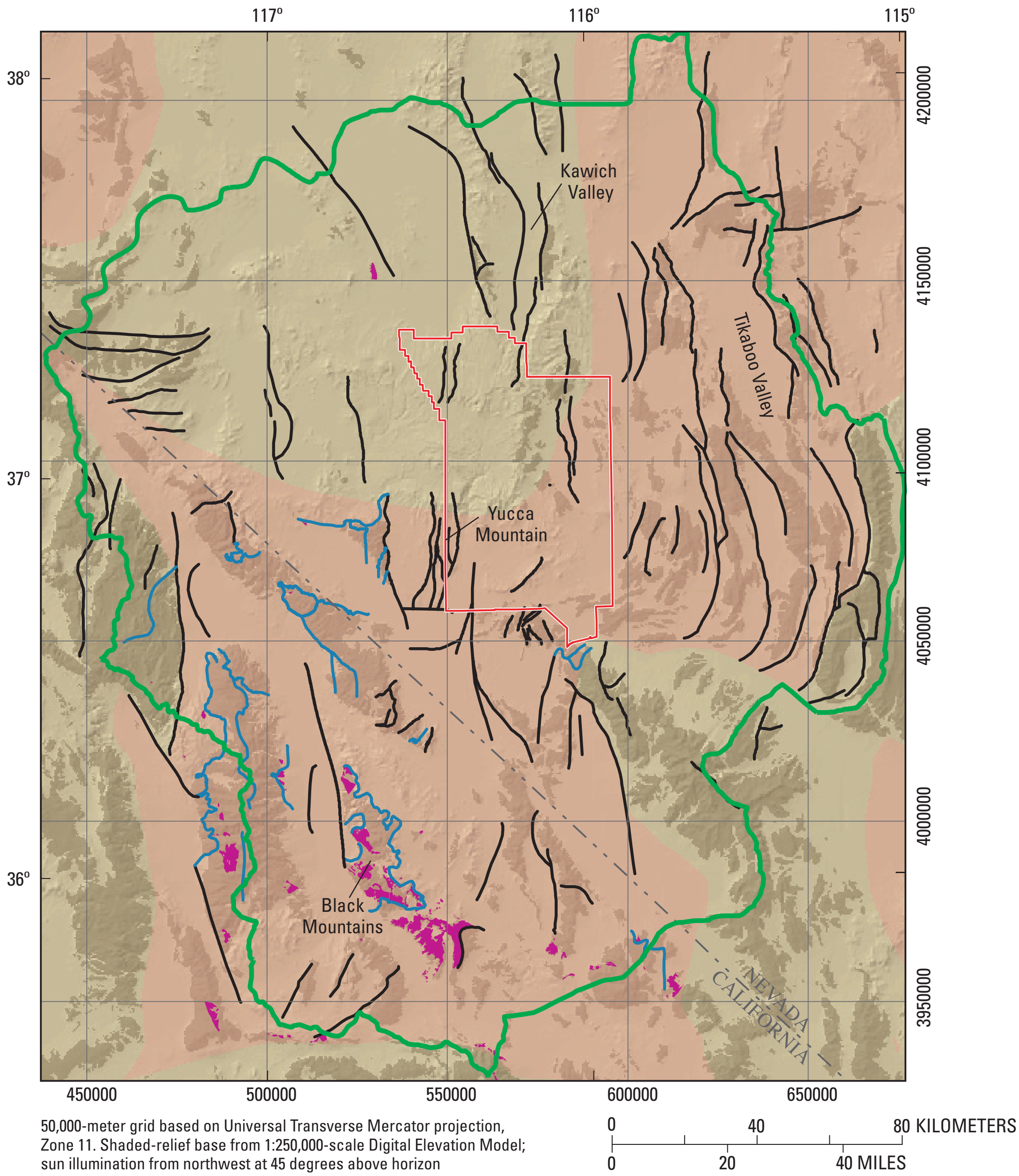
The northwest-trending Walker Lane belt (Stewart, 1988; Stewart and Crowell, 1992) transects the DVRFS region (fig. B–7). The Walker Lane belt is a complex structural zone that is dominated by large right-lateral faults with northwest orientations, such as the Pahrump-Stewart Valley fault zone and the Las Vegas Valley shear zone (LVVSZ) (fig. B–7). The belt also contains a variety of structures that are discontinuous and appear to interact complexly in accommodating an overall mixed right-shear and extensional strain field (Stewart, 1988; Stewart and Crowell, 1992). The Walker Lane belt has been subdivided into a series of structural blocks according to their style of deformation (Stewart, 1988; Stewart and Crowell, 1992) (fig. B–7). In the northwestern part of the DVRFS region, the Goldfield block is notable for its lack of through-going strike-slip faults and relative lack of normal faults (fig. B–6). The Spotted Range–Mine Mountain block is characterized by east-northeast-trending, left-lateral strike-slip faults, such as the Rock Valley fault zone and the Cane Spring and Mine Mountain faults (fig B–7). The Spring Mountains block is a relatively intact block that is bounded by the Pahrump-Stewart Valley fault zone and the LVVSZ. The Inyo-Mono block (redefined as part of the Basin and Range province of eastern California by Workman, Menges, Page, Ekren, and others, 2002) features large, northwest-striking right-lateral faults, such as the Furnace Creek fault zone and the southern Death Valley fault zone and also features major extensional detachment faults (fig. B–7). Most of the deformation in the Walker Lane belt may have occurred during Middle Miocene time (Hardyman and Oldow, 1991; Dilles and Gans, 1995), although deformation in the vicinity of Death Valley continued into Late Miocene time (Wright and others, 1999; Snow and Wernicke, 2000). Some structures in the belt, such as the Rock Valley fault zone, continue to be active (Rogers and others, 1987; von Seggern and Brune, 2000).

Hydrogeologic Units

The rocks and deposits forming the hydrostratigraphic framework for a ground-water flow system are termed hydrogeologic units (HGUs). An HGU has considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics.

Previous Use

The basic pre-Cenozoic hydrostratigraphic setting for the DVRFS region, particularly in the vicinity of the NTS, was established by Winograd and Thordarson (1975). The pre-Cenozoic sedimentary rocks were grouped into four HGUs:



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 45 degrees above horizon

EXPLANATION

Map units

- Pre-Cenozoic bedrock
- Middle Proterozoic metamorphic rocks (from Workman, Menges, Page, Taylor, and others, 2002)
- Greatly extended domains (after Wernicke, 1992)
- Pre-Cenozoic bedrock and greatly extended domains (after Wernicke, 1992)

- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary
- Normal fault, mapped or inferred (from Potter, Sweetkind, and others, 2002)
- Low-angle normal fault or detachment fault (from Potter, Sweetkind, and others, 2002)

Figure B–6. Normal faults and greatly extended domains of the Death Valley regional ground-water flow system region.

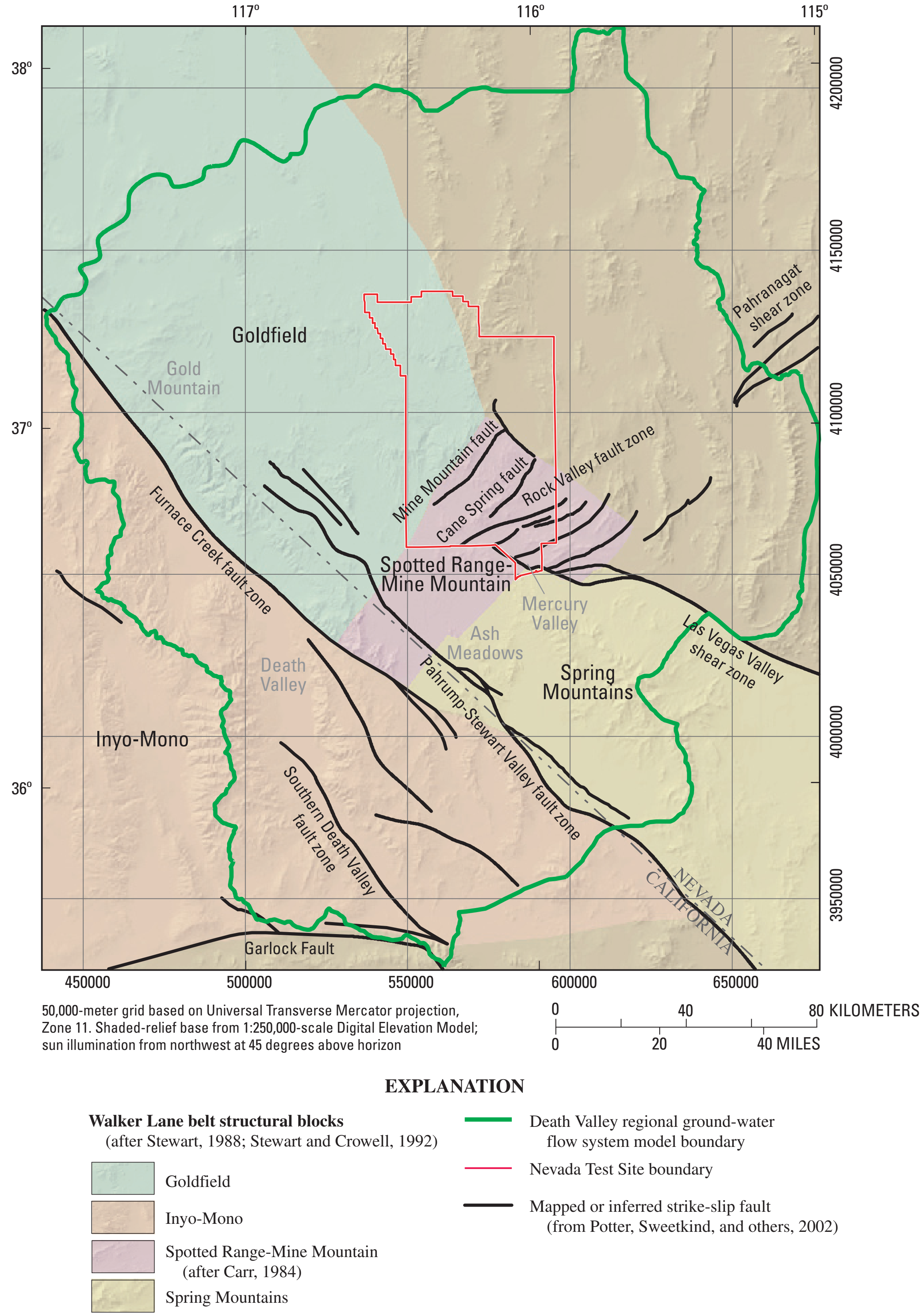


Figure B–7. The Walker Lane belt and strike-slip faults of the Death Valley regional ground-water flow system region.

the lower clastic aquitard (confining unit), composed of Late Proterozoic through Middle Cambrian siliciclastic rocks; the lower carbonate aquifer, composed of Middle Cambrian through Devonian mostly carbonate rocks; the upper clastic aquitard, composed of Devonian and Mississippian siliciclastic rocks; and the upper carbonate-rock aquifer, composed of Pennsylvanian and Permian carbonate rocks which, in the vicinity of the NTS, overlie the rocks of the upper clastic aquitard. Most subsequent tabulations of HGUs and ground-water flow models of the region (Waddell, 1982; Luckey and others, 1996; Laczniak and others, 1996; IT Corporation, 1996a; D'Agnese and others, 1997) have honored these HGU subdivisions of the pre-Cenozoic sedimentary section. For example, table B–1 shows similar treatment of these units in the two recent regional ground-water flow models (IT Corporation, 1996b; D'Agnese and others, 1997).

In contrast to the general consistency in the treatment of the pre-Cenozoic section, a number of approaches have been taken to subdividing the Cenozoic section into HGUs, particularly the volcanic rocks at the NTS. Past approaches have differed in the number of HGUs used and in the treatment of spatially variable material properties in the volcanic-rock units. Winograd and Thordarson (1975; their table 1) assigned the volcanic rocks at the NTS to HGUs based upon lithology and inferred hydrologic significance—for example, tuff aquitard, bedded tuff aquifer, welded tuff aquifer, lava flow aquifer. The geologic units described and their stratigraphic position, however, were based upon older 1960's-era geologic mapping, and the designations did not necessarily account for spatial variability of properties in an HGU. Laczniak and others (1996; their table 1) extended the work of Winograd and Thordarson (1975) to produce a more detailed description of volcanic-rock HGUs in the area around the NTS. The updated designations were based on new volcanic-rock stratigraphic unit assignments (Sawyer and others, 1994); each formation was assigned as a welded tuff aquifer, lava flow aquifer, or tuff confining unit and also designated as to where on the NTS the units were important aquifers or confining units. Both of these studies provided essential descriptions of the volcanic-rock HGUs; however, neither study was sufficiently detailed to define the stratigraphic complexities throughout the DVRFS region and model domain.

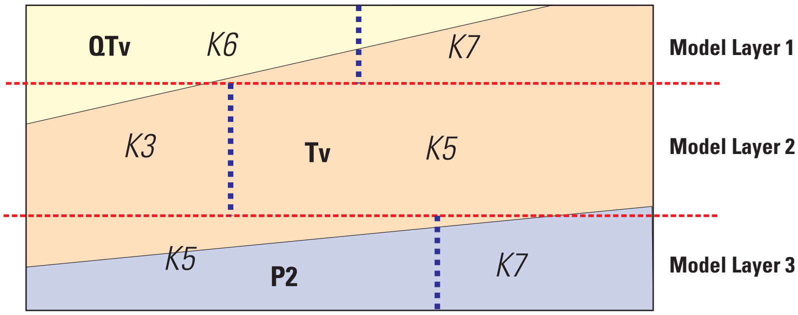
The two recent regional ground-water flow models (IT Corporation, 1996a; D'Agnese and others, 1997) differ significantly in how the Cenozoic section of the DVRFS region has been grouped into HGUs, both in terms of the number of units and in how the spatial variability of material properties in the volcanic units is addressed (table B–1, fig. B–8). The volcanic rock HGUs in the YMP/HRMP model (D'Agnese and others, 1997) were based on a hydrogeologic map compilation (Faunt

Table B–1. Hydrogeologic units used in previous U.S. Department of Energy ground-water flow models in the Death Valley region.

[---, unit not used in model]

DOE/NV-UGTA model units (IT Corporation, 1996b)	YMP/HRMP model units (D'Agnese and others, 1997)	Description of geologic unit
AA	QTvf	Basin-fill deposits
AA	QTvf	Playa deposits
AA	QTvf	Lacustrine limestone and spring deposits
VA, VCU, VU	QTv, Tv	Younger Tertiary volcanic rocks
VCU, TSDVS, VU	Tvs	Younger Tertiary sedimentary rocks
TMA, VA	QTv, Tv	Timber Mountain Group
TC, VA	QTv, Tv	Paintbrush Group
TC	QTv, Tv	Calico Hills Formation
VA	QTv, Tv	Wahmonie Formation
TBCU	QTv, Tv	Prow Pass Tuff, Crater Flat Group
TCB	QTv, Tv	Bullfrog Tuff, Crater Flat Group
TBCU	QTv, Tv	Tram Tuff, Crater Flat Group
TBA	QTv, Tv	Belted Range Group
TBCU, TBQ, VCU, VU	QTv, Tv	Older Tertiary volcanic rocks (pre-Belted Range Group)
VCU, TSDVS	Tvs	Older Tertiary sedimentary rocks
---	Mvs	Mesozoic volcanic and sedimentary rocks
LCA3	---	Upper Paleozoic carbonate rocks
UCCU	ECU	Mississippian and Devonian siliciclastic rocks (Eleana Formation and Chainman Shale)
LCA, LCA1	P2	Middle Cambrian through Devonian mostly carbonate rocks
LCCU	P1	Late Proterozoic through Middle Cambrian siliciclastic rocks
LCCU	PCgm	Metamorphic and igneous rocks
---	TJg	Intrusive rocks, undifferentiated

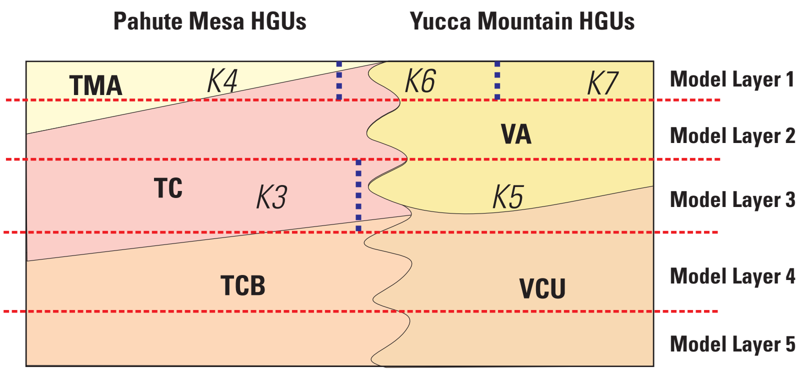
A YMP/HRMP model (D'Agnese and others, 1997)



Abbreviations: QTv, Quaternary and Tertiary volcanic rocks;
Tv, Tertiary volcanic rocks; P2, Paleozoic carbonate-rock aquifer

HGUs from 3D framework model are discretized into the three layers of the flow model. To approximate the hydrologic effects of spatially varying material properties, different hydraulic conductivities (K3, K5,...) were applied to specific parts of each model layer during flow modeling.

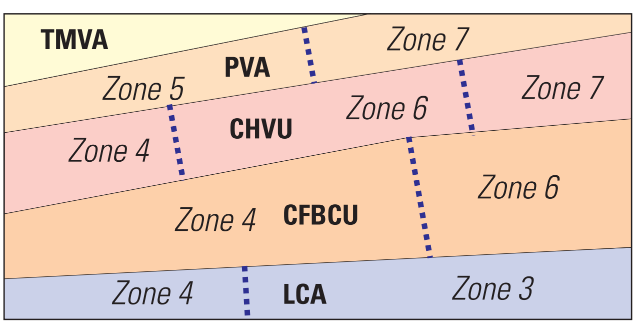
B DOE/NV-UGTA model (IT Corporation, 1996b)



Abbreviations: TMA, Timber Mountain aquifer; TC, Paintbrush tuff cone;
TCB, Bullfrog confining unit; VA, volcanic aquifer; VCU, volcanic confining unit

HGUs change for different geographic regions represented in the 3D framework model based on stratigraphic changes in the volcanic section. To approximate the hydrologic effects of spatially varying material properties, different hydraulic conductivities (K3, K4,...) were applied to specific parts of each model layer during flow modeling.

C Current model



Abbreviations: TMVA, Timber Mountain volcanic aquifer; PVA, Paintbrush volcanic aquifer; CHVU, Calico Hills volcanic unit; CFBCU, Crater Flat–Bullfrog confining unit; LCA, Lower carbonate-rock aquifer

HGUs remain consistently named throughout the 3D framework model and are referenced to geologic map units, geologic cross sections, and borehole logs. Spatially varying material properties based upon geologic judgment are derived for each HGU (zone 1, zone 2...). Assignment of hydraulic conductivities and modification of geologically based zonations are discussed in Chapter F.

Figure B–8. Treatment of hydrogeologic units and spatially varying material properties in previous and current regional models.

and others, 1997) and geologic cross sections (Grose, 1983) in which all volcanic rocks were designated as Tertiary volcanic rocks (Tv) or Tertiary-Quaternary volcanic rocks (QTv) (table B–1). Spatial variability in hydrologic properties in the volcanic-rock section was addressed using zones of variable hydraulic conductivity in the flow model (D'Agnese and others, 1997, 2002) (fig. B–8). The volcanic rock HGUs in the DOE/NV-UGTA model (IT Corporation, 1996b) were based on abundant borehole data from the NTS and are considerably more detailed (table B–1). Spatial variation in the volcanic units was handled in part by developing different HGU schemes for specific parts of the NTS (fig. B–8), with specific aquifers (primarily lava flow and welded tuff) and confining units assigned for each geographic area. Belcher and others (2002) merged these two HGU schemes in the creation of a 3D HFM for the DVRFS region by using the DOE/NV-UGTA model (IT Corporation, 1996b) HGUs in the immediate vicinity of the NTS and the volcanic-rock HGUs of the YMP/HRMP model (D'Agnese and others, 1997) outside of the NTS. This HFM was used as input for a steady-state prepumping ground-water flow model of the DVRFS region (D'Agnese and others, 2002).

Volcanic-rock HGUs for the current model (fig. B–8) remain consistently named throughout the entire HFM and are defined by group-level stratigraphic designations that are based on recent geologic map compilations (Slate and others, 2000; Workman, Menges, Page, Taylor, and others, 2002), geologic cross sections (Sweetkind, Dickerson, and others, 2001), and borehole lithologic data. The spatial variability of material properties is defined for each volcanic-rock HGU on geologic grounds, discussed herein.

Description of Hydrogeologic Units

The unconsolidated sediments and consolidated rocks of the DVRFS region have been subdivided into 25 HGUs (table B–2). These HGUs are based primarily on the work of Laczniak and others (1996). Lithologically similar HGUs are discussed together in this section. In general, HGUs whose abbreviated names end in the letter "A", such as LCA, are considered aquifer units; those names ending in "CU" are considered confining units, and those ending in "U" are units that can function either as aquifers or confining units. These designations are only generally applicable because almost all of the HGUs have spatially varying material and hydraulic properties throughout the DVRFS region.

Unconsolidated Cenozoic Basin-Fill Sediments and Local Young Volcanic Rocks

Unconsolidated Cenozoic basin-fill sediments consist of coarse-grained alluvial and colluvial deposits, fine-grained basin axis deposits, and local lacustrine limestones and spring discharge deposits and are divided into six HGUs. Relatively local basaltic- and rhyolitic-lava flows and tuffs form another HGU. All seven of these HGUs are defined on the basis of geologic map data from a 1:250,000-scale geologic compilation of the DVRFS region (Workman, Menges, Page, Taylor, and others, 2002) (fig. B–9). The age terms "younger" and "older" in the names of the alluvial aquifer and confining unit HGUs refer to the relative ages of mapped surficial-deposit units, as described by Workman, Menges, Page, Taylor, and others (2002).

Younger and Older Alluvial Aquifers (YAA and OAA)

Coarse-grained surficial units are included in the younger alluvial aquifer (YAA) and the older alluvial aquifer (OAA). The YAA and OAA consist of Holocene to Pliocene alluvium, colluvium, and minor eolian and debris-flow sediments associated with alluvial geomorphic surfaces (Swan and others, 2001; Potter, Dickerson and others, 2002). In general, fluvial deposits are predominant sandy gravel with interbedded gravelly sand and sand, whereas alluvial fans have a more gradational decrease in grain size from proximal to distal fan. Local eolian accumulations consist of Holocene sand sheets or dune fields or relict upper to middle Pleistocene sand-ramp deposits that are banked along the flanks of some ranges. Sediments generally are not cemented but are more indurated with increasing depth. These HGUs tend to be aquifers, but finer grained sediments and intercalated volcanic rocks locally can impede ground-water movement.

Younger and Older Alluvial Confining Units (YACU and OACU)

The alluvial confining units (YACU and OACU) consist of Holocene to Pliocene fine-grained basin-axis deposits. These units consist of late Holocene playa and (or) salt-pan deposits that are commonly underlain by older playa or lacustrine sequences of middle to early Holocene and Pleistocene age. These rocks typically are mixtures of moderately to well stratified silt, clay, and fine sand. The thickness is poorly constrained but may range from 1 to 10 m for Holocene deposits and may be greater than 300 m for the older deposits (Workman, Menges, Page, Taylor, and others, 2002).

Limestone Aquifer (LA)

The limestone aquifer (LA) consists of Holocene to Pliocene lacustrine and spring deposits that are interfingered with the alluvial basin-fill units. Typically, these are dense, crystalline deposits of limestone or travertine. The hydrologic properties of these deposits can differ greatly over short distances because of abrupt changes in grain size, fracturing, and consolidation. These deposits can be productive local aquifers, such as in parts of the Amargosa Desert. In general, the LA does not crop out and is identified only from drill holes in the basin-filling units.

Table B–2. Geologic and hydrogeologic units of the Death Valley regional ground-water flow system (DVRFS) model.

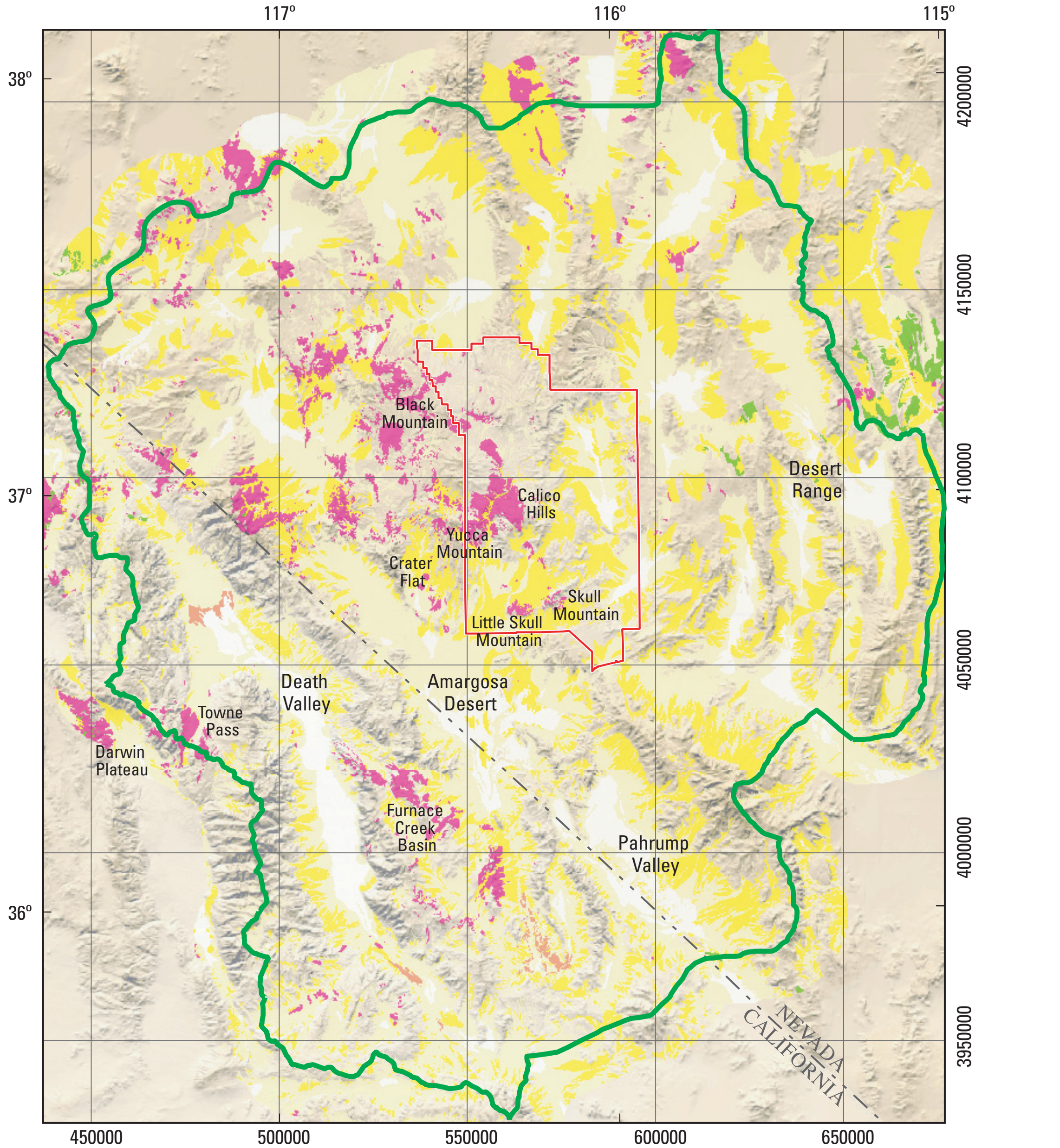
[SWNVF, southwestern Nevada volcanic field]

Hydrogeologic unit abbreviation and name	Age and description of geologic units
Unconsolidated Cenozoic basin-fill sediments and local younger volcanic rocks	
YAA; Younger alluvial aquifer	Pliocene to Holocene coarse-grained basin-fill deposits
YACU; Younger alluvial confining unit	Pliocene to Holocene playa and fine-grained basin-fill deposits
OAA; Older alluvial aquifer	Pliocene to Holocene coarse-grained basin-fill deposits
OACU; Older alluvial confining unit	Pliocene to Holocene playa and fine-grained basin-fill deposits
LA; Limestone aquifer	Cenozoic limestone, undivided
LFU; Lava-flow unit	Cenozoic basalt cones and flows and surface outcrops of rhyolite-lava flows
YVU; Younger volcanic-rock unit	Cenozoic volcanic rocks that overlie the Thirsty Canyon Group
Consolidated Cenozoic basin-fill deposits	
Upper VSU; Volcanic- and sedimentary-rock unit (upper)	Cenozoic volcanic and sedimentary rocks, undivided, that overlie volcanic rocks of SWNVF
Lower VSU; Volcanic- and sedimentary-rock unit (lower)	Cenozoic volcanic and sedimentary rocks, undivided; where named Cenozoic volcanic rocks exist, lower VSU underlies them.
Cenozoic volcanic rocks of the southwestern Nevada volcanic field	
TMVA; Thirsty Canyon–Timber Mountain volcanic-rock aquifer	Miocene Thirsty Canyon and Timber Mountain Groups, plus Stonewall Mountain tuff, undivided
PVA; Paintbrush volcanic-rock aquifer	Miocene Paintbrush Group
CHVU; Calico Hills volcanic-rock unit	Miocene Calico Hills Formation
WVU; Wahmonie volcanic-rock unit	Miocene Wahmonie and Salyer Formations
CFPPA; Crater Flat–Prow Pass aquifer	Miocene Crater Flat Group, Prow PassTuff
CFBCU; Crater Flat–Bullfrog confining unit	Miocene Crater Flat Group, Bullfrog Tuff
CFTA; Crater Flat–Tram aquifer	Miocene Crater Flat Group, Tram Tuff
BRU; Belted Range unit	Miocene Belted Range Group
OVU; Older volcanic-rock unit	Oligocene to Miocene; near the Nevada Test Site consists of all volcanic rocks older than the Belted Range Group. Elsewhere, consists of all tuffs that originated outside of the SWNVF.
Hydrogeologic units associated with Mesozoic, Paleozoic and Late Proterozoic sedimentary rocks	
SCU; Sedimentary-rock confining unit	Paleozoic and Mesozoic sedimentary and volcanic rocks
UCA; Upper carbonate-rock aquifer	Paleozoic carbonate rocks (UCA only used where UCCU exists, otherwise UCA is lumped with LCA)
UCCU; Upper clastic-rock confining unit	Upper Devonian to Mississippian Eleana Formation and Chainman Shale
LCA; Lower carbonate-rock aquifer	Cambrian through Devonian predominantly carbonate rocks
LCCU; Lower clastic-rock confining unit	Late Proterozoic through Lower Cambrian primarily siliciclastic rocks (including the Pahrump Group and Noonday Dolomite)
Hydrogeologic units associated with crystalline metamorphic rocks and plutons	
XCU; Crystalline-rock confining unit	Early Proterozoic metamorphic and igneous rocks and metamorphosed Middle and Late Proterozoic sedimentary rocks
ICU; Intrusive-rock confining unit	All intrusive rocks, regardless of age

Lava-Flow Unit (LFU)

The lava-flow unit (LFU) consists of local Neogene (generally 11 Ma and younger) basalt- and rhyolite-lava flows in the DVRFS region. Pliocene and Pleistocene volcanism on the NTS is expressed by isolated, relatively small basaltic cinder cones and associated lava flows. The eruptive style and chemical composition of the basalts is typical of Pliocene and Pleistocene basalts throughout most of the western part of the Basin and Range province (Hedge and Noble, 1971). They probably represent the waning stages of regional volcanism that peaked around 11 Ma.

Basalts of about 10 Ma in the vicinity of the NTS include lava flows on Skull Mountain and Little Skull Mountain, the southern part of Crater Flat, Black Mountain and to the west of the NTS (fig. B–9). Basalts of similar ages are part of the Funeral Formation in the Furnace Creek basin (Cemen and others, 1985; Greene, 1997; Wright and others, 1999). The LFU also includes volcanic rocks of the Towne Pass area and west of the model domain in the Darwin plateau. Younger basalts in the Amargosa Desert and in the southeast part of Crater Flat include an approximately 3.7-Ma event (Crowe and others, 1995) that is characterized by basalt-lava flows and exposed dikes along a north-trending



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

0 40 80 KILOMETERS
0 20 40 MILES

EXPLANATION

Hydrogeologic units
(from Workman, Menges, Page, Taylor, and others, 2002)

- Younger alluvial aquifer (YAA)
- Younger alluvial confining unit (YACU)
- Older alluvial aquifer (OAA)
- Older alluvial confining unit (OACU)
- Younger volcanic-rock unit (YVU)
- Lava-flow unit (LFU)

- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary

Figure B–9. Outcrop distribution of hydrogeologic units associated with alluvial sediments and local young volcanic rocks.

alignment of vents, four 1.0-Ma cinder cones that form a slightly curved north-northeast alignment in Crater Flat, and a single cinder cone (Lathrop Wells cone, 77.76 ka, Heizler and others, 1999) at the southern end of Yucca Mountain. Aeromagnetic anomalies and local basaltic float are evidence for shallowly buried basalt flows at several locations in the northern part of Amargosa Desert (O'Leary and others, 2002).

The LFU also includes Miocene rhyolite-lava flows in the northern part of Yucca Mountain and the Calico Hills, where they form extensive surface outcrops (fig. B–9). Individual lava flows are not laterally extensive. Because the LFU is typically above the water table, the unit is not a regional aquifer.

Younger Volcanic-Rock Unit (YVU)

The younger volcanic-rock unit (YVU) consists of Neogene (mostly 15 to 11 Ma) tuffs and other volcanic rocks that are not associated with sources in the SWNVF. Individual units are not laterally extensive, such as the isolated exposures of Kane Wash Tuff to the north of the Desert Range (fig. B–9); these are outliers of much more extensive volcanic outcrops that lie to the northeast of the model domain (Ekren and others, 1977). Most of the unit lies above the water table and is thought to have limited influence on ground-water flow in the DVRFS region.

Consolidated Cenozoic Basin-Fill Deposits—Volcanic- and Sedimentary-Rock Unit (VSU)

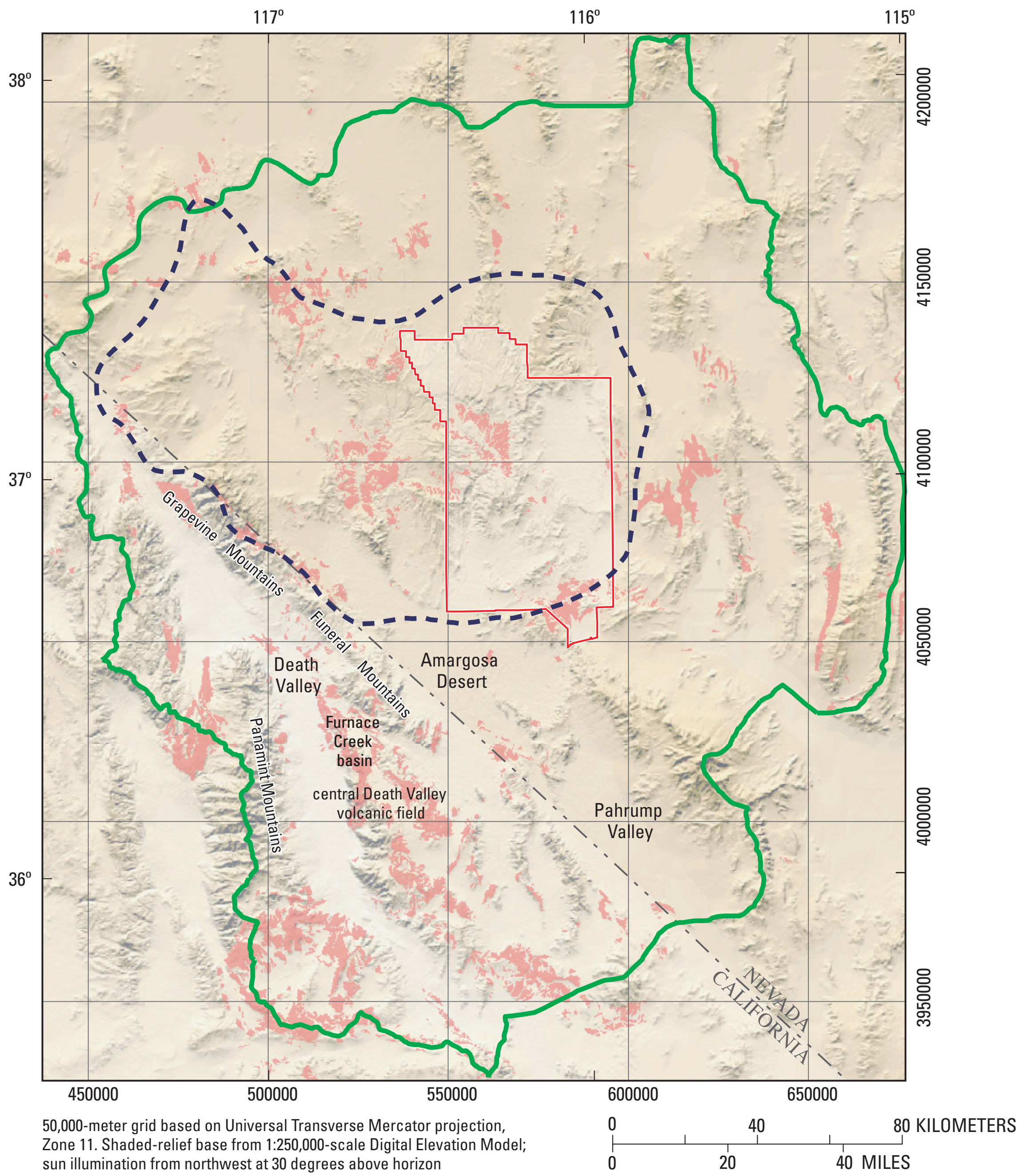
The volcanic- and sedimentary-rock unit (VSU) (fig. B–10) consists of all Cenozoic basin-filling sedimentary and volcanic rocks, except for the named volcanic-rock units in the vicinity of the SWNVF and the alluvial HGUs discussed previously. Consolidated Cenozoic basin-fill units of the DVRFS region range from late Eocene to Pliocene in age and generally underlie the more recent alluvial sediments assigned to the alluvial aquifers and confining units described herein. They consist of a broad range of both volcanic and sedimentary rocks including lavas, welded and nonwelded tuffs, and alluvial, fluvial, colluvial, eolian, paludal, and lacustrine sediments. Cenozoic volcanic and sedimentary rocks in the DVRFS region may be generalized into three sequences according to their relation to the tectonic evolution of the region (Snow and Lux, 1999): (1) an early extensional sequence that generally predates the formation of basin-range topography; (2) a synextensional and synvolcanic sequence that corresponds to the major period of formation of basin-range topography in this region and to the peak of volcanic activity in the southwestern Nevada and central Death Valley volcanic fields; and (3) a 6-Ma to present, late extensional to post-extensional sequence. This general subdivision is similar to that used by Ekren and others (1977) and Workman, Menges, Page, Taylor, and others (2002) and is more clearly documented in Fridrich and others (2000).

Rocks in the early extensional sequence are late Eocene to Miocene in age and have variable thickness and facies, and their distribution is discontinuous, probably because they were deposited on the irregular pre-Cenozoic erosional surface. Many of these rocks were deposited in a fluvio-lacustrine regime. Included in this sequence are the Titus Canyon Formation along the east side of the Funeral and Grapevine Mountains (Reynolds, 1974; Wright and Troxel, 1993), sedimentary rocks informally called the "rocks of Winapi Wash" that occur in and near the NTS, 25- to 14-Ma sedimentary strata including the Rocks of Pavits Spring in the vicinity of the NTS (Slate and others, 2000), and unnamed units widely exposed in and around the Grapevine Mountains and the Funeral Mountains.

Rocks in the synextensional and synvolcanic sequence are middle Miocene in age and include such units as the Artist Drive Formation in the Furnace Creek Basin and similar sedimentary rocks that probably underlie parts of the Amargosa Desert, Pahrump Valley, and Death Valley. Middle Miocene synextensional sedimentary rocks consist of coarse, tuffaceous clastic types, locally derived megabreccias, and tuffaceous sandstone locally interbedded with lavas that range in composition from basalt through rhyolite. The geology and stratigraphic relations of these middle Miocene rocks are discussed by Cemen and others (1985), Greene (1997), and Wright and others (1999).

Also included in the synextensional and synvolcanic sequence are the volcanic rocks of the central Death Valley volcanic field and volcanic rocks around the margins of the SWNVF that have not been correlated to a specific unit. Volcanic rocks of the central Death Valley volcanic field consist of predominantly silicic- to intermediate-composition lava flows and associated fallout tephra (Wright and others, 1991). Only one relatively widespread welded ash-flow tuff, the Rhodes Tuff, is recognized in the volcanic field (Wright and others, 1991); most of the volcanic-rock units appear to be associated with local source areas and have limited areal distribution (Wright and others, 1991). The general absence of strong magnetic anomalies in the vicinity of the Amargosa Desert between the SWNVF and the central Death Valley volcanic field implies that strongly magnetic volcanic rocks from either volcanic field are thin or absent (Carr, 1990; Blakely and others, 2000).

Rocks of the late extensional to post-extensional sequence include units such as the Funeral Formation of the Furnace Creek Basin that were deposited mostly in restricted, intermontane basins that developed as extension progressed (Snow and Lux, 1999). Synextensional sedimentary rocks were deposited during this time in the Nova basin on the western side of the Panamint Mountains (Hodges and others, 1989).



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

EXPLANATION

Units that compose volcanic- and sedimentary-rock unit (VSU; from Workman, Menges, Page, Taylor, and others, 2002)

Boundary of southwestern Nevada volcanic field (from Laczniak and others, 1996)

Death Valley regional ground-water flow system model boundary

Nevada Test Site boundary

Figure B–10. Outcrop distribution of the volcanic- and sedimentary-rock unit (VSU).

The VSU is lithologically diverse and rock types are complexly interfingered. For example, interpreted lithologic data from boreholes in the southern part of the Amargosa Desert (fig. B–11) reveal a heterogeneous basinfill with few lithologically similar intervals that can be correlated between adjacent boreholes. Interpolation of lithologic data between boreholes indicates complex interfingering of basin-fill lithologies (Oatfield and Czarnecki, 1989). In order to generalize the basin-fill lithologic diversity for use in a regional model, Sweetkind, Fridrich, and Taylor (2001) delineated regional facies trends on the basis of borehole and outcrop data. Five zones of potential hydrologic significance were defined on the basis of the relative amounts of coarse- and fine-grained sedimentary rocks compared to volcanic rocks at each locality (fig. B–12). Mapped zones (fig. B–12) do not imply the existence of the VSU throughout the region; rather, they are a guide to which set of material properties applies where the VSU exists in the 3D HFM (Chapter E, this volume).

In order for units to stack correctly when constructing a 3D HFM of the DVRFS region (Chapter E, this volume), the VSU was divided into two units. The lower VSU consists of those rocks that underlie these named volcanic rocks (table B–3); the upper VSU consists of those rocks that overlie the named volcanic rocks of the SWNVF (table B–4). Outside of the SWNVF, the boundary between the two units is arbitrary. Upper VSU hydrogeologic zones are delineated by their relation to aquifer and confining units in the overlying basin-fill material.

Volcanic Rocks of the Southwestern Nevada Volcanic Field

Volcanic rocks that emanated from the SWNVF are widely distributed in the west-central part of the DVRFS region; associated caldera collapse structures of the SWNVF dominate the northwestern and west-central parts of the NTS (fig. B–13). Volcanism associated with the SWNVF occurred episodically between about 15 and 9 Ma (Byers, Carr, Orkild, and others, 1976; Sawyer and others, 1994). Eruption of voluminous, extensive ash-flow-tuff sheets resulted in the collapse of at least seven known calderas, two of which overlapped to form the Silent Canyon caldera complex (SCCC), and three of them overlapped or were nested to form the Timber Mountain caldera complex (TMCC) and the Claim Canyon caldera. The sources of many of the older ash-flow tuffs remain uncertain because associated calderas have been buried or destroyed by younger calderas. Volumetrically subordinate, but related, silicic-lava flows and minor pyroclastic flows were erupted from the calderas and from isolated volcanic vents in the field (Sawyer and others, 1994). Numerous authoritative sources exist for more detailed information on the volcanic rocks (Byers, Carr, Orkild, and others, 1976; Christiansen and others, 1977; Carr, Byers, and Orkild, 1986; Sawyer and Sargent, 1989; Ferguson and others, 1994; Sawyer and others, 1994), and for a number of geologic-map compilations that portray the volcanic rocks at the NTS (Byers, Carr, Christiansen, and others 1976; Frizzell and Shulters, 1990; Wahl and others, 1997; Slate and others, 2000).

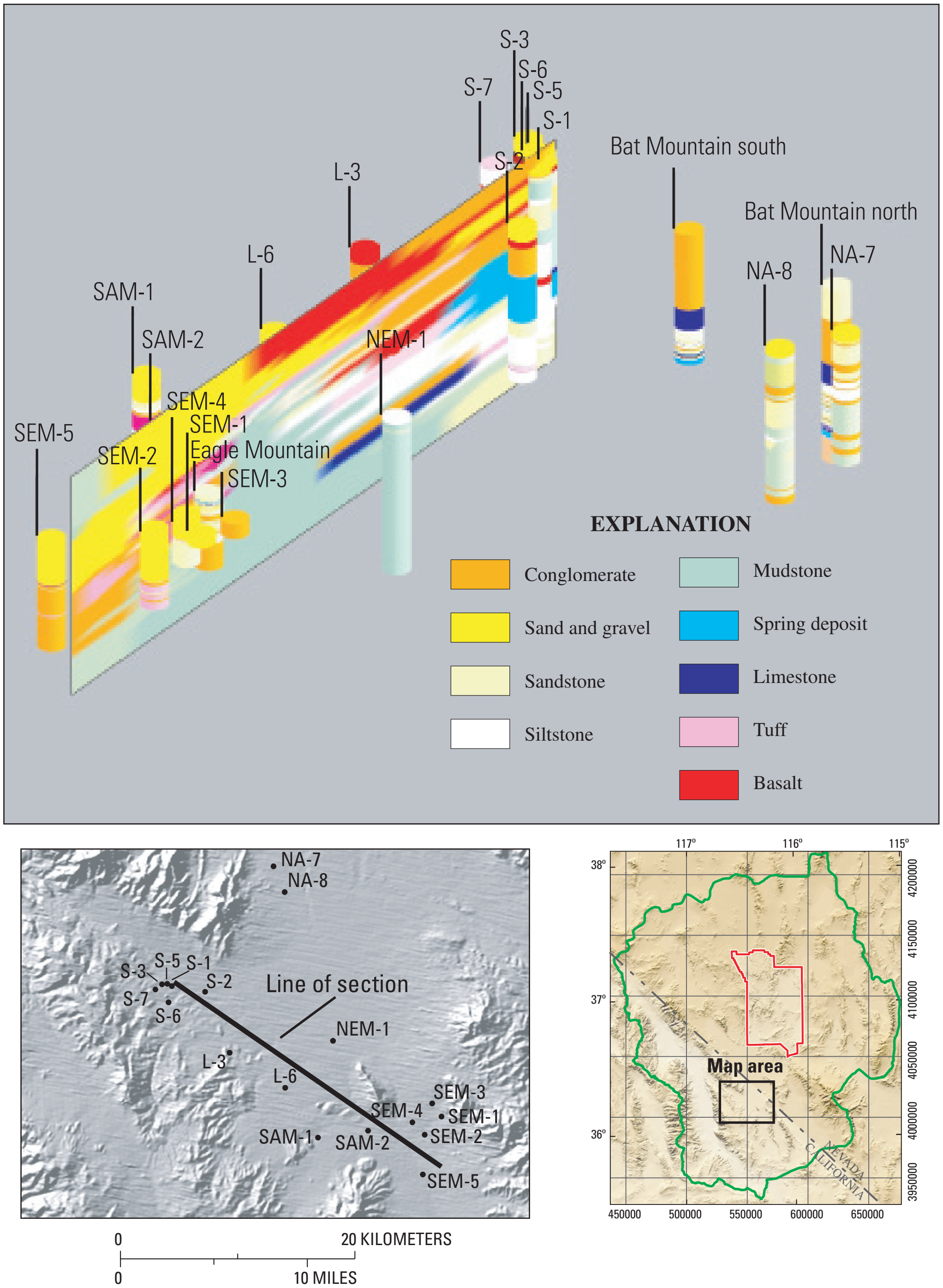
The volcanic-rock units of the SWNVF are important hydrogeologic units because they are thick enough in the vicinity of the NTS to be important subregional aquifers, and a number of nuclear weapons tests were conducted in the volcanic rocks at Rainier Mesa and Pahute Mesa at the NTS. The proposed high-level radioactive waste repository at Yucca Mountain on the western edge of the NTS would be located in these volcanic rocks.

Volcanic rocks of the SWNVF consist of the pre-Belted Range Group rocks, the Belted Range and Crater Flat Groups, the Calico Hills and Wahmonie Formations, the Paintbrush, Timber Mountain, and Thirsty Canyon Groups, and the Stonewall Mountain Tuff. The volcanic-rock units are divided at the group level into nine HGUs, except for the Crater Flat Group (table B–2). In order to maintain consistency with the Yucca Mountain 3D geologic framework model (YMP-GFM) (Bechtel SAIC Company, 2002), the Crater Flat Group is subdivided at the formation level with separate HGUs for the Prow Pass, Bullfrog, and Tram Tuffs (table B–2).

Method for Assigning Material Property Variations to Hydrogeologic Units of the Southwestern Nevada Volcanic Field

The Cenozoic volcanic rocks of the SWNVF have varying degrees of both fracture and matrix permeability. Most of the crystallized and densely welded tuffs have very low matrix permeabilities (Montazer and Wilson, 1984); consequently, fracture networks and faults are the primary pathways for gas and water flow through the welded parts of the rock mass. Poorly welded to nonwelded ash-flow tuffs and ash-fall tuff, reworked tuff, and volcaniclastic rocks have higher matrix permeabilities but poorly developed and connected fracture networks. Fracture-dominated flow in the welded portions of the tuffs of the SWNVF changes to matrix-dominated flow in the comparatively unfractured units (Blankennagel and Weir, 1973; Montazer and Wilson, 1984; Laczniak and others, 1996). Alteration of rock-forming minerals to zeolite, clay, carbonate, silica, and other minerals, most prevalent in nonwelded rocks, can reduce permeability.

At the group and formation level, mapped volcanic-rock units commonly display widely variable lithology and degree of welding both vertically and horizontally (fig. B–14). The hydraulic properties of these deposits depend mostly on the mode of eruption and cooling, by the extent of primary and secondary fracturing, and by the degree to which secondary alteration (crystallization of volcanic glass and zeolitic alteration) has affected primary permeability. Fractured rhyolite-lava flows and moderately to densely welded ash-flow tuffs are the principal volcanic-rock aquifers. Rhyolite-lava flows and thick intracaldera welded tuff (fig. B–15*A*) are relatively restricted areally, whereas outflow welded-tuff sheets are more



Vertical panel is a slice through a three-dimensional rock properties model of basin-filling deposits corresponding to the lower volcanic- and sedimentary-rock hydrogeologic unit (lower VSU) beneath the Amargosa Desert. Model was created by numerical interpolation of borehole lithologic data from the southern Amargosa Desert. Cylinders represent the location and drilled depth of boreholes; colors represent lithologic units penetrated by the boreholes. View is to the southwest. Cross section panel is approximately 25 kilometers long and 1 kilometer deep. With the exception of thin surficial units, the various lithologic units penetrated by all of the boreholes shown correspond to hydrogeologic unit lower VSU.

Figure B–11. Lithologic variability in the volcanic- and sedimentary-rock unit (VSU).

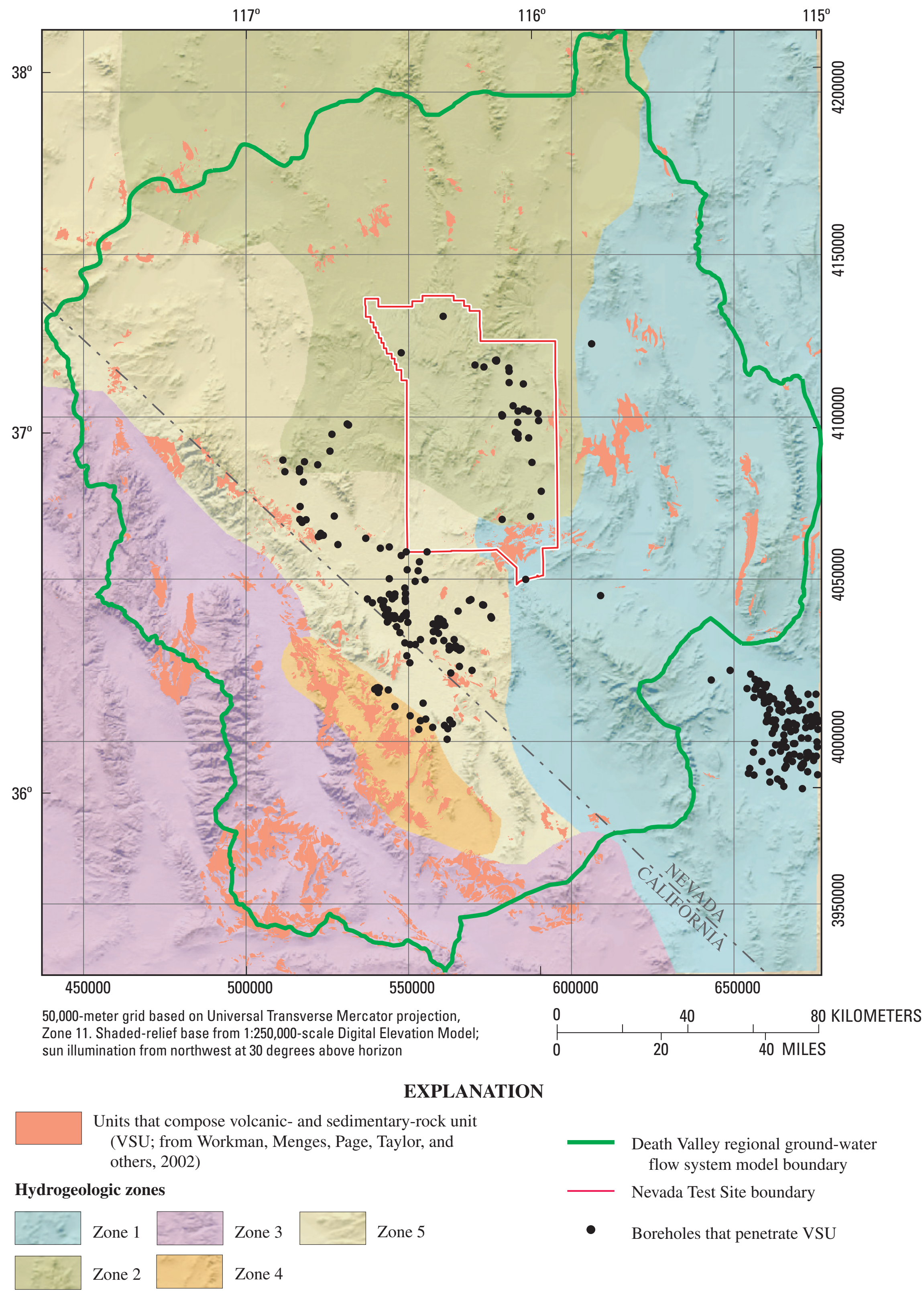


Figure B–12. Hydrogeologic zones in the volcanic- and sedimentary-rock unit (VSU).

Table B–3. Hydrogeologic zones in the lower volcanic- and sedimentary-rock unit (lower VSU).

[SWNVF, southwestern Nevada volcanic field]

Zone number	Description
1	Fluvial and lacustrine sedimentary rocks with few or no volcanic units. Mostly fine-grained deposits.
2	VSU in and to the north of the SWNVF includes Cenozoic sedimentary rocks that may underlie the volcanic section. Volcanic rocks penetrated by boreholes may be lumped with the underlying sedimentary rocks in some places.
3	Coarse gravels and megabreccias.
4	This zone consists of the volcano-sedimentary trough that incorporates the central Death Valley volcanic field and the Furnace Creek Basin. Stratigraphic successions are a mixed assemblage of coarse and fine sedimentary rocks and basalt- and rhyolite-lava flows and minor ash-flow tuff.
5	Stratigraphic successions in this zone are similar only in the diversity of their lithologies. Sedimentary rocks consist of coarse-and fine-grained alluvial deposits, lacustrine and playa deposits, fluvially reworked tuffs, and tuffaceous sedimentary rocks that span an age range from Oligocene to the Pliocene. Volcanic rocks are present in the northeastern and southwestern parts of the zone.

regionally distributed and may provide lateral continuity for water to move through the regional flow system. The confining units are formed generally by nonwelded or partly welded tuff that has low fracture permeability (fig. B–15*B*) and can be zeolitically altered in the older, deeper parts of the volcanic sections (Laczniak and others, 1996). The hydraulic properties of the volcanic rocks underlying Pahute Mesa were described by Blankennagel and Weir (1973); analysis of additional volcanic rock material and hydraulic properties (Belcher and others, 2001) indicates that these concepts may apply throughout the SWNVF.

For each of the volcanic-rock HGUs of the SWNVF, zones of potential enhanced and reduced permeability (termed hydrogeologic zones) were evaluated on the basis of lithologic and material property information available from boreholes (Warren and others, 1999) and surface localities (R.M. Drake, U.S. Geological Survey, written commun., 2001). At each location, the percentage of welded, fractured rock and percentage of altered rock were calculated by dividing the aggregate thickness of brittle (welded-tuff and lava-flow lithologies) or altered rock, respectively, by the total thickness of the HGU (R.M. Drake, written commun., 2001). The brittle rock and alteration data were interpolated and extrapolated from the available data over the modeled spatial extent of each HGU (see Chapter E, this volume) to produce gridded surfaces of these respective properties. Areas with greater than 50 percent brittle rock were considered potential enhanced permeability zones, whereas areas with less than 50 percent brittle rock were considered potential reduced permeability zones (table B–5). Areas with greater than 60 percent altered rock were considered potential reduced permeability zones, while

Table B–4. Hydrogeologic zones in the upper volcanic- and sedimentary-rock unit (upper VSU).

Zone number	Description
1	Upper VSU underlying the younger alluvial confining unit (YACU) and older alluvial confining unit (OACU)
2	Upper VSU underlying the older alluvial aquifer (OAA) and younger alluvial aquifer (YAA)

areas with less than 60 percent altered rock were considered potential enhanced permeability zones (table B–5). The brittle rock and alteration characteristics were combined to produce four types of zones: brittle rock that is not altered; brittle, altered rock; nonbrittle rock that is altered; and nonbrittle rock that is unaltered. Zones with a combination of a high percentage of brittle rock and a small degree of alteration are inferred to have enhanced permeability (zone 1, table B–5); zones with a combination of a low percentage of brittle rock and a high degree of alteration are inferred to have reduced permeability (zone 3, table B–5). The combined effects of fracturing and alteration on permeability are less predictable for highly altered brittle rocks (zone 2, table B–5) and unaltered nonbrittle rocks (zone 4, table B–5). Mapped zones do not imply the existence of each HGU throughout the zone; rather, they are a guide to which set of material properties applies where the HGU exists in the 3D HFM (Chapter E, this volume).

Volcanic-Rock Hydrogeologic Units of the Southwestern Nevada Volcanic Field

Thirsty Canyon–Timber Mountain Volcanic-Rock Aquifer (TMVA)

The Thirsty Canyon–Timber Mountain volcanic-rock aquifer (TMVA) is composed of the volcanic rocks of the 11.6- to 11.45-Ma Timber Mountain Group, the 9.4- to 9.15-Ma Thirsty Canyon Group, and the 7.5-Ma Stonewall Flat Tuff (Sawyer and others, 1994; Slate and others, 2000). Volcanic activity in the SWNVF peaked volumetrically with the eruption of the Timber Mountain Group ash-flow tuffs, which were erupted from the TMCC (Christiansen and Lipman, 1965; Byers, Carr, Orkild, and others, 1976; Byers, Carr, Christiansen, and others, 1976; Christiansen and others, 1977; Sawyer and others, 1994). The TMCC consists of the Rainier Mesa caldera, which formed as a result of the eruption of the 11.6-Ma Rainier Mesa Tuff, and the Ammonia Tanks caldera, which formed as a result of the eruption of the 11.45-Ma Ammonia Tanks Tuff (Sawyer and others, 1994;

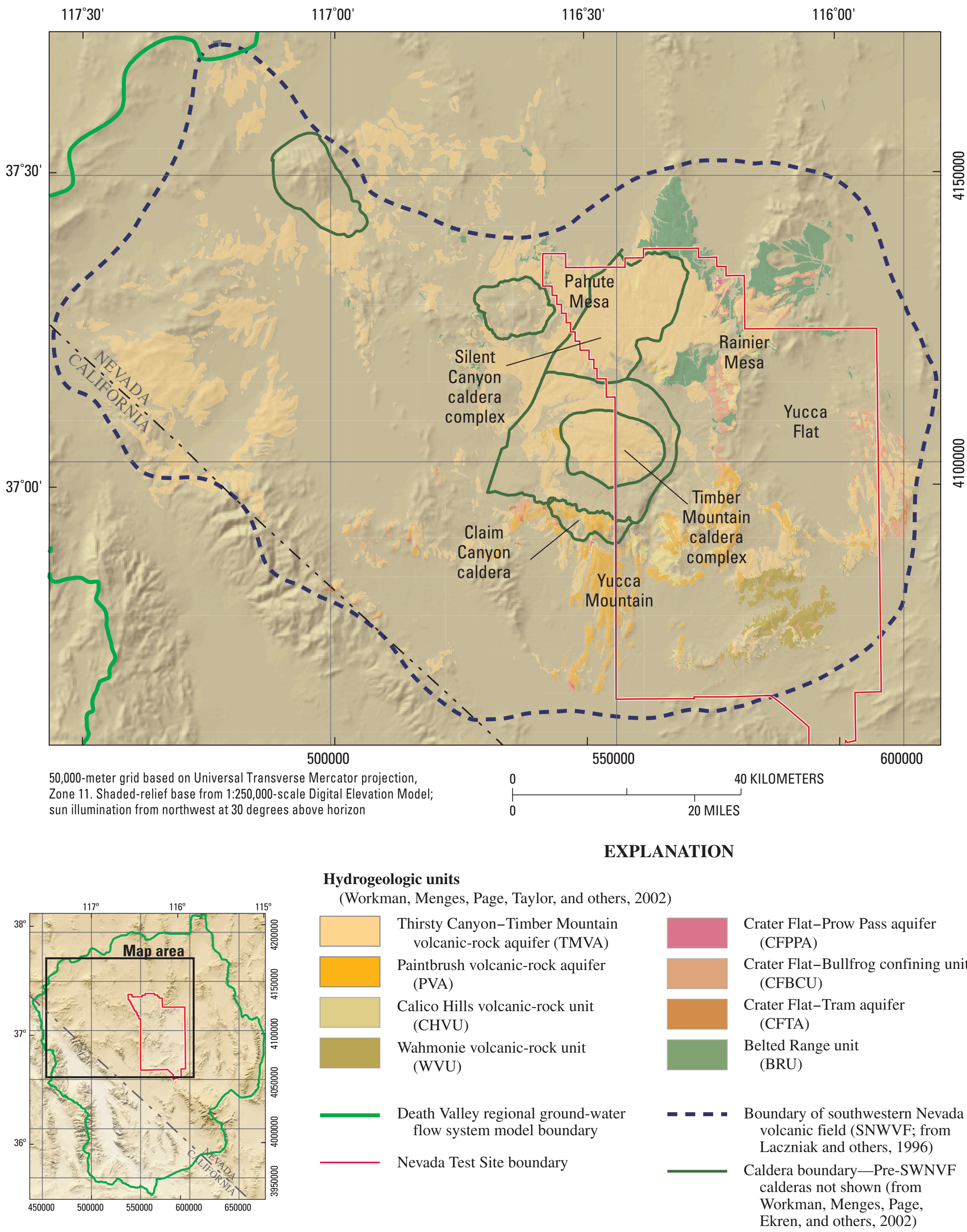
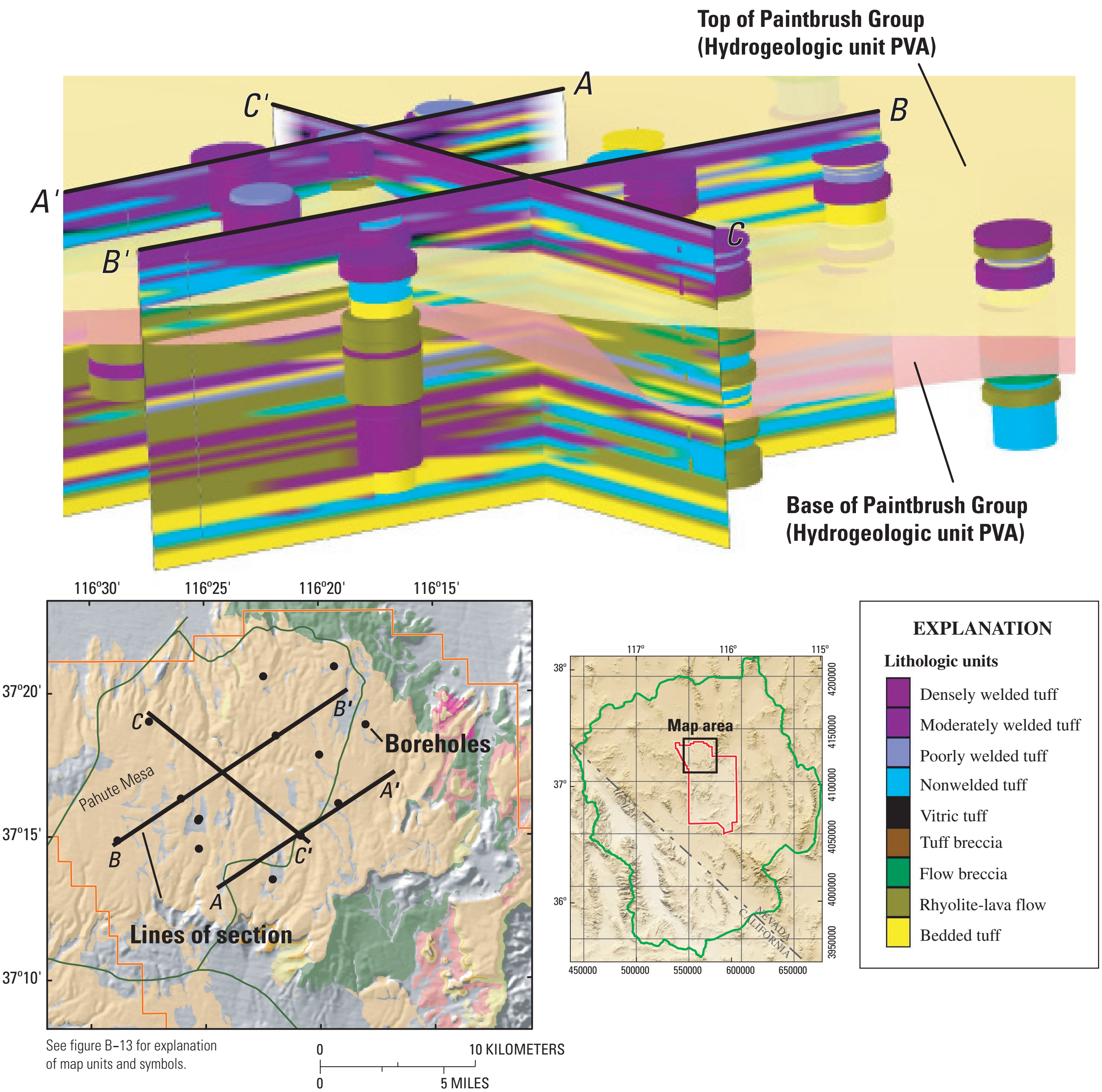


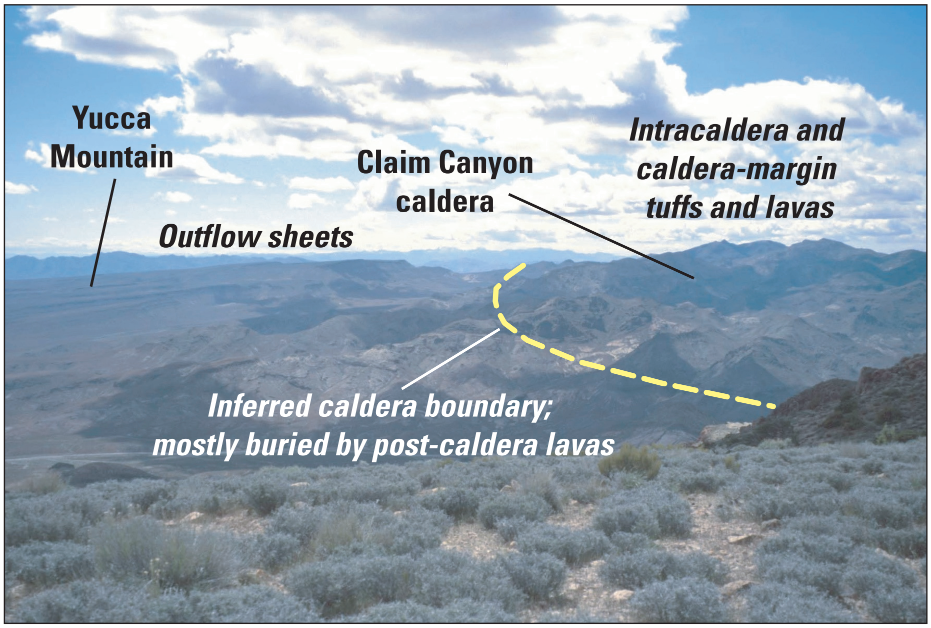
Figure B–13. Outcrop distribution of hydrogeologic units associated with volcanic rocks of the southwestern Nevada volcanic field.



Vertical panels are slices through a three-dimensional rock-properties model of volcanic rocks within the southwestern Nevada volcanic field at Pahute Mesa. Cylinders represent the location and drilled depth of boreholes; colors represent lithologic units and welding variations in the Cenozoic volcanic rocks penetrated by the boreholes. View is from north to the south. Cross-section panels are approximately 20 kilometers long and 1 kilometer deep.

Figure B–14. Variability in lithology and relative degree of welding in volcanic rocks of the southwestern Nevada volcanic field.

A View of the north end of Yucca Mountain, looking WSW



Example of regional-scale lithologic variability associated with calderas of the southwestern Nevada volcanic field. A heterogeneous assemblage of partly to densely welded tuff, volcanic megabreccia, and rhyolite lava flows within the Claim Canyon caldera. The stratigraphic complexity of the intracaldera rocks contrasts with the regionally widespread outflow tuffs exposed at Yucca Mountain. Field of view shown in the photograph is approximately 10 kilometers. Photograph by C.J. Potter, U.S. Geological Survey.

B Tiva Canyon Tuff, Paintbrush Group

Example of welding controls on fracture connectivity in the Tiva Canyon Tuff, Paintbrush Group. Well-developed columnar joints in densely welded tuff terminate abruptly at the transition to partly welded, vitric rock at the base of the ash-flow tuff (approximate contact shown by arrows). The partly welded rock is characterized by short, irregular, poorly connected fractures. Outcrop is approximately 2 meters in height. Photograph by D.S. Sweetkind, U.S. Geological Survey.

Figure B–15. Examples of lithologic and welding variability in volcanic rocks of the southwestern Nevada volcanic field.

Table B–5. Hydrogeologic zones for Cenozoic volcanic-rock hydrogeologic units of the southwestern Nevada volcanic field.

[Zonation applies to most Cenozoic volcanic-rock hydrogeologic units including the Belted Range unit (BRU), Crater Flat–Tram aquifer (CFTA), Crater Flat–Bullfrog confining unit (CFBCU), Crater Flat–Prow Pass aquifer (CFPPA), Wahmonie volcanic-rock unit (WVU), Calico Hills volcanic-rock unit (CHVU), Paintbrush volcanic-rock aquifer (PVA), and Thirsty Canyon–Timber Mountain volcanic-rock aquifer (TMVA)]

Zone number	Description
1	Brittle—Nonaltered: Contains greater than 50 percent brittle (fractured) rock and less than 60 percent altered rock.
2	Brittle—Altered: Contains greater than 50 percent brittle (fractured) rock and greater than 60 percent altered rock.
3	Nonbrittle—Altered: Contains less than 50 percent brittle (fractured) rock and greater than 60 percent altered rock.
4	Nonbrittle—Nonaltered: Contains less than 50 percent brittle (fractured) rock and less than 60 percent altered rock.

Sawyer and others, 1995). Borehole UE–18r, located to the north of Timber Mountain, penetrated up to 1,200 m of Timber Mountain Group rocks (Warren and others, 1999) and provides clear evidence for the structural collapse of both calderas (Christiansen and others, 1977). Timber Mountain Group rocks were deposited in a generally radial pattern surrounding the caldera complex, with some preferential flow to the west (fig. B–16). In addition to the two regionally extensive ash-flow tuffs, the Timber Mountain Group includes minor ash-flow tuffs, rhyolite-lava flows and domes, and intracaldera landslide breccia (Wahl and others, 1997; Slate and others, 2000). Thirsty Canyon Group rocks were erupted from the Black Mountain caldera (Noble and others, 1964; 1984) and cover large areas of the Pahute Mesa area and the northwestern part of the NTS.

Similar to most of the HGUs in the SWNVF, hydrologically significant material properties vary spatially on the basis of the presence of rhyolite-lava flows, the degree of welding of the ash-flow tuffs, and the presence of alteration. Hydrogeologic zones in the TMVA are mapped in fig. B–16.

Paintbrush Volcanic-Rock Aquifer (PVA)

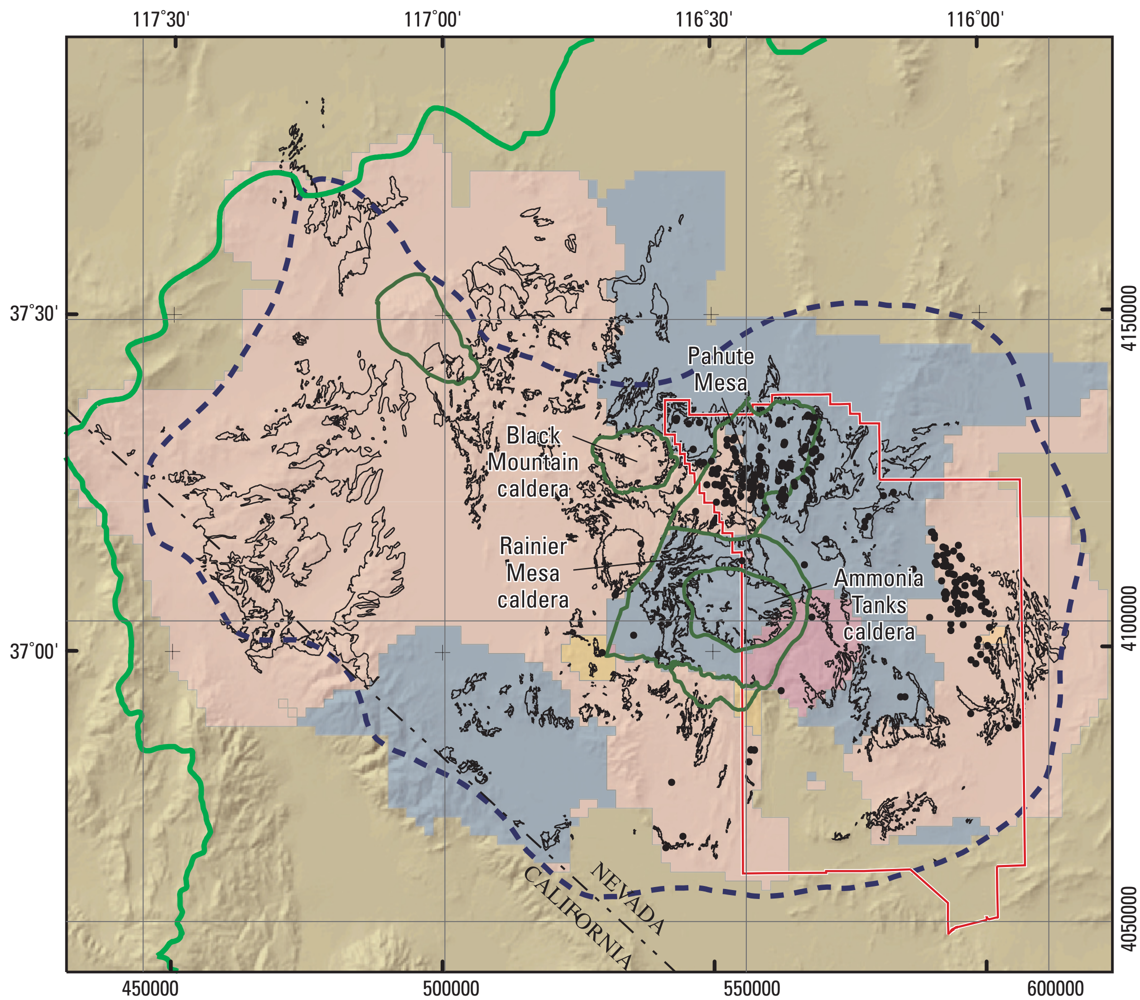
The Paintbrush volcanic-rock aquifer (PVA) is composed of rhyolite tuffs and lavas of the Paintbrush Group, whose source was the Claim Canyon caldera north of Yucca Mountain (Christiansen and Lipman, 1965; Byers, Carr, Christiansen, and others, 1976; Byers, Carr, Orkild and others, 1976; Potter, Dickerson, and others, 2002). The Paintbrush Group includes rhyolite-lava flows and four densely welded tuffs near the Claim Canyon caldera and at the northernmost part of Yucca Mountain. To the south, the Paintbrush Group consists of the densely welded 12.7-Ma Tiva Canyon and 12.8-Ma Topopah Spring Tuffs separated by a comparatively thin interval of mostly nonwelded, vitric pyroclastic deposits and minor bedded tuff units (Sawyer and others, 1994; Buesch and others, 1996). These two densely welded ash-flow tuffs are the thickest stratigraphic units exposed on Yucca Mountain.

Hydrogeologic zones for the PVA are mapped in figure B–17. Paintbrush Group rocks at Yucca Mountain are generally above the water table; alteration in these rocks is primarily local argillic or zeolitic alteration of the nonwelded interval between the Tiva Canyon Tuff and the Topopah Spring Tuff (Moyer and others, 1996). Paintbrush Group rocks lie above the water table in the eastern and central parts of Pahute Mesa, and below the water table in the western part of Pahute Mesa, where they are zeolitically altered locally in downfaulted blocks (Laczniak and others, 1996, plate 4). The Topopah Spring Tuff is zeolitically altered in southern and central Yucca Flat where it approaches its depositional terminus. Paintbrush Group rocks are affected by silicic, argillic, and hematitic alteration in the vicinity of Tram Ridge and in the Calico Hills (Simonds, 1989).

Calico Hills Volcanic-Rock Unit (CHVU)

The Calico Hills Formation is the Calico Hills volcanic-rock unit (CHVU). The 12.9-Ma Calico Hills Formation is a sequence of thick rhyolite-lava flows and intercalated, variably welded ash-flow deposits and nonwelded ash-fall deposits that lie between the Crater Flat Group and Paintbrush Group rocks at Yucca Mountain and Pahute Mesa (Sawyer and others, 1994). Thick lava flows and intercalated tuffs of the Calico Hills Formation are exposed in the Calico Hills and Fortymile Canyon and to the north of Crater Flat and are penetrated in several boreholes at Yucca Mountain (Moyer and Geslin, 1995) and at Pahute Mesa (fig. B–18). Rhyolite lavas in the Calico Hills Formation are common proximal to source vents (Dickerson and Drake, 1998); elsewhere the unit is dominated by nonwelded pyroclastic flows that commonly are zeolitically altered. The rocks were erupted from vents in two spatially distinct volcanic centers—the Calico Hills and Fortymile Canyon area and beneath Pahute Mesa (Sawyer and others, 1994) (fig. B–18).

Hydrogeologic zones of potential enhanced permeability in the CHVU are controlled by the distribution of fractured, vent-proximal, rhyolite-lava flows. For example, the CHVU is an aquifer in the central and western parts of Pahute Mesa (Blankennagel and Weir, 1973; Laczniak and others, 1996, plate 4), where thick accumulations of rhyolite-lava flows function as a single fractured aquifer (brittle, nonaltered zone, fig. B–18). In the northeastern part of Pahute Mesa (nonbrittle, nonaltered zone, fig. B–18) and beneath the southern part of Yucca Mountain (nonbrittle, altered zone, fig. B–18), relatively minor lava flows are isolated between thick intervals of nonwelded ash-flow tuff, and the CHVU functions as a confining unit (Blankennagel and Weir, 1973; Moyer and Geslin, 1995; Laczniak and others, 1996; Prothro and Drellack, 1997).



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

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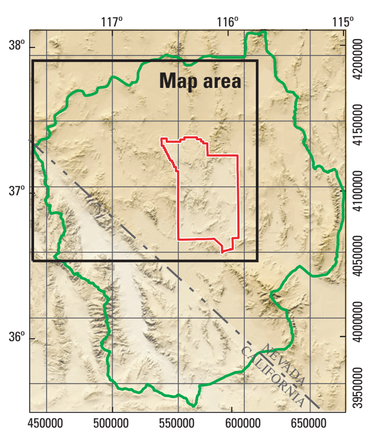


EXPLANATION

Hydrogeologic zones

- Brittle—Nonaltered
- Nonbrittle—Altered
- Brittle—Altered
- Nonbrittle—Nonaltered

- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary
- Boundary of southwestern Nevada volcanic field (SWNVF; from Laczniak and others, 1996)
- Caldera boundary—Pre-SWNVF calderas not shown (from Workman, Menges, Page, Ekren, and others, 2002)
- Outcrop of units that compose Thirsty Canyon–Timber Mountain volcanic-rock aquifer (TMVA; from Workman, Menges, Page, Ekren, and others, 2002)
- Boreholes that penetrate TMVA

Figure B–16. Hydrogeologic zones in the Thirsty Canyon–Timber Mountain volcanic-rock aquifer (TMVA).

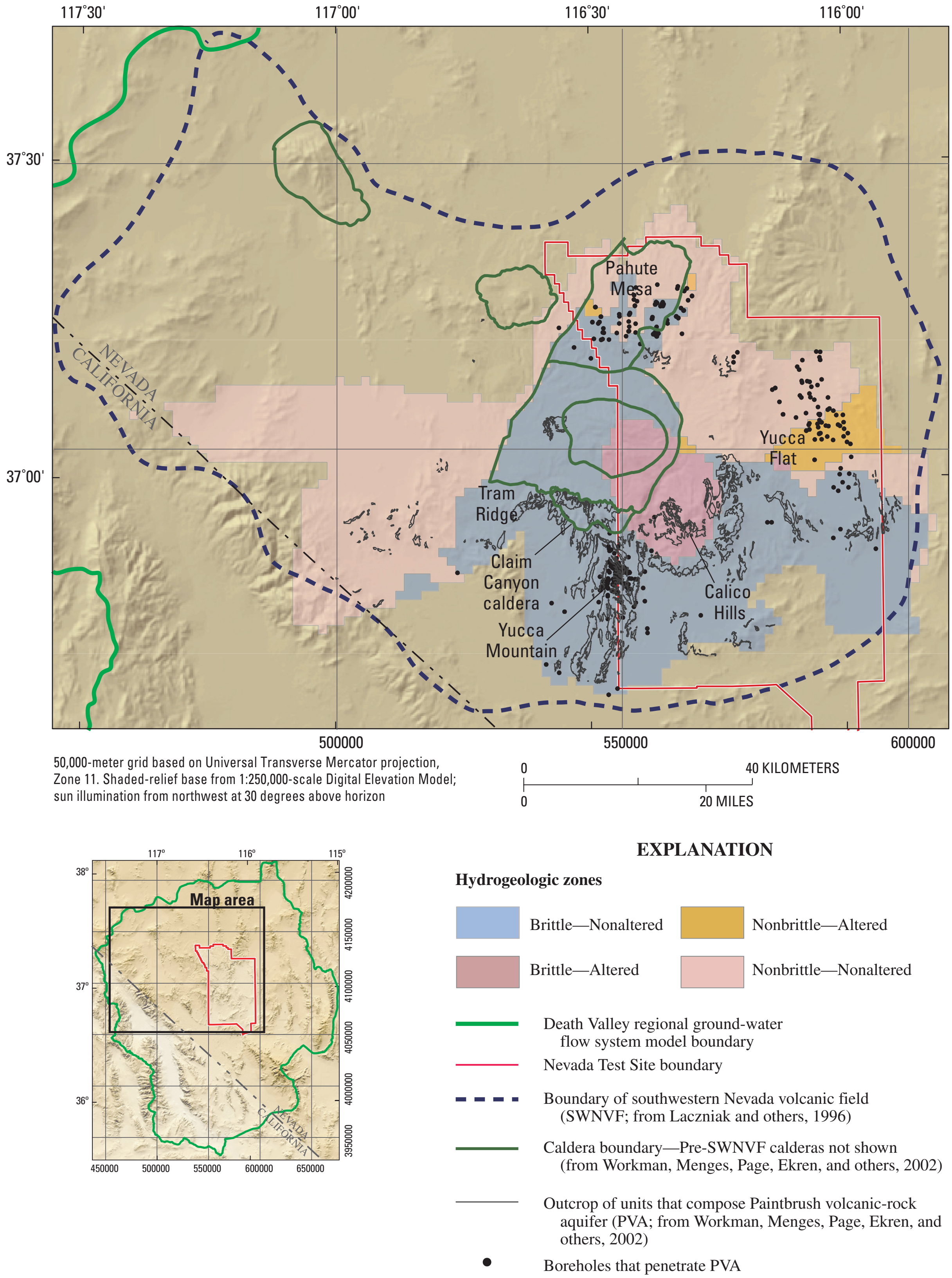


Figure B–17. Hydrogeologic zones in the Paintbrush volcanic-rock aquifer (PVA).

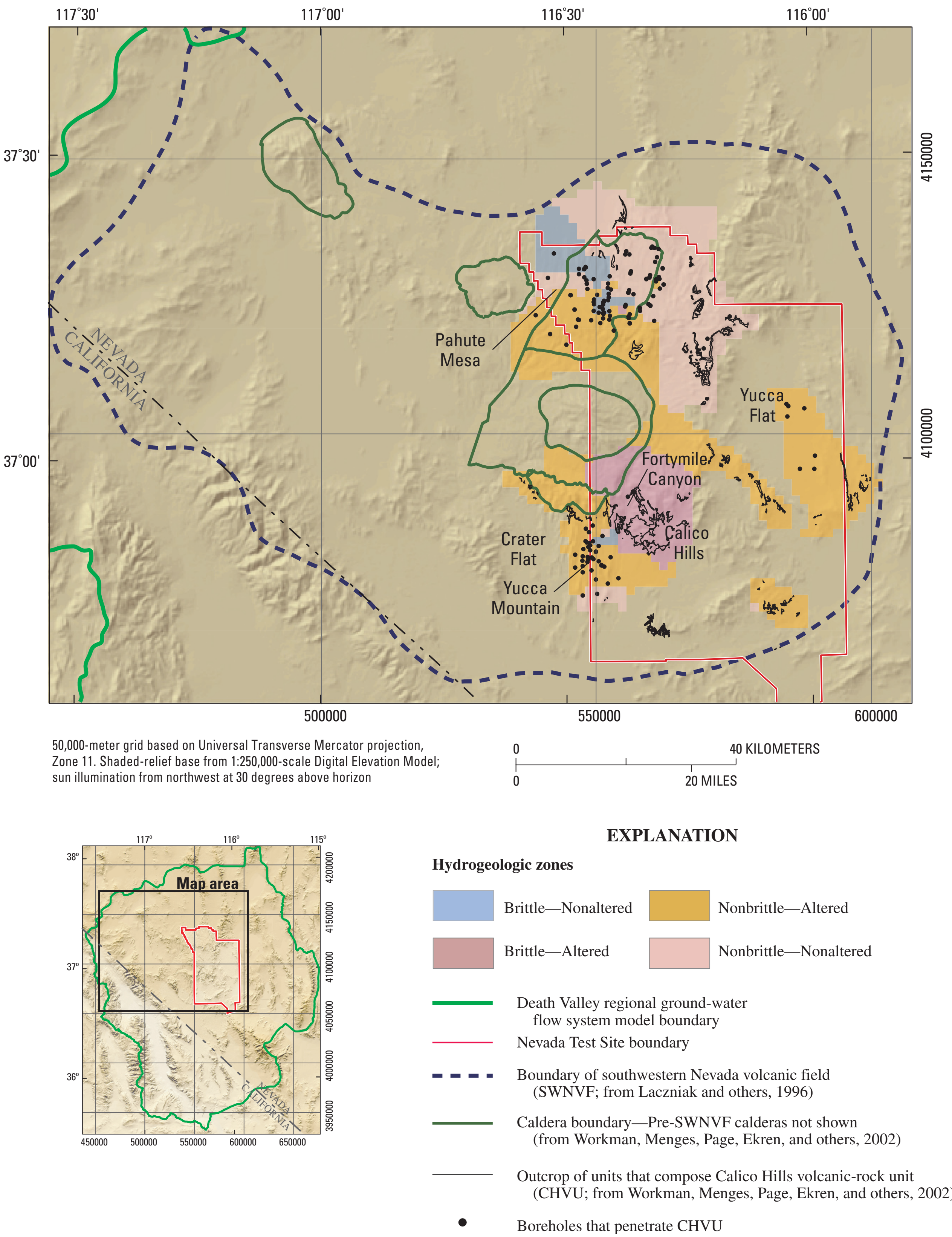


Figure B–18. Hydrogeologic zones in the Calico Hills volcanic-rock unit (CHVU).

Hydrogeologic zones of potential reduced permeability are related to zeolitic and other alteration of nonwelded and bedded tuffs. The nonwelded ash-flow tuffs of the Calico Hills Formation are zeolitically altered throughout most of the southern part of Pahute Mesa (nonbrittle, altered zone, fig. B–18) (Blankennagel and Weir, 1973; Laczniak and others, 1996) and Yucca Flat (Winograd and Thordarson, 1975, IT Corporation, 1996b). Calico Hills Formation tuffs are zeolitically altered beneath the northern part of Yucca Mountain but are locally vitric and classified as nonbrittle and nonaltered (fig. B–18) beneath southern and southwestern parts of Yucca Mountain (Moyer and Geslin, 1995). Brittle facies containing lava flows are pervasively hydrothermally altered in the Calico Hills with argillic alteration, silicification, and pyritization (Simonds, 1989).

Wahmonie Volcanic-Rock Unit (WVU)

The Wahmonie volcanic-rock unit (WVU) is composed of the Wahmonie Formation. The 13.0-Ma (Sawyer and others, 1994) Wahmonie Formation consists of andesitic- and dacitic-lava flows, tephra, and related volcaniclastic deposits that become thinner away from the Wahmonie volcanic center north of Skull Mountain (fig. B–19) (Poole, Carr, and Elston, 1965; Sawyer and others, 1994). The lavas are restricted in extent to the Wahmonie volcanic center, but a distinctive biotite-rich, nonwelded tuff is widespread and forms a marker bed between the Calico Hills Formation and the Crater Flat Group. Regionally, this tuff extends east to Yucca Flat, north to Rainier Mesa, and southwest to Little Skull Mountain and the southern part of Yucca Mountain. The Wahmonie Formation is more than 1,300 m thick in exposures north and east of Skull Mountain (Poole, Carr, and Elston, 1965; Poole, Elston, and Carr, 1965; Ekren and Sargent, 1965).

The criteria for selecting hydrogeologic zones of potential enhanced and reduced permeability (fig. B–19) were similar to those used for the CHVU, a unit that is lithologically similar to the WVU. The distribution of potentially fractured lava flows and the pattern of alteration in the vicinity of the Wahmonie volcanic center is based on surface geologic mapping (Poole, Elston, and Carr, 1965; Ekren and Sargent, 1965).

Crater Flat Group

The Crater Flat Group (Carr, Byers, and Orkild, 1986; Sawyer and others, 1994) consists of three principal units: the Tram Tuff, overlain by the 13.25-Ma Bullfrog Tuff, and the Prow Pass Tuff and two local units, the tuff of Pool, and the rhyolite of Inlet (Sawyer and others, 1994). In order to maintain consistency with the 3D geologic framework model constructed for the proposed geologic repository for high-level radioactive waste at Yucca Mountain (Bechtel SAIC Company, 2002), the Prow Pass, Bullfrog, and Tram Tuffs of the Crater Flat Group are treated as separate HGUs.

The Crater Flat Group rocks are present in the Pahute Mesa area as well as in the vicinity of Yucca Mountain and Crater Flat. A proposed source caldera beneath Crater Flat (Carr, 1982; Carr, Byers, and Orkild, 1986) has been questioned on geologic and geophysical grounds (Scott, 1990; Brocher and others, 1998); a source for the Bullfrog Tuff has been inferred to be the Area 20 caldera (part of the Silent Canyon caldera complex) (Sawyer and others, 1994), but this also has been questioned on geophysical grounds (Hildenbrand and others, 1999).

Crater Flat–Prow Pass Aquifer (CFPPA)

The Crater Flat–Prow Pass aquifer (CFPPA) consists of the Prow Pass Tuff of the Crater Flat Group and local time-equivalent tuffs and rhyolite-lava flows present in the subsurface beneath Pahute Mesa. The Prow Pass Tuff is exposed to the northwest of Yucca Mountain (Moyer and Geslin, 1995) and at the south end of Yucca Mountain (fig. B–20); drilling indicates that it exists in the subsurface in Crater Flat (Carr, Byers, and Orkild, 1986; Moyer and Geslin, 1995). The unit is thickest and most densely welded beneath Yucca Mountain; it thins westward into Crater Flat and southward. Tuffs and rhyolite-lava flows present in the subsurface beneath Pahute Mesa that are equivalent in age to the Prow Pass Tuff include the Andesite of Grimy Gulch, Tuff of Jorum, Rhyolite of Sled, and Rhyolite of Kearsarge (Ferguson and others, 1994).

Hydrogeologic zones for the CFPPA are mapped in figure B–20. Nonwelded to partly welded parts of the unit are zeolitically altered.

Crater Flat–Bullfrog Confining Unit (CFBCU)

The Bullfrog Tuff of the Crater Flat Group composes the Crater Flat–Bullfrog confining unit (CFBCU). The Bullfrog Tuff is widely distributed around the TMCC (Carr, Byers, and Orkild, 1986). The thickness of the outflow tuff is 100 to 150 m in the Bullfrog Hills, at Yucca Mountain, and in Jackass Flats, but it may be greater than 400 m thick in Crater Flat (Carr, Byers, and Orkild, 1986). Maximum thickness in boreholes in intracaldera tuff in the SCCC is about 680 m (Ferguson and others, 1994; Sawyer and others, 1994).

The CFBCU is nonwelded to poorly welded throughout most of the SCCC and Yucca Flat, where it is classified as nonbrittle and altered (fig. B–21) and is a confining unit (Blankennagel and Weir, 1973; Laczniak and others, 1996). In the vicinity of Yucca Mountain, the Bullfrog Tuff forms a compound-cooling unit with variable welding and alteration characteristics (fig. B–21). In general, the unit has a moderately to densely welded and devitrified interior with nonwelded to partly welded margins in the Yucca Mountain area. The Bullfrog Tuff at Yucca Mountain was included in a “lower volcanic aquifer” HGU described by Luckey and others (1996), primarily because of fracture permeability in the interior welded zone.

Crater Flat–Tram Aquifer (CFTA)

The Tram Tuff of the Crater Flat Group constitutes the Crater Flat–Tram aquifer (CFTA). The Tram Tuff is a mostly nonwelded to partially welded, ash-flow tuff (fig. B–22), but

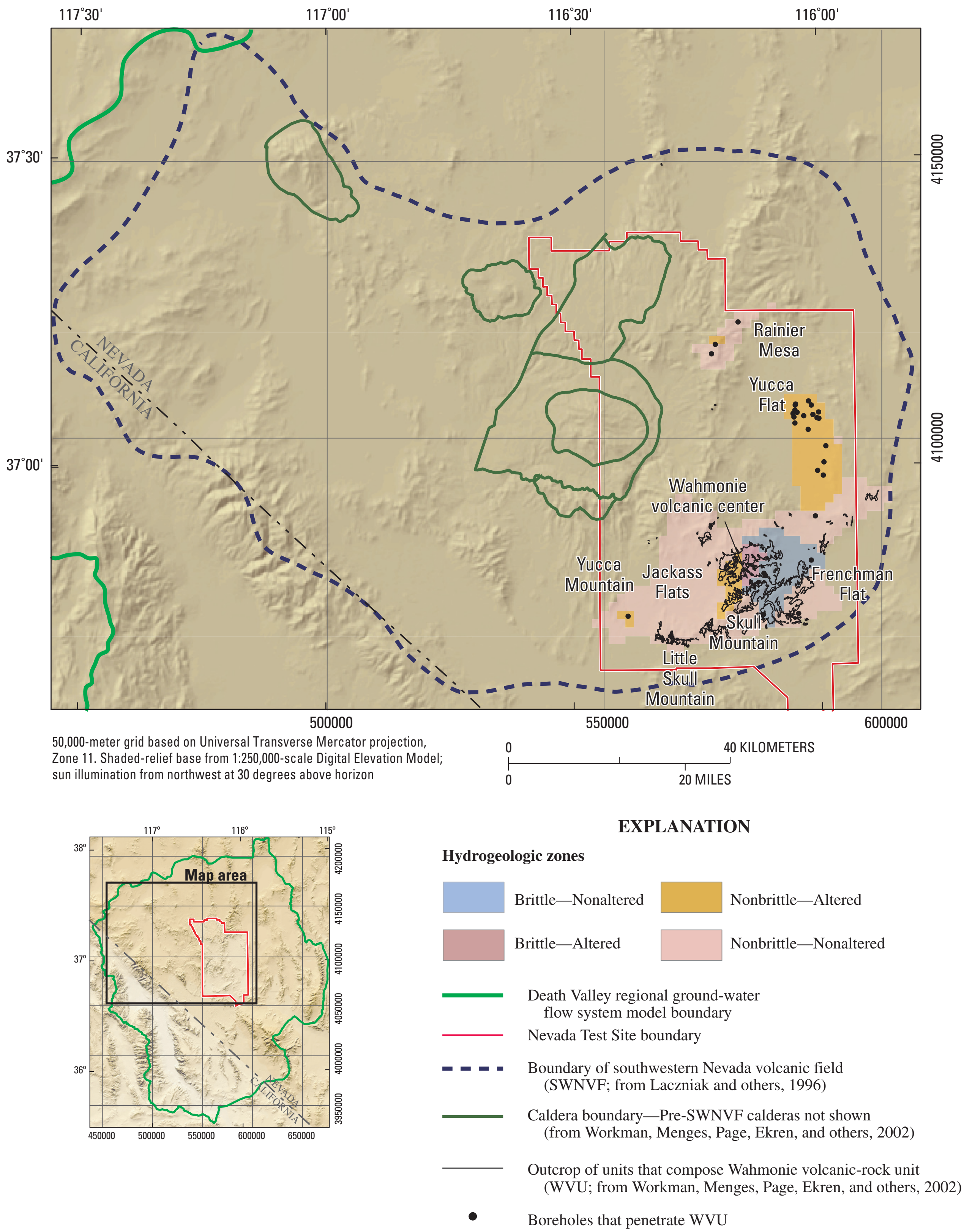


Figure B–19. Hydrogeologic zones in the Wahmonie volcanic-rock unit (WVU).

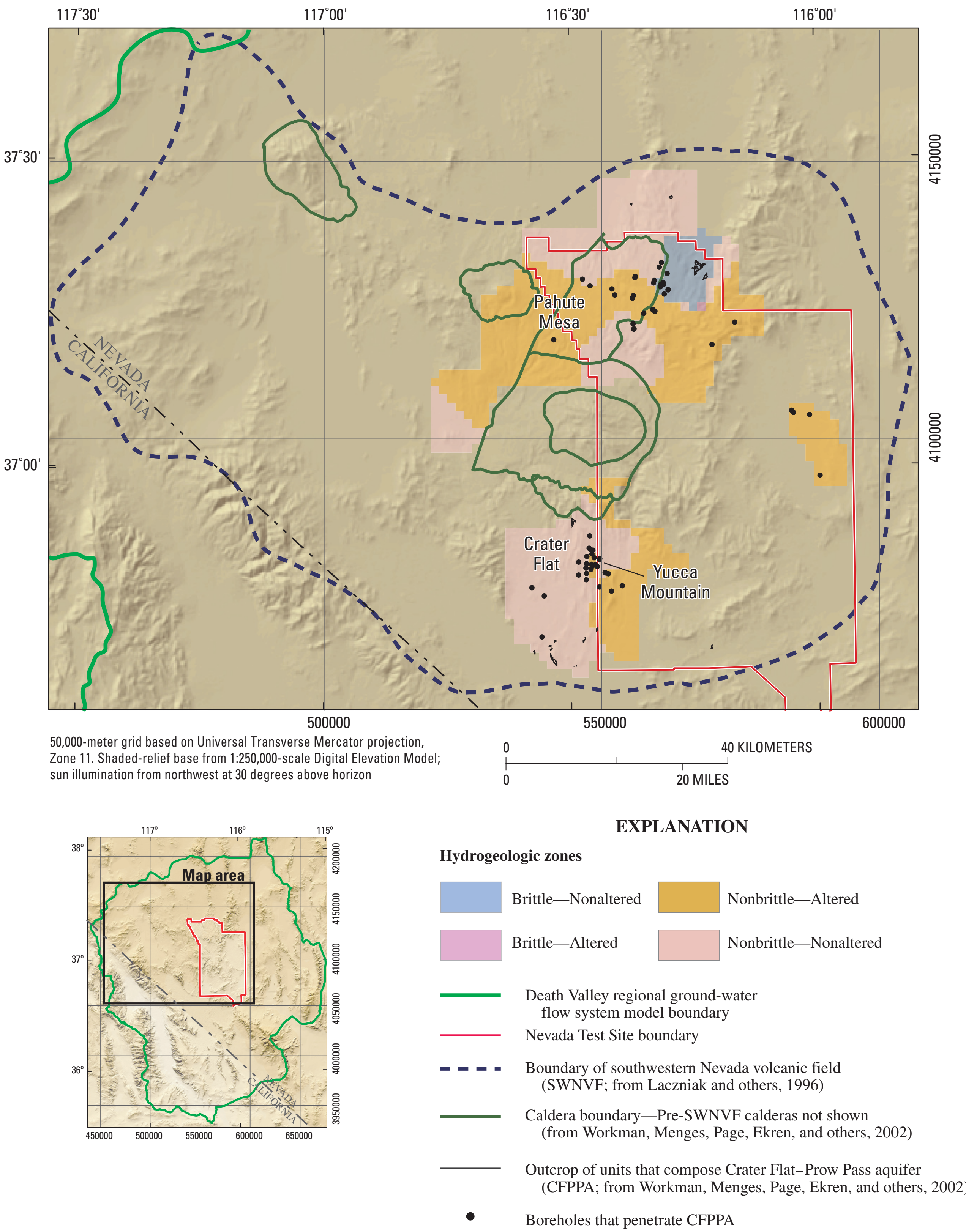


Figure B–20. Hydrogeologic zones in the Crater Flat–Prow Pass aquifer (CFPPA).

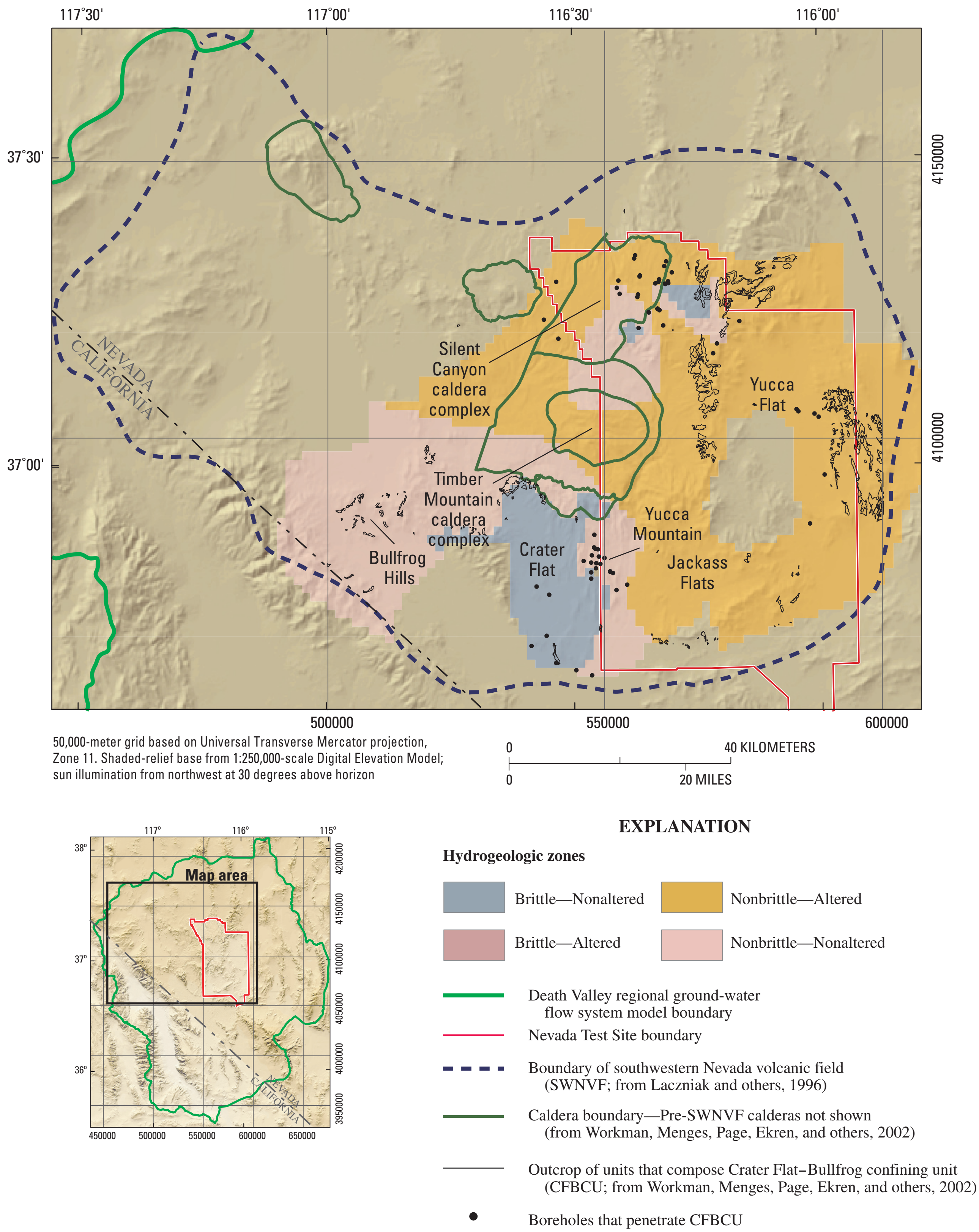
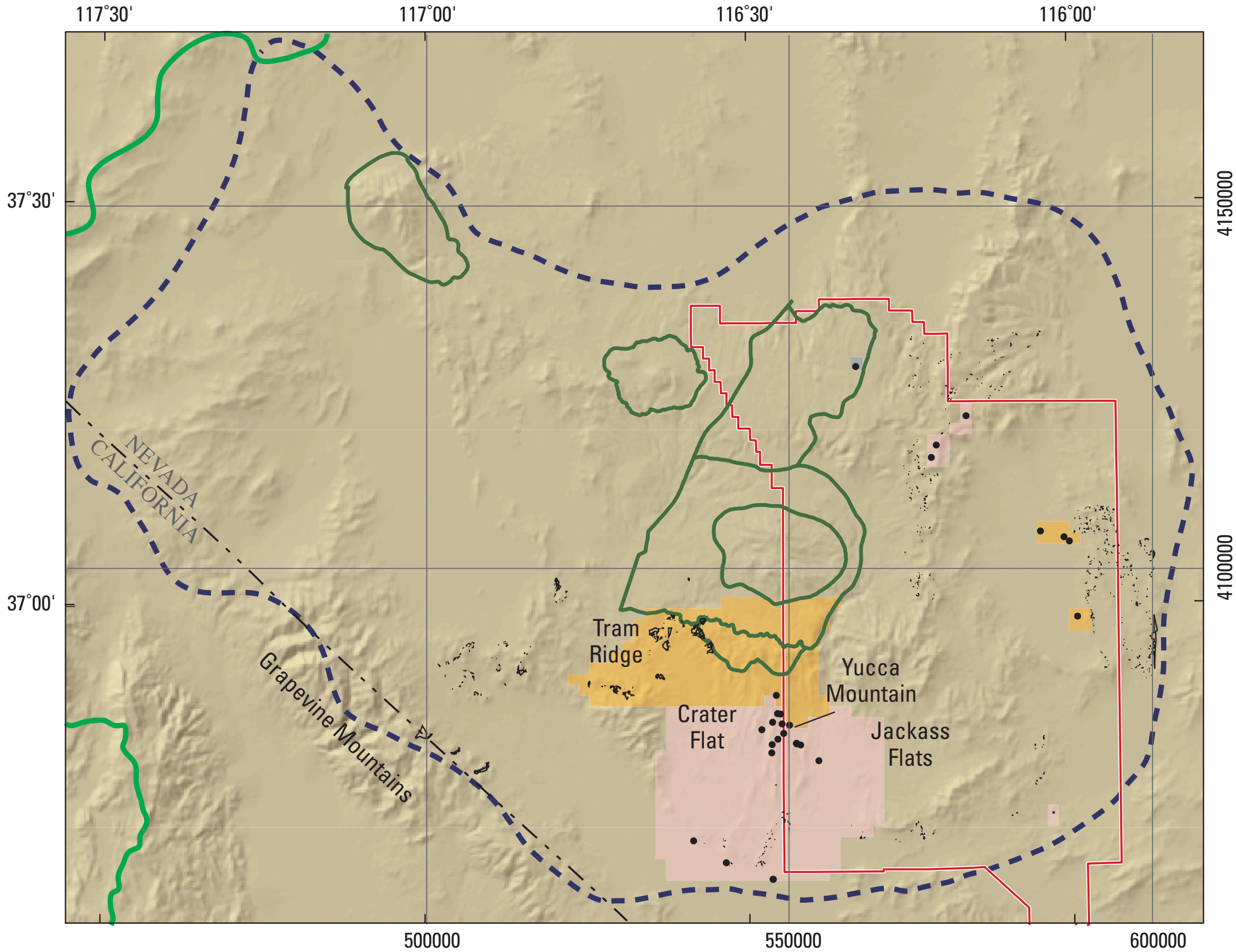


Figure B–21. Hydrogeologic zones in the Crater Flat–Bullfrog confining unit (CFBCU).



50,000-meter grid based on Universal Transverse Mercator projection, Zone 11. Shaded-relief base from 1:250,000-scale Digital Elevation Model; sun illumination from northwest at 30 degrees above horizon

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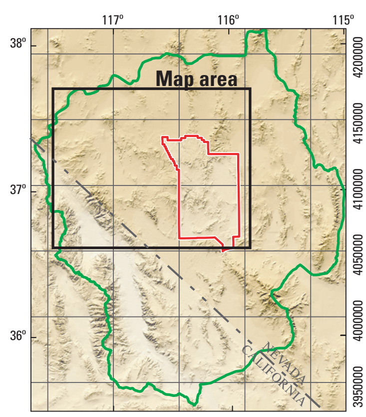

EXPLANATION

Hydrogeologic zones

Brittle—Nonaltered

Nonbrittle—Altered

Brittle—Altered

Nonbrittle—Nonaltered

Death Valley regional ground-water flow system model boundary

Nevada Test Site boundary

Boundary of southwestern Nevada volcanic field (SWNVF; from Laczniak and others, 1996)

Caldera boundary—Pre-SWNVF calderas not shown (from Workman, Menges, Page, Ekren, and others, 2002)

Outcrop of units that compose Crater Flat–Tram aquifer (CFTA; from Workman, Menges, Page, Ekren, and others, 2002)

Boreholes that penetrate CFTA

Figure B–22. Hydrogeologic zones in the Crater Flat–Tram aquifer (CFTA).