is densely welded at Tram Ridge (Fridrich and others, 1999). It is locally exposed and also encountered in boreholes in the Crater Flat and Yucca Mountain areas (Carr, Byers, and Orkild, 1986). Regionally, the Tram Tuff extends as far west as the Grapevine Mountains and east beneath Jackass Flats (Carr, Byers, and Orkild, 1986). Hydrogeologic zones for the CFTA are mapped in figure B–22.

Belted Range Unit (BRU)

Rocks of the Belted Range Group constitute the Belted Range unit (BRU). The Belted Range Group is composed of the 13.7-Ma Grouse Canyon Tuff and associated pre-caldera lava flows and post-caldera lavas and tuffs of the Dead Horse Flat Formation (Sawyer and others, 1994). Belted Range Group rocks are interpreted to have erupted between 13.85 Ma and 13.5 Ma from the Grouse Canyon caldera, now buried in the SCCC. Syn- and post-collapse volcanic-rock units thicken toward the eastern margin of the caldera, on the basis of borehole data and gravity inversion analysis (Ferguson and others, 1994; Hildenbrand and others, 1999). Thick post-caldera rhyolitic lavas of the Dead Horse Flat Formation accumulated in the eastern and northeastern parts of the caldera (Laczniak and others, 1996, plate 4; McKee and others, 1999). Belted Range Group rocks are not present in the southern parts of the SWNVF, including Yucca Mountain.

Aquifers in the BRU include both thick post-caldera rhyolitic lavas of the Dead Horse Flat Formation and welded Grouse Canyon Tuff. The lavas are highly fractured and form the principal aquifer unit on the eastern part of Pahute Mesa (Blankennagel and Weir, 1973; Prothro and Drellack, 1997; Laczniak and others, 1996, plate 4). The 50-percent brittle rock area (fig. B–23) incorporates all of the thick intracaldera lava flows of the Dead Horse Flat Formation that dominate the deeper parts of the eastern one-half of the SCCC, plus the thickest welded intervals of Grouse Canyon Tuff that are proximal to the SCCC.

Older Volcanic-Rock Unit (OVU)

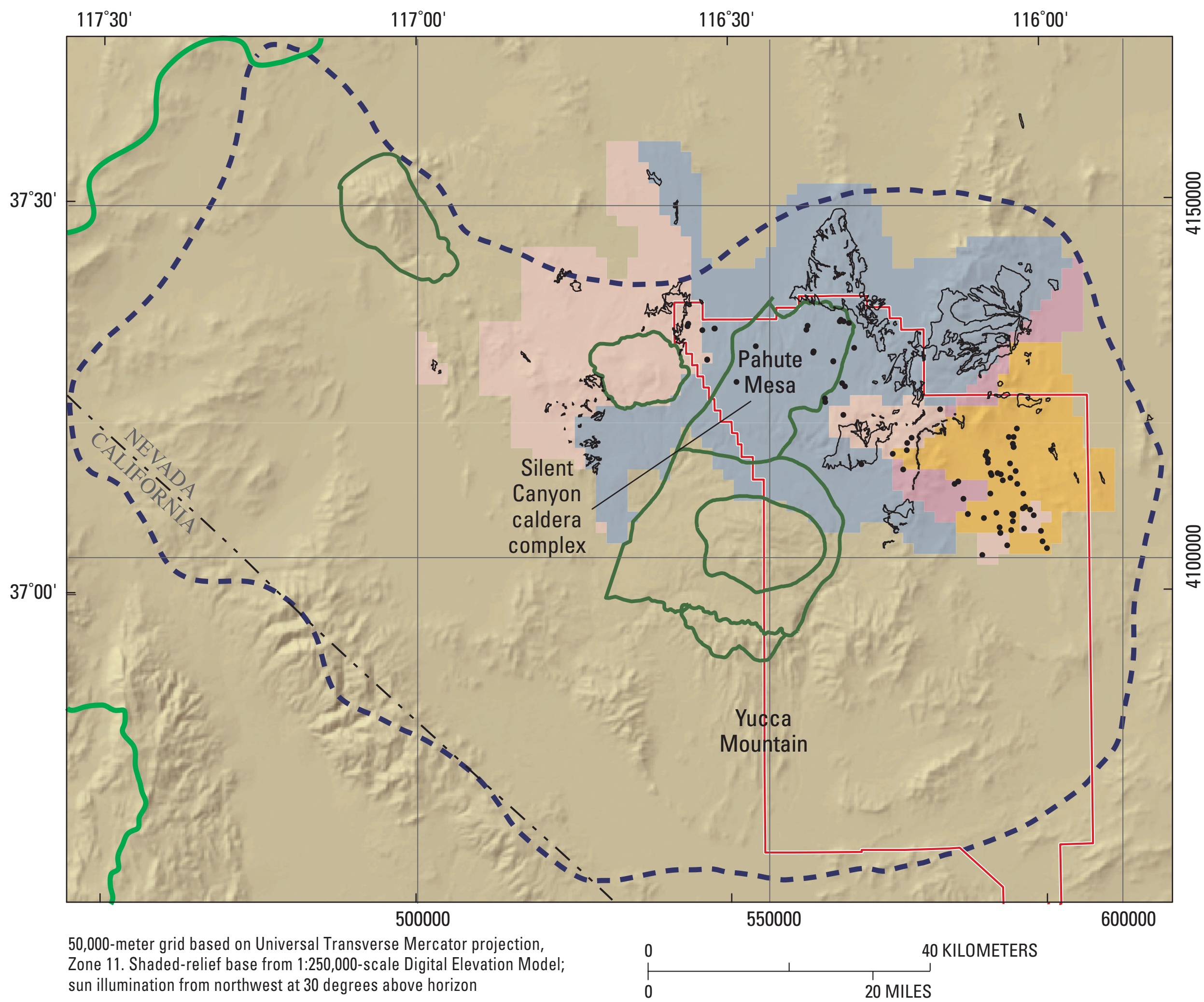
The older volcanic-rock unit (OVU) consists of Oligocene and early Miocene volcanic rocks that consist of ash-flow tuff, ash-fall tuff, reworked tuff, tuff breccia, lava flows, and volcaniclastic rocks. The OVU may be subdivided into two general groups: (1) those volcanic rocks in and near, and perhaps originating from, the SWNVF, and (2) volcanic rocks that originated from volcanic centers to the north of the SWNVF. Volcanic rocks associated with these two general groups are for the most part separated from each other. The older volcanic rocks of the NTS (almost entirely within the SWNVF) do not extend more than a few tens of kilometers north of the northern boundary of the NTS (Slate and others, 2000), whereas older volcanic rocks derived from outside the SWNVF are common to the north and northeast of the NTS but are known only in the extreme northeastern and northern parts of the NTS (Ekren and others, 1971; Workman, Menges, Page, Taylor, and others, 2002).

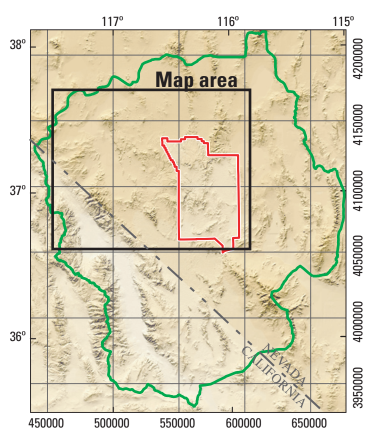
Oligocene and lower Miocene volcanic rocks north of the NTS consist predominantly of partly to densely welded ash-flow tuffs that have an aggregate thickness of up to several hundred meters over large parts of western Lincoln County and central Nye County, Nev. (Ekren and others, 1971; Workman, Menges, Page, Taylor, and others, 2002). Regionally distributed, welded ash-flow tuffs include the Monotony Tuff, the Shingle Pass Tuff, the “Tuffs of Antelope Springs,” and the Tuff of White Blotch Springs. Proposed source areas for these units are volcanic centers to the north of the SWNVF that include known or inferred calderas in the Cactus Range, the Kawich Range, the Quinn Canyon Range, and the Mt. Helen area (Ekren and others, 1971; Best and others, 1989; McKee, 1996; Workman, Menges, Page, Ekren, and others, 2002).

A locally thick section of 15.5- to 13.8-Ma pre-Belted Range Group volcanic rocks is associated with, and perhaps originated from, the SWNVF. These units are known from limited outcrops at the NTS and from boreholes in Pahute Mesa, Yucca and Frenchman Flats, and Yucca Mountain. Most of these units do not extend more than a few tens of kilometers north of the northern boundary of the NTS. Most of the pre-Belted Range Group volcanic-rock units are nonwelded to partly welded, with the exception of the densely welded Redrock Valley and Tub Spring Tuffs (Sawyer and others, 1995), and the nonwelded tuffs typically are devitrified and zeolitically altered (Drellack, 1997; Prothro and others, 1999).

Because of the large number of volcanic-rock units that are included in this HGU, the OVU has widely varying material properties. The OVU may be subdivided into areas of potentially different material and hydrologic properties on the basis of geography and the presence of calderas (fig. B–24). OVU rocks north of the NTS form a series of regionally extensive ash-flow tuffs that are locally fractured volcanic-rock aquifers throughout a large part of southern Nye County (Plume and Carlton, 1988). OVU rocks to the north of the NTS can be divided into intracaldera and outflow components (fig. B–24), on the basis of caldera boundaries shown in Workman, Menges, Page, Ekren, and others (2002). This zonation is based on the presence of thick intracaldera accumulations of tuff and lavas, regardless of their correlation to specific ash-flow sheets.

In most places in the SWNVF, OVU rocks likely act as a confining unit because they generally are nonwelded to partially welded and zeolitic alteration is widespread (Sawyer and others, 1995; Drellack, 1997; Prothro and others, 1999). Lava flows and densely welded tuffs in this section can form fracture-flow aquifers but are generally too localized or too deep in the section to be significant. The OVU is important in Yucca and Frenchman Flats, where it separates the overlying fractured volcanic-rock aquifers from the underlying regional carbonate-rock aquifer. The OVU is saturated in much of the central part of Yucca Flat, and measured transmissivities are very low (IT Corporation, 1996b).





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 Belted Range unit (BRU; from Workman, Menges, Page, Ekren, and others, 2002)

Boreholes that penetrate BRU

Figure B–23. Hydrogeologic zones in the Belted Range unit (BRU).

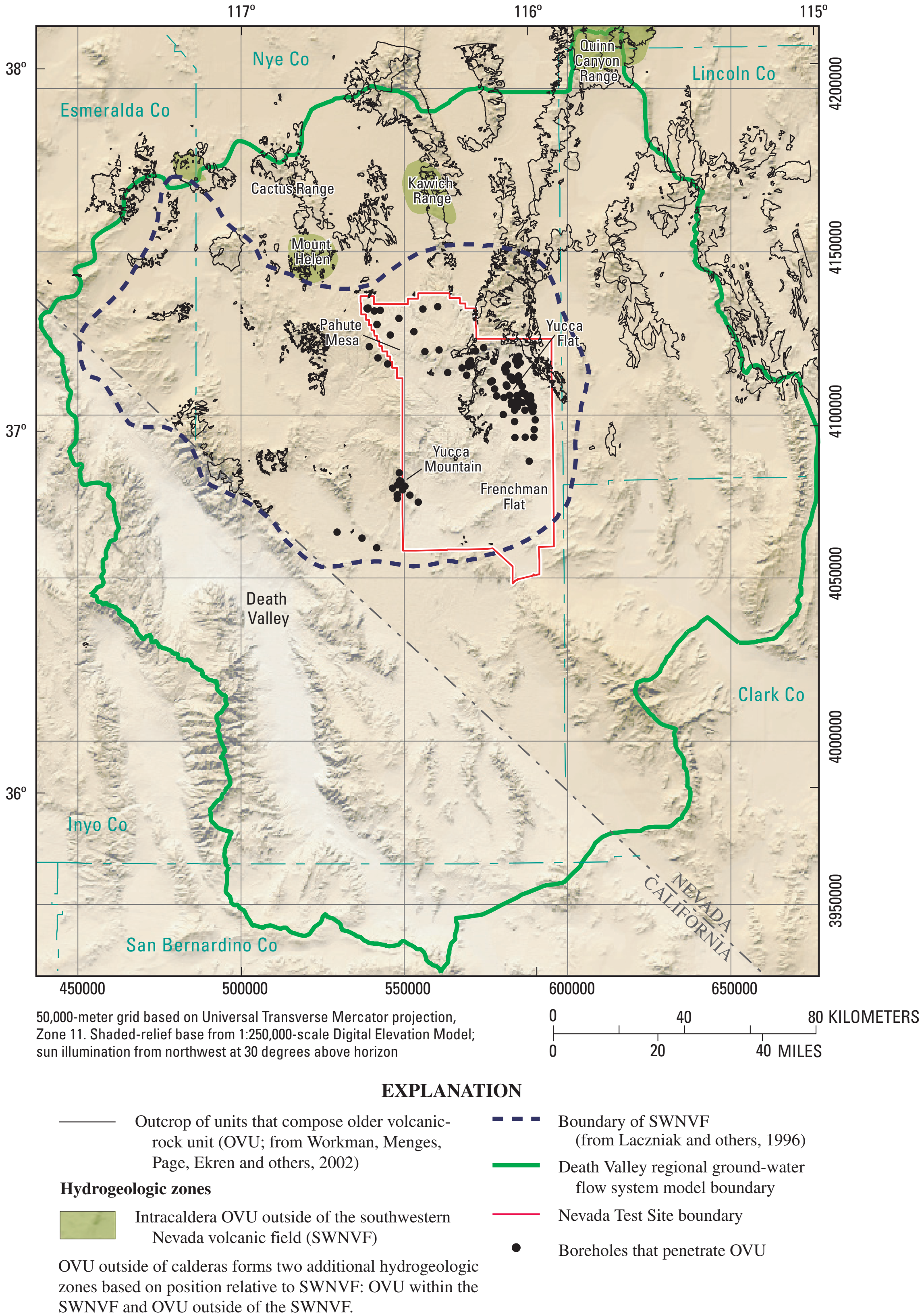


Figure B–24. Hydrogeologic zones in the older volcanic-rock unit (OVU).

Hydrogeologic Units Associated with Mesozoic, Paleozoic, and Late Proterozoic Sedimentary Rocks

The pre-Cenozoic sedimentary rocks of the DVRFS region are grouped into five HGUs: the sedimentary-rock confining unit (SCU), the upper carbonate-rock aquifer (UCA), the upper clastic-rock confining unit (UCCU), the lower carbonate-rock aquifer (LCA), and the lower clastic-rock confining unit (LCCU) (table B–2; fig. B–25). This usage is similar to that established by Winograd and Thordarson (1975), particularly for the vicinity of the NTS.

Sedimentary-Rock Confining Unit (SCU)

The sedimentary-rock confining unit (SCU) consists of unmetamorphosed Mesozoic cratonic sedimentary rocks in the eastern part of the DVRFS region (fig. B–25) and Mesozoic metasedimentary and metavolcanic rocks that are sparsely exposed in the western part of the DVRFS region. Local exposures of Mesozoic sedimentary rocks as young as the Lower Jurassic Aztec Sandstone crop out in the Las Vegas, Nev., area. Triassic rocks (Middle(?) and Lower Triassic Moenkopi Formation and Upper Triassic Chinle Formation) crop out in the Pahrump Valley and Spring Mountains area. These units consist of interbedded conglomerate, sandstone, siltstone, shale, calcareous shale, limestone, and gypsum. Mesozoic metasedimentary and metavolcanic rocks are exposed in the extreme southwestern part of the DVRFS region in the southern Panamint Mountains and Avawatz Mountains.

Hydraulic properties of the SCU vary according to grain size and sorting in the different units. Some of these rocks are regional aquifers on the Colorado Plateau east of the DVRFS region, but most exposures of the SCU either lie outside the boundary of the DVRFS region or are too small or shallow to have significance in the regional ground-water flow system.

Upper Carbonate-Rock Aquifer (UCA)

The upper carbonate-rock aquifer (UCA) includes Pennsylvanian and Mississippian limestone, dolomite, and calcareous shales in the vicinity of the NTS that are stratigraphically above the Eleana Formation and Chainman Shale (Winograd and Thordarson, 1975; Laczniak and others, 1996). Where the Eleana Formation and Chainman Shale are absent to the southeast of the NTS, the Pennsylvanian and Mississippian carbonate rocks are included in the lower carbonate-rock aquifer (LCA). The UCA exists primarily in the area of Yucca Flat (fig. B–25), where Pennsylvanian carbonate rocks are preserved in a syncline at Syncline Ridge. In general, the rocks of the UCA are of only local importance and are not significant in the regional flow system.

Upper Clastic-Rock Confining Unit (UCCU)

The upper clastic-rock confining unit (UCCU) is composed of Upper Devonian through Mississippian synorogenic siliciclastic and carbonate rocks including the Eleana Formation and the Chainman Shale (Laczniak and others, 1996). The Eleana Formation is present in parts of the western and northern part of the DVRFS region and consists of up to 2,000 m of siltstone, argillite, sandstone, conglomerate, and minor limestone deposited as turbidites and debris flows filling the Antler foredeep to the east of the Antler orogenic belt (Poole and others, 1961; Nilsen and Stewart, 1980; Poole, 1981; Trexler and others, 1996). The Eleana Formation grades laterally into and is thrust eastward over the 1,200-m-thick Mississippian Chainman Shale in Yucca Flat and the northern part of Jackass Flats at the NTS (Trexler and others, 1996) (fig. B–25).

The Eleana-Chainman section is a locally important siliciclastic-rock confining unit in the vicinity of the NTS. Steep hydraulic gradients in the area of Yucca Flat are attributed to the low transmissivity values of the Eleana Formation (Winograd and Thordarson, 1975; D'Agnese and others, 1997). Southeast of the NTS in the Spotted Range and in the Indian Springs Valley carbonate platform limestones of Mississippian age are less than 350 m thick (Poole and others, 1961; Barnes and others, 1982). In the Cottonwood Mountains and the Last Chance Range in the western part of the DVRFS region, the Mississippian section is represented by carbonate-dominated units such as the Tin Mountain limestone and the Perdido Group (Stevens and others, 1991; 1996). These Mississippian carbonate rocks that occur outside of the NTS vicinity are not designated as part of the UCCU but instead are considered part of the lower carbonate-rock aquifer (LCA).

Lower Carbonate-Rock Aquifer (LCA)

The lower to middle Paleozoic carbonate-rock succession forms the major regional carbonate-rock aquifer in the eastern two-thirds of the Great Basin (Winograd and Thordarson, 1975; Bedinger and others, 1989a; Dettinger and others, 1995; Harrill and Prudic, 1998). As in previous regional analyses of ground-water flow in the southern Great Basin, these carbonate rocks are treated as a single HGU, the lower carbonate-rock aquifer (LCA) (Winograd and Thordarson, 1975; Laczniak and others, 1996).

The Paleozoic carbonate rocks of the LCA are widely distributed in the eastern part of the DVRFS region (fig. B–25). These rocks consist of a Middle Cambrian through Middle Devonian carbonate-dominated succession, about 4,500 m thick in this region, that includes dolomite, interbedded limestone, and thin but persistent shale, quartzite, and calcareous clastic units (Burchfiel, 1964). The lower part of this carbonate-rock section (Lower and Middle Cambrian Carrara Formation, Middle and Upper Cambrian Bonanza King Formation, Upper Cambrian Nopah Formation, Lower and Middle Ordovician Pogonip Group) is exposed in most of the mountain

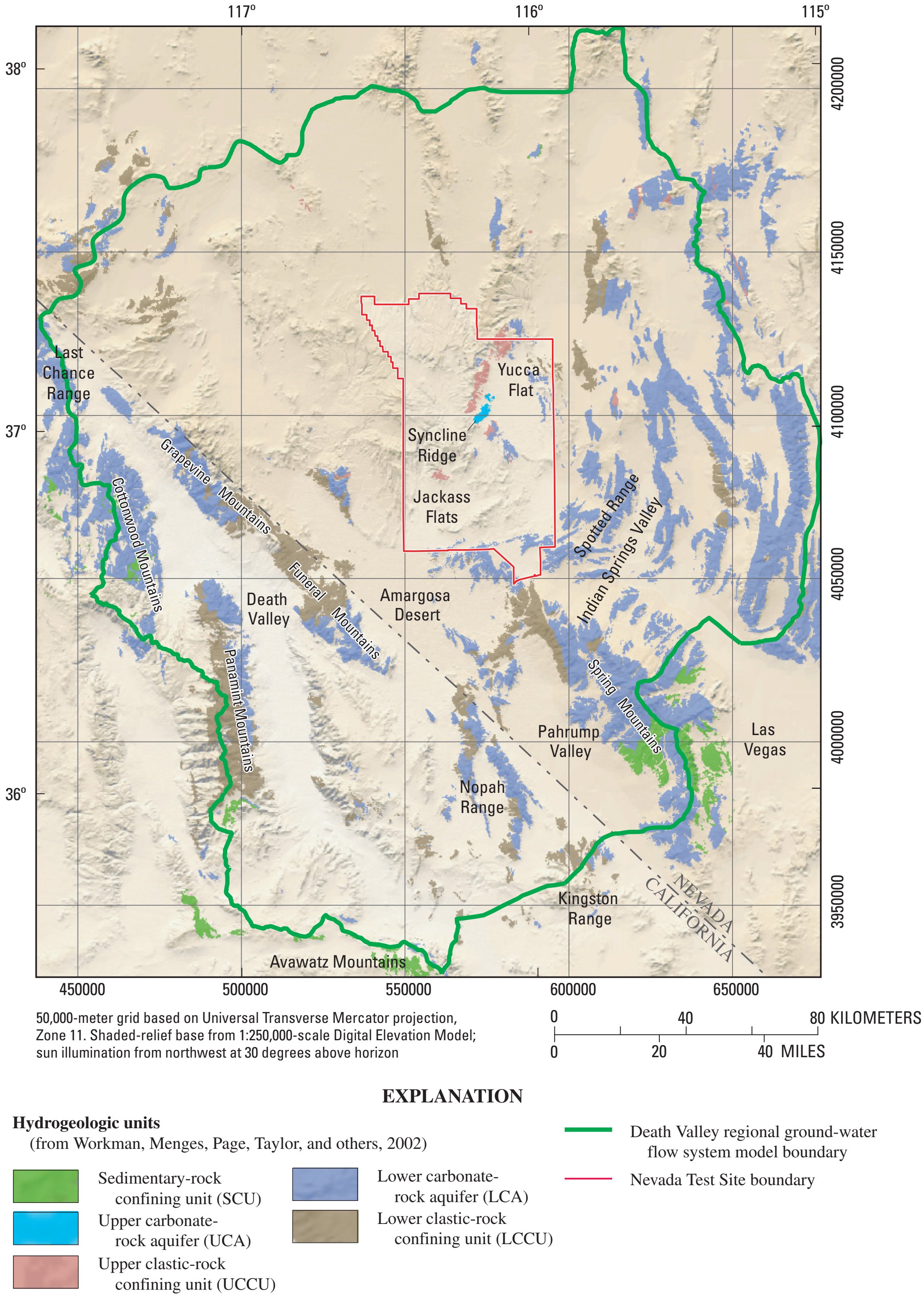


Figure B–25. Outcrop distribution of hydrogeologic units associated with Mesozoic, Paleozoic, and Late Proterozoic sedimentary rocks.

ranges in the central and southern parts of the DVRFS region (fig. B–25). In contrast to the Proterozoic siliciclastic rocks, thickness variations in this interval are generally small across much of the DVRFS region (fig. B–2) (Cornwall, 1972). In the northwestern part of the DVRFS region, the Middle Cambrian through Middle Devonian rocks are somewhat thicker and represent a somewhat deeper-water facies of shale and impure carbonate rocks, including the Campito Formation (Cornwall, 1972; Burchfiel and others, 1982).

Southeast of the NTS, the LCA consists of Mississippian and Pennsylvanian carbonate rocks where the siliciclastic rocks of the UCCU do not separate the Paleozoic carbonate rocks into an upper and lower aquifer. The Bird Spring Formation is nearly 2,000 m thick in the central part of the Spring Mountains (Langenheim and Larson, 1973; Burchfiel and others, 1974). In the west and northwest parts of the DVRFS region, predominantly carbonate rocks of Mississippian, Pennsylvanian, and Permian age are exposed in the Grapevine, Cottonwood, and Panamint Mountains (Workman, Menges, Page, Taylor, and others, 2002).

The LCA carbonate rocks have an aggregate thickness of as much as 8,000 m and are generally the most permeable rocks in the DVRFS region (Bedinger and others, 1989b; Belcher and others, 2001). Where hydraulically connected, they provide a path for interbasinal flow (Dettinger and Schaefer, 1996; D'Agnese and others, 1997; Harrill and Prudic, 1998). Most of the springs in the area are associated with the carbonate rocks (Winograd and Thordarson, 1975). Compared to flow through secondary openings in the carbonate rocks of the LCA, intergranular flow is relatively insignificant. The large hydraulic conductivities reported for rocks of this unit primarily are because of fractures, faults, 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 a factor of 25 or more (Dettinger and others, 1995). Areas affected by multiple deformational events are inferred to have potentially greater secondary fracture permeability.

Eleven hydrogeologic zones are defined for the LCA (fig. B–26, table B–6) on the basis of stratigraphic facies, inferred continuity of the aquifer, and degree of structural deformation. As with previous maps, 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).

In the eastern part of the DVRFS region, shelf sequence rocks of the central carbonate corridor (Dettinger and others, 1995) are differentiated from the basinal facies that exist in the extreme northwestern part of the region (Zone 9, fig. B–26*A* and table B–6). Outcrops of Paleozoic rocks are extremely sparse northwest of the NTS; in this region, the aquifer properties of the LCA are highly uncertain (Zone 10, fig. B–26*A* and table B–6). Paleozoic carbonate rocks are inferred to be absent or highly altered in the vicinity of the calderas of the SWNVF and exist only as tectonically dismembered blocks in a broad belt through the southern part of Death Valley (Zone 5, fig. B–26*A* and table B–6).

Rocks of the central carbonate corridor are subdivided on the basis of the inferred degree of structural disruption (fig. B–26*B*). The magnitude of Cenozoic extension was heterogeneous in the DVRFS region; regions of large-magnitude extension alternated with areas of lesser extension (Wernicke and others, 1984; Wernicke, 1992). Relatively undeformed stable blocks of the Sheep Range and Spring Mountains occupy the eastern part of the DVRFS region (Zone 1, fig. B–26*B* and table B–6). To the west of each of these blocks, the LCA is broken into a series of back-rotated, extended range blocks in the vicinity of the Desert Range and the Nopah Range (Zone 4, fig. B–26*B* and table B–6). Abundant normal faults in these extended blocks may provide potential flow pathways; however, structural thinning could limit the available thickness of the carbonate aquifer (Dettinger and Schaefer, 1996). East of the NTS is a regional syncline (Zone 3, fig. B–26*B* and table B–6). Increased fracture permeability may exist along the axis of this fold. Much of the northeastern and central parts of the DVRFS region have been affected by basin-range faulting (Zone 8, fig. B–26*B* and table B–6). The degree of deformation and amount of extension in these areas is not as high as in the rotated, extended blocks to the southeast. In the western part of the DVRFS region, relatively large blocks have been displaced by extension and by movement on large regional strike-slip faults (Zone 7, fig. B–26*B* and table B–6). These blocks may be isolated from the regional carbonate aquifer (Dettinger and Schaefer, 1996) but may be of local importance.

Three additional types of deformation that potentially increase fracture-related permeability of the LCA are regional shear zones, oroflexural bending associated with regional strike-slip faults, and the presence of brittle detachments (fig. B–26*C*). In addition to major northwest-striking strike-slip faults, the Walker Lane belt includes northeast-striking shear zones that are transverse to the main trend of the belt (Carr, 1984; Stewart, 1988; Stewart and Crowell, 1992). These zones (Zone 2, fig. B–26*C* and table B–6) are characterized by subparallel, northeast-striking faults that accommodate relatively small amounts of sinistral and normal offset across a broad regional zone. Two such zones in the DVRFS region are the Spotted Range–Mine Mountain shear zone in the southern part of the NTS (Carr, 1984; Stewart, 1988) and the Pahranagat shear zone along the eastern boundary of the DVRFS region (Jayko, 1990). Broad areas of oroflexural bending (Albers, 1967) associated with major northwest-striking strike-slip faults have been defined by arcuate trends in the strike of tilted beds and fold axes (Burchfiel, 1965; Guth, 1981; Wernicke and others, 1984) (Zone 6, fig. B–26*C* and table B–6). In the vicinity of the LVVSZ, the clockwise bending appears to be related to the dextral slip and represents a broad zone of shear accommodated by crushing and local vertical axis rotation of blocks on the order of a few kilometers in lateral dimension (Nelson and Jones, 1987; Sonder and others, 1994). Local zones of potential enhanced permeability also are inferred in the upper plates of certain shallow-level, low-angle normal faults in the LCA (Zone 11, fig. B–26*C* and table B–6).

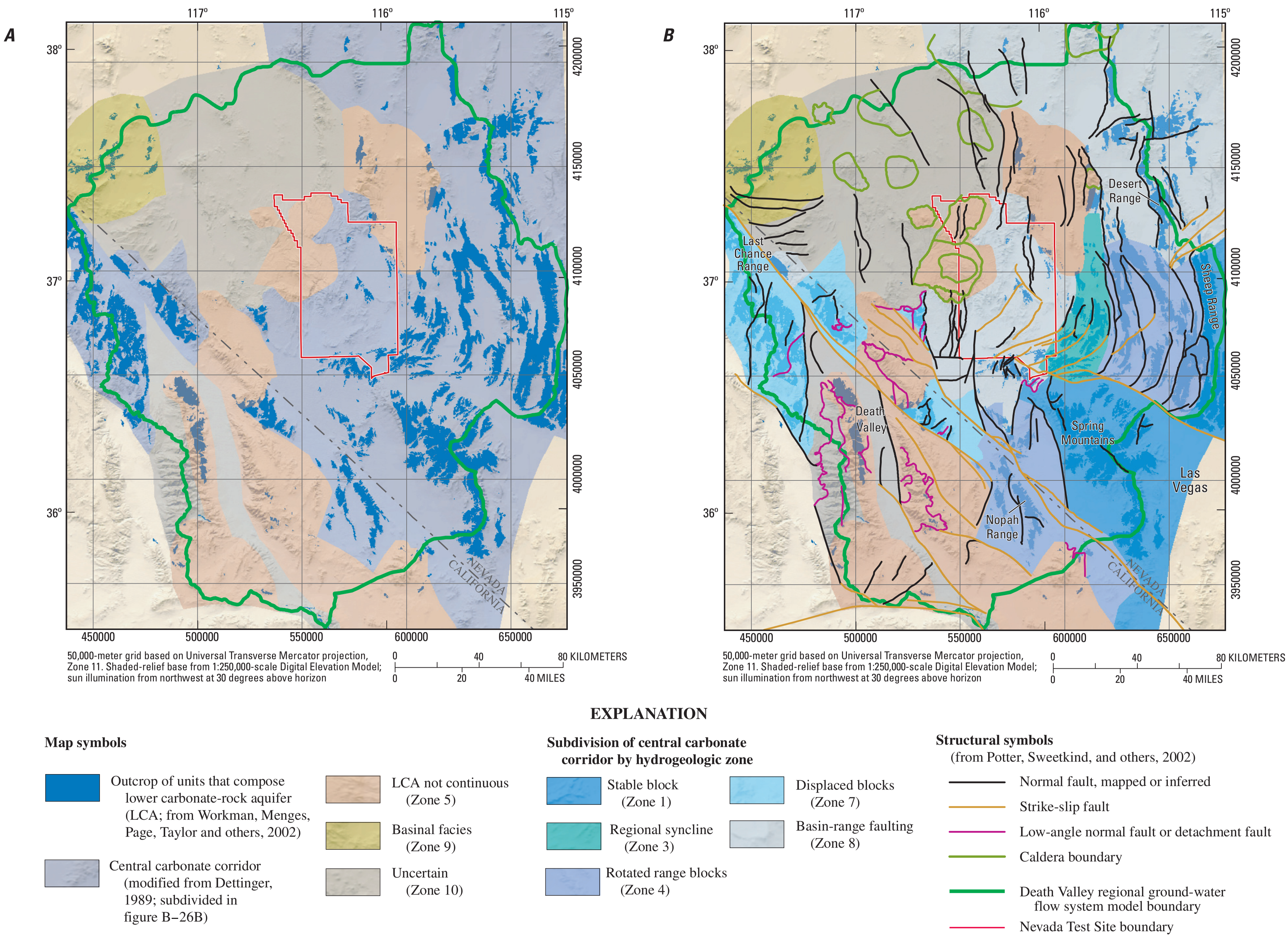
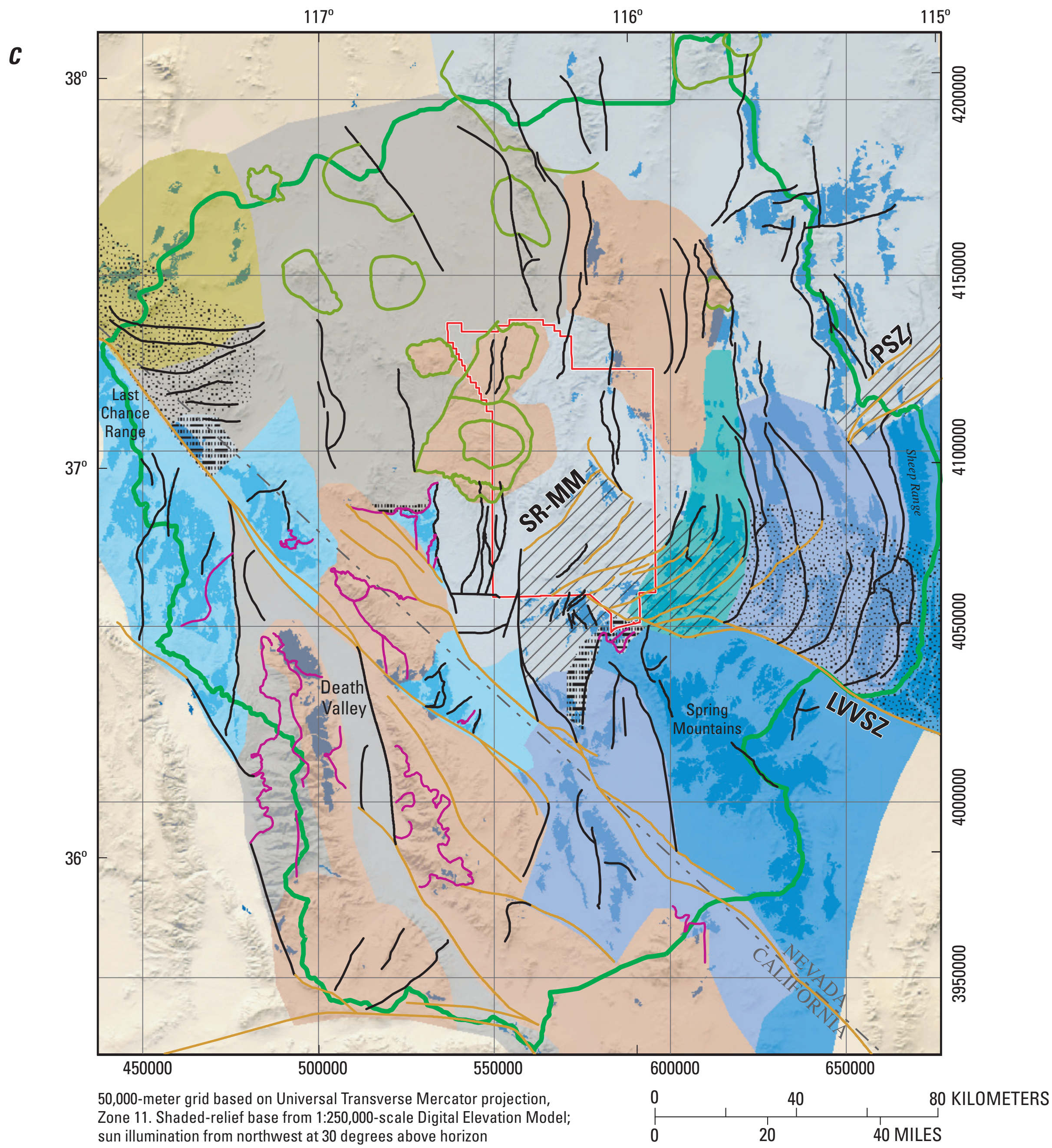


Figure B–26. Hydrogeologic zones in the lower carbonate-rock aquifer (LCA). *A*, Based on facies and continuity. *B*, Addition of zones based on degree of structural disruption. *C*, Addition of zones based on deformation that potentially increases fracture permeability.



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

Map symbols

Regional shear zone (Zone 2)

Oroflexural bending (Zone 6)

Brittle detachment (Zone 11)

All other map symbols as in figure B–26*A* and B–26*B*

Abbreviations: PSZ, Pahranagat shear zone; LVVSZ, Las Vegas Valley shear zone; SR-MM, Spotted Range–Mine Mountain shear zone

Figure B–26. Hydrogeologic zones in the lower carbonate-rock aquifer (LCA). *A*, Based on facies and continuity. *B*, Addition of zones based on degree of structural disruption. *C*, Addition of zones based on deformation that potentially increases fracture permeability.—Continued

Table B–6. Hydrogeologic zones for the lower carbonate-rock aquifer (LCA).

[SWNVF, southwestern Nevada volcanic field]

Zone	Description
1	Stable block: Relatively unextended and unfaulted blocks of the Spring Mountains and Sheep Range.
2	Regional shear zone: Spotted Range–Mine Mountain and Pahranagat shear zones. High fault/fracture densities associated with numerous minor strike-slip faults.
3	Regional syncline: Spotted Range syncline, a large regional fold; moderate fault/fracture density along axis of fold.
4	Rotated range blocks: Highly extended, rotated range blocks. May be associated with detachment at depth. Moderate to high fault/fracture density.
5	LCA not continuous: LCA is absent (near calderas of the SWNVF) or exists as tectonically dismembered blocks in areas of extreme extension.
6	Oroflexural bending: Associated with major strike-slip faults. High fault and fracture density associated with rotation of kilometer-scale (and smaller) blocks of LCA.
7	Displaced blocks: Relatively intact blocks of carbonate rocks that are involved in regional extension. Mesozoic thrusts reactivated as normal faults; moderate fault/fracture density. May be associated with detachment at depth.
8	Basin-range faulting: LCA that occurs in basin-range fault blocks. Low to moderate fault/fracture density.
9	Basinal facies: Low matrix permeability as carbonate rocks transition to shale in the extreme northwest part of the DVRFS region.
10	Uncertain: Aquifer properties of LCA highly uncertain.
11	Brittle detachment: Upper plate of shallow-level brittle detachment faults. High fault/fracture density.

Lower Clastic-Rock Confining Unit (LCCU)

The lower clastic-rock confining unit (LCCU) consists of Middle Proterozoic to Cambrian siliciclastic rocks and subordinate dolomite, and locally, their metamorphic equivalents. Throughout much of the central part of the DVRFS region, Late Proterozoic to Lower Cambrian strata consist of a westward-thickening wedge of fine- to coarse-grained sandstone, conglomeratic sandstone, siltstone, and minor amounts of carbonate rock (Stewart, 1970). The stratigraphic section includes the Late Proterozoic Johnnie Formation and Stirling Quartzite, the Late Proterozoic to Lower Cambrian Wood Canyon Formation, the Lower Cambrian Zabriskie Quartzite (Stewart, 1970), and the lower one-third of the interbedded carbonate and quartzose rocks of the Lower and Middle Cambrian Carrara Formation (Palmer and Halley, 1979). These rocks are exposed in the northwestern part of the Spring Mountains where they are about 3,000 m thick (Burchfiel, 1964; Stewart, 1970); in the Nopah Range, where the interval is up to 3,300 m thick, to the east of the NTS (Barnes and Christiansen, 1967; Reso, 1963); and in the Panamint Mountains west of Death Valley (Hunt and Mabey, 1966; Diehl, 1974; Wright and others, 1974) where they are about 2,500 m thick; and in the Funeral Mountains (Labotka and others, 1980; Wernicke and others, 1986; Wright and Troxel, 1993). Strata of equivalent age to the east of the DVRFS region are only a few hundred meters thick, mostly Early Cambrian, and are similar to the cratonic sections exposed in the Grand Canyon (Rowland, 1987; Poole and others, 1992).

Stratigraphically underlying the rocks described above are the oldest sedimentary rocks in the DVRFS region, which are exposed in a relatively small area of the southern part of the region. These consist of the Middle and Late Proterozoic carbonate and siliciclastic rocks of the Pahrump Group and the Late Proterozoic Noonday Dolomite. These rocks unconformably overlie the Early Proterozoic basement gneiss and intrusive rocks and are as thick as 2,500 m in an east-west-trending trough that extends from southern Death Valley to the Kingston Range (Wright and others, 1974). Pahrump Group rocks thin to the north, south, and east (Stewart, 1972; Wright and others, 1974). Abrupt stratigraphic pinch-outs and facies changes have been used to infer that these rocks were deposited in a fault-controlled, rift basin setting (Wright and others, 1974). The extent and thickness of Pahrump Group rocks throughout most of the DVRFS region are not known, however, because this stratigraphic unit is not exposed.

In the northwestern part of the DVRFS region, Late Proterozoic and Cambrian strata that correlate with those of the central part of the DVRFS region are thicker and finer grained and contain significant amounts of carbonate rocks. They consist of interbedded siltstone, shale, limestone, dolomite, and fine-grained quartzite (Nelson, 1962; Stewart, 1970; Albers and Stewart, 1972). The stratigraphic section of this region includes the Late Proterozoic Wyman Formation, Reed Dolomite and Deep Spring Formation, and the Lower Cambrian Campito, Poleta, and Harkless Formations. These strata are considered to be the White-Inyo assemblage (Stewart, 1970). They contrast with their more quartzose correlatives to the south—the Death Valley assemblage. Typical exposures are found in the White and Inyo Mountains and Last Chance Range in California (Nelson, 1962; McKee, 1985; Signor and Mount, 1986) and exposures in Esmeralda County, Nev. (McKee and Moiola, 1962; Stewart, 1970; Albers and Stewart, 1972; Nelson, 1978).

The LCCU has long been considered a major confining unit in the DVRFS region (Winograd and Thordarson, 1975) and, along with the crystalline confining unit (XCU), represents the hydraulic basement for the DVRFS region (D'Agnese and others, 1997). The low hydraulic conductivity of the rock matrix permits negligible ground-water movement, but in many places the rocks 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).

The LCCU has been subdivided into six hydrogeologic zones based on lithology and structural considerations (Sweetkind and White, 2001) (fig. B–27, table B–7). The main facies transition in the Late Proterozoic through Lower Cambrian stratigraphic section of the DVRFS region is from an eastern region dominated by thick intervals of coarse siliciclastic rocks interbedded with shale (Zone 2; fig. B–27 and table B–7) to a more shale-dominated region with significant amounts of carbonate rocks (Zone 3; fig. B–27 and table B–7). Rocks of the LCCU are metamorphosed to medium and high grades where present in the lower plates of major detachment faults in the Panamint and Funeral Mountains (Labotka and others, 1980; Wernicke and others, 1986; Wright and Troxel, 1993) (Zone 5; fig. B–27 and table B–7). In the southernmost part of the DVRFS region, thick sections of Middle and Late Proterozoic carbonate rocks of the Pahrump Group are shallow enough that they could potentially be aquifers (Zone 4; fig. B–27 and table B–7).

Hydrogeologic Units Associated with Crystalline Metamorphic Rocks and Plutons

Intrusive-Rock Confining Unit (ICU)

The rocks of the intrusive-rock confining unit (ICU) include granodiorite, quartz monzonite, granite, and tonalite. Mesozoic and Cenozoic plutonic rocks in the DVRFS region are widely scattered, poorly exposed, and not abundant in the northeastern two-thirds of the DVRFS (fig. B–28). Plutonic rocks are much more common in the southwestern and western parts of the DVRFS region and include both plutons of the Mesozoic Sierran arc and synextensional plutons of the southern DVRFS region (Workman, Menges, Page, Ekren, and others, 2002).

Mesozoic granitic rocks include the Late Triassic to Early Jurassic quartz monzodioritic plutonic rocks underlying most of the Avawatz Mountains, Jurassic (mostly 186–161 Ma) plutons mostly to the west of Death Valley, and Cretaceous (mostly 100–92 Ma) in the Panamint Mountains and Owlshead Mountains. Small exposures of Cretaceous plutonic rocks in the vicinity of the NTS include the Climax stock on the northern side of Yucca Flat, the Gold Meadows stock north of Rainier Mesa, and granitic rocks on the eastern flank of the southern Kawich Range.

Oligocene and Miocene plutonic rocks crop out locally in the vicinity of the NTS, some of which are associated with caldera-related volcanism ranging in age from 32 to 11 Ma (Ekren and others, 1971; Cornwall, 1972; Ekren and others, 1977; Kleinhampl and Ziony, 1985; Slate and others, 2000). To the north of the NTS, a subcaldera pluton has been inferred in the Quinn Canyon Range (Workman, Menges, Page, Ekren, and others, 2002). At the NTS, outcrops of Neogene plutonic rocks include those near Wahmonie Flat and small intrusive bodies mapped in the Calico Hills and near Timber Mountain (Maldonado, 1985; Potter, Dickerson, and others, 2002). Neogene plutonic rocks that are associated with extension crop out in the southern part of Death Valley (Wright and others, 1999). These rocks include the gabbro to diorite intrusive rocks in the Black Mountains (about 10.3 Ma, Holm and others, 1992), the granites of the Kingston Range (12.4 Ma, Fowler and Calzia, 1999), the Little Chief stock in the Panamint Mountains, and other Neogene plutons of the Greenwater Range and central Death Valley volcanic field (Wright and others, 1991).

The ICU unit acts mostly as a confining unit. Although small quantities of water may pass through these intrusive crystalline rocks, where fractures or weathered zones exist, the fractures are poorly connected, and these rocks generally impede ground-water flow (Winograd and Thordarson, 1975).

Crystalline-Rock Confining Unit (XCU)

The crystalline-rock confining unit (XCU) consists of Early Proterozoic (about 1.7 Ga, Wright and Troxel, 1993) quartzofeldspathic schist, augen gneiss, granitic intrusive rocks, and metamorphosed Middle and Late Proterozoic sedimentary rocks. Early Proterozoic rocks are present in scattered exposures in the southern and southwestern parts of the DVRFS region and are rarely exposed throughout most of the rest of the DVRFS region (fig. B–28). These rocks crop out in the central part of the Panamint Mountains (Labotka and others, 1980), in the southern part of the Black Mountains (Holm and others, 1994), in the southern end of the Nopah Range, and in small exposures in the Funeral Mountains (Wright and Troxel, 1993) and the Bullfrog Hills (Hoisch and others, 1997) (fig. B–28). In many of these places, the Early Proterozoic crystalline rocks are in the lower plates of detachment faults. The Early Proterozoic crystalline rocks presumably form a continuous basement beneath most of the DVRFS region; they have been tectonically thickened and thinned and are locally invaded by younger plutons.

Ground water likely is present only locally in the XCU where the rock is fractured. Much of the XCU has gneissic or schistose foliation and lacks a continuous fracture network. Because the fractures are poorly connected, these rocks act mostly as confining units or barriers to flow (D'Agnese and others, 1997).

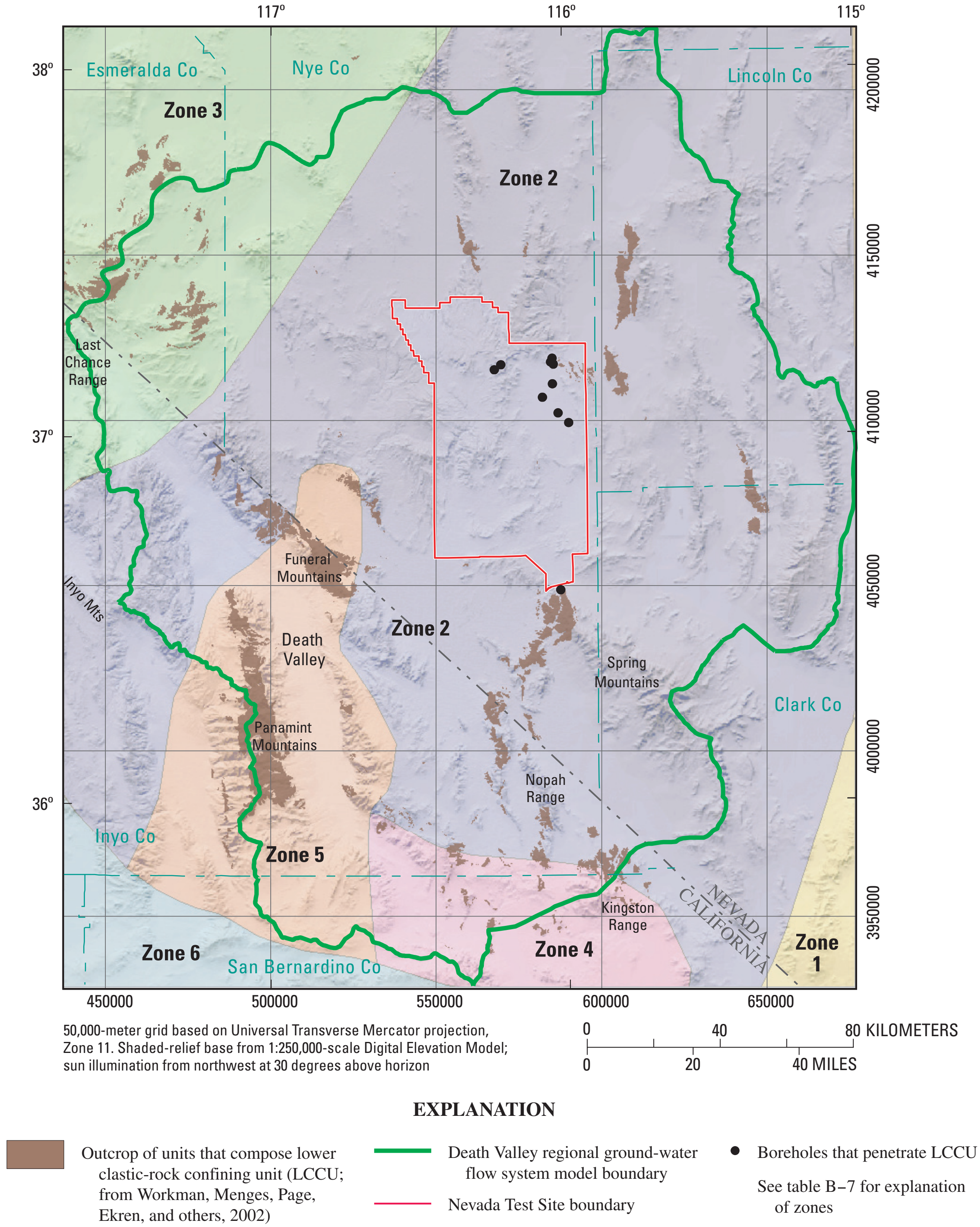


Figure B–27. Hydrogeologic zones in the lower clastic-rock confining unit (LCCU).

Table B–7. Hydrogeologic zones for the lower clastic-rock confining unit (LCCU).

Zone	Description
1	LCCU is very thin (a few hundred meters) and is similar to the cratonic sedimentary interval exposed in the Grand Canyon. Fine-grained siliciclastic rocks that generally act as a confining unit.
2	LCCU forms a westward-thickening wedge (generally 2,000 to 3,000 m thick) of fine- to coarse-grained sandstone, siltstone, conglomeratic sandstone, shale, and minor amounts of carbonate rock. Generally low permeability but may form local aquifer where highly deformed and complexly fractured.
3	LCCU is a thick (greater than 3,000 m) section of interbedded siltstone, limestone, dolomite, and fine-grained sandstone. Generally finer grained and more poorly sorted than rocks in Zone 2; however, interbedded sandstones and carbonate rocks locally may act as aquifers.
4	LCCU includes rocks of the Pahrump Group, a locally thick accumulation of Middle and Late Proterozoic sedimentary rocks. The Pahrump Group includes a significant thickness of dolomite and locally might be important to ground-water flow.
5	LCCU exposed beneath regional detachment structures. In these exposures, metamorphic grade is high, and the rocks are foliated and are of relatively low permeability. Possibly the lowest permeability of the LCCU.
6	LCCU either missing or properties are completely unknown.

Structural Factors Affecting Ground-Water Flow

The hydrogeologic effects of faulting in the DVRFS region result from either fault-caused juxtaposition of HGUs with contrasting hydrologic properties or from the physical characteristics of the fault zones themselves that may cause specific parts of the fault zone to act either as conduits or barriers to flow. Faults can have two effects on ground-water flow: direct effects associated with alterations to flow rates and ground-water velocities within the faulted zone, and indirect effects associated with alterations to the flow field in the area near the faulted zone (Black and others, 1987). Direct effects are related to (1) the physical characteristics of the fault-zone material or the material properties of the rock on either side of the fault that may cause specific parts of the zone to act either as conduits or as barriers to ground-water flow, (2) orientation of a fault with respect to the present stress field that affects dilatancy and possibly influences hydraulic conductivity along the fault zone, and (3) the recency of fault motion or association with contemporary seismicity where active stresses maintain fault openings and enhance permeabilities. Indirect effects are related to (1) fault juxtaposition of HGUs with contrasting hydrologic properties that may cause ground-water discharge and other perturbations in the flow system, and (2) the orientation of the structure with respect to the flow field. Structural controls on ground-water flow in the DVRFS region have long been recognized (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Dudley and Larsen, 1976; Laczniak and others, 1996; Dettinger and Schaefer, 1996; McKee and others, 1998). Matrix permeability is low for both the LCA (Winograd and Thordarson, 1975) and for the welded parts of the volcanic-rock aquifers (Blankennagel and Weir, 1973). As such, faults, shear zones, and fractures largely determine the secondary water-transmitting properties of these rocks (McKee, 1997; McKee and others, 1998).

Juxtaposition of Hydrogeologic Units

Fault juxtaposition of hydrogeologic units with contrasting hydraulic and hydrologic properties may result in ground-water discharge and other perturbations in the regional flow system. Regional flow of ground water in the LCA in the DVRFS region is greatly influenced by the structural position of the relatively low permeability clastic-rock confining units (fig. B–29) (Winograd and Thordarson, 1975). Previous ground-water modeling studies (D'Agnese and others, 1997; IT Corporation, 1996a) have inferred that structurally elevated confining units divert ground-water flow in the central Funeral Mountains, the northwestern part of the Spring Mountains, and in the western part of Yucca Flat (fig. B–29). D'Agnese and others (1998) show that steep hydraulic gradients correlate in general with places where relatively low permeability rocks or structures are juxtaposed with aquifers.

The influence of structures and the juxtaposition of HGUs on a ground-water flow system emphasize the importance of subsurface geologic interpretation and the resulting depiction in a 3D digital HFM (Chapter E, this volume). The two recent regional ground-water flow models (IT Corporation, 1996a; D'Agnese and others, 1997) differ substantially in their subsurface structural geologic interpretation of the DVRFS region in terms of level of detail and structural style portrayed and internal consistency of the interpretations. The geologic framework in the YMP/HRMP model (D'Agnese and others, 1997) was based on a regional geologic map compilation (Faunt and others, 1997) and on a set of regional geologic cross sections (Grose, 1983; Grose and Smith, 1989). The cross sections did not include interpretations of large-magnitude extension (Wernicke and others, 1988; Snow, 1992; Snow and Wernicke, 2000) and more recent interpretations of regional thrust correlation (Trexler and others, 1996; Cole and Cashman, 1999). The DOE/NV-UGTA geologic framework model (IT Corporation, 1996b) incorporated recent interpretations of compressional and extensional structures, but cross sections drawn by multiple authors led to some inconsistencies in the geologic interpretations. Further, the cross sections were not referenced to a regional geologic map to guide structural interpretations.

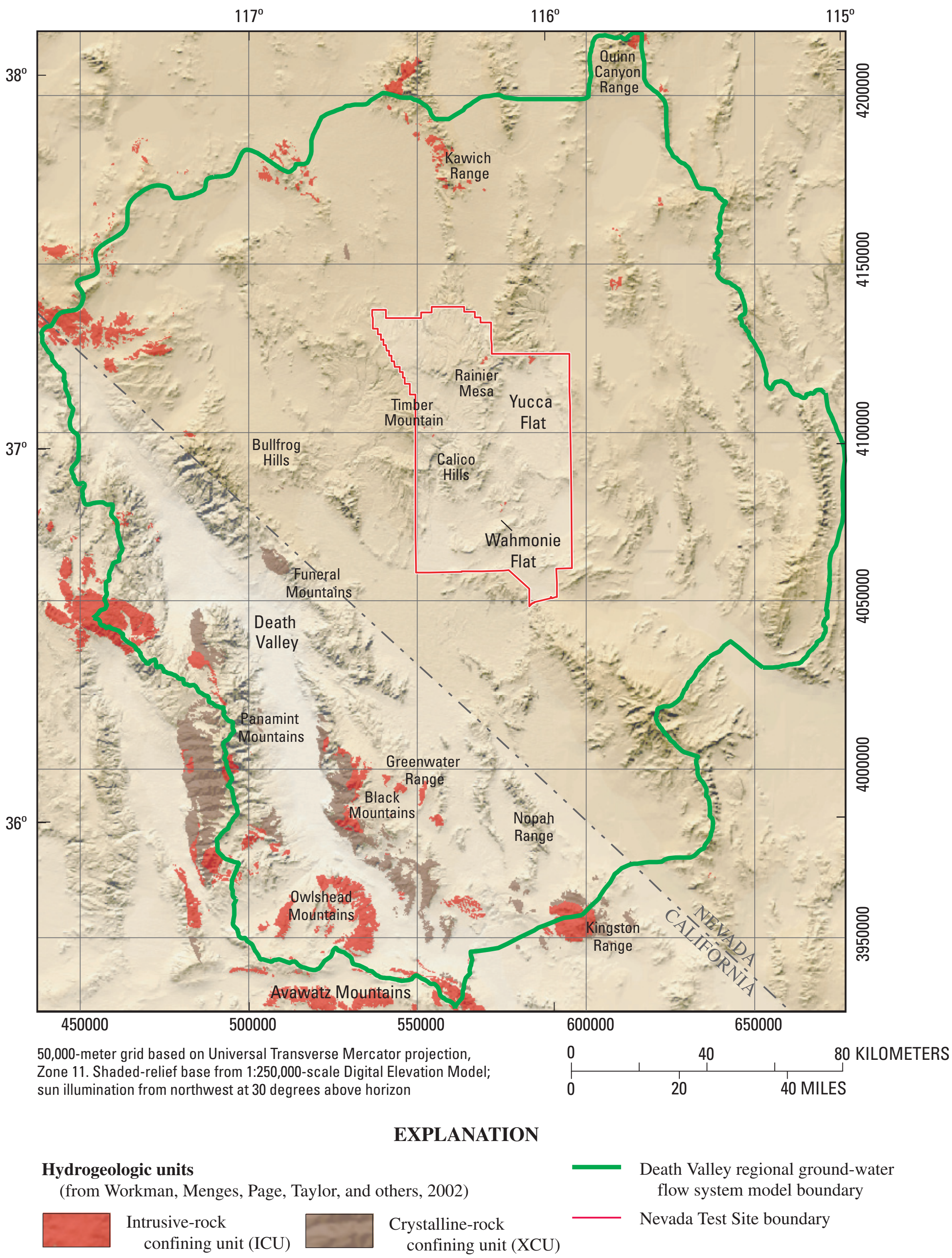
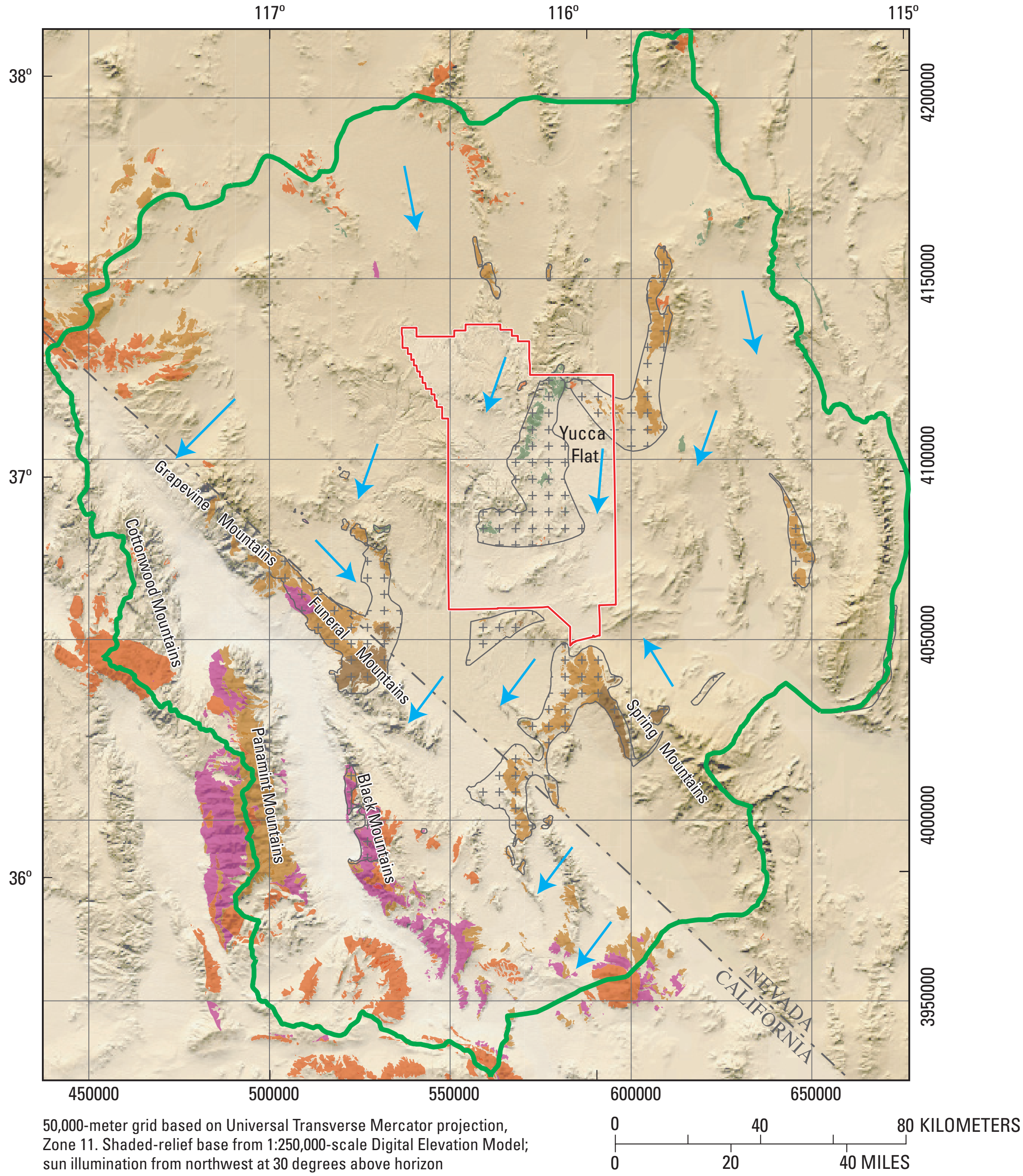


Figure B–28. Outcrop distribution of hydrogeologic units associated with metamorphic rocks and igneous plutons.



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

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

- Upper clastic-rock confining unit (UCCU)
- LCCU in thrust plates
- Lower clastic-rock confining unit (LCCU)
- Intrusive-rock confining unit (ICU)
- Crystalline-rock confining unit (XCU)
- Inferred subsurface extent of barriers related to structurally high siliciclastic rocks (from Winograd and Thordarson, 1975)
- General direction of ground-water flow (from D'Agnese and others, 1997; Laczniak and others, 1996)
- Death Valley regional ground-water flow system model boundary
- Nevada Test Site boundary

Figure B–29. Outcrop distribution of confining unit hydrogeologic units that potentially influence ground-water flow through juxtaposition of hydrogeologic units.

The current HFM (Chapter E, this volume) incorporates data from an integrated series of geologic investigations to develop a subsurface structural geologic interpretation. A regional geologic map compilation (Workman, Menges, Page, Taylor, and others, 2002) was created using a regionally consistent set of geologic map units and incorporating numerous sources of recent unpublished mapping. An accompanying regional tectonic map (Workman, Menges, Page, Ekren, and others, 2002) was created using regional magnetic and gravity compilations (Ponce and others, 2001; Ponce and Blakely, 2001; Blakely and Ponce, 2001) to interpret buried structures. A derivative regional structural map (Potter, Sweetkind, and others, 2002) interpreted the hydrologic significance of the features on the tectonic map on the basis of the regional potentiometric surface, springs, and structural evidence such as magnitude of fault offset. Subsurface geologic interpretation is depicted on 28 geologic cross sections (Sweetkind, Dickerson, and others, 2001) that were explicitly referenced to the geologic and structural map compilations. Cross-section interpretations used by the previous regional models were incorporated where appropriate.

Juxtaposition of Hydrogeologic Units by Thrust Faults

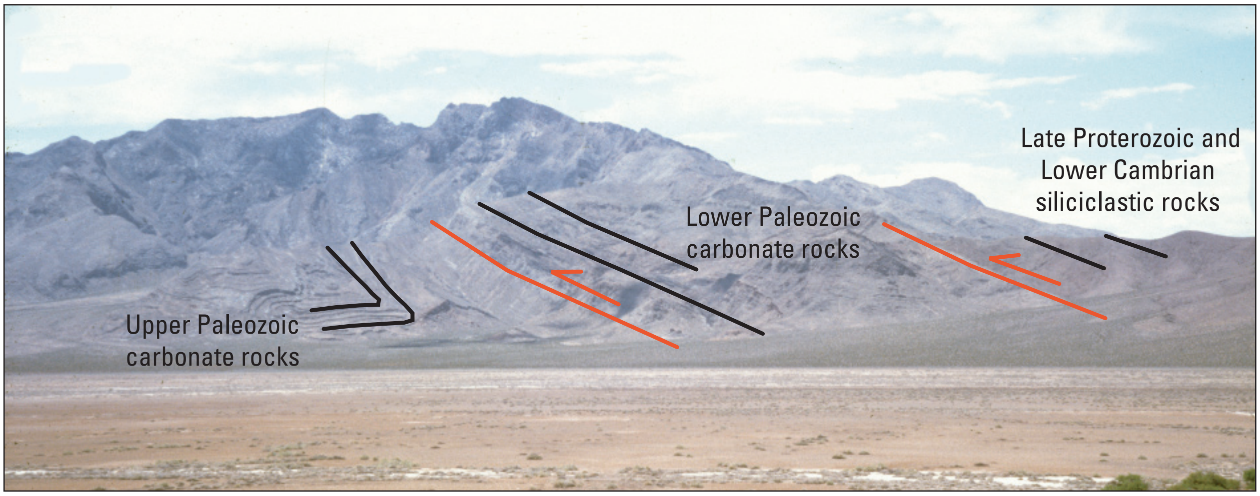
Thrust faults in the DVRFS region juxtapose hydrogeologic units of contrasting hydrologic properties and complicate the ground-water flow patterns by serving as local barriers (Winograd and Thordarson, 1975; McKee and others, 1998). These thrust faults are capable of causing significant diversion of ground-water flow or steep hydraulic gradients in the DVRFS region (Winograd and Thordarson, 1975; D'Agnese and others, 1998; Potter, Sweetkind, and others, 2002). The major thrust faults of the DVRFS region have stratigraphic offsets of several kilometers and horizontal displacements of up to several tens of kilometers based on offsets in regional facies trends (Fleck, 1970; Snow, 1992). This magnitude of stratigraphic offset typically results (for all thrusts except the frontal Keystone thrust and its equivalents; fig. B–5) in the juxtaposition of the older Late Proterozoic to Lower Cambrian siliciclastic-rock section in the upper plate against the younger Paleozoic Cambrian through Permian, predominantly carbonate-rock section in the lower plate (fig. B–30) (Armstrong, 1968; Fleck, 1970; Burchfiel and others, 1974). A complete description of thrust faults in the area is found in the tectonic map compilation of the DVRFS region (Workman, Menges, Page, Ekren, and others, 2002); thrust faults in the vicinity of the NTS are described by Cole and Cashman (1999). Structural reconstructions based on thrust correlation are summarized in Snow and Wernicke (2000).

To affect regional ground-water flow, thrust faults in the DVRFS region (fig. B–31) must have sufficient stratigraphic offset and along-strike continuity and be at an angle to the regional flow direction. Thrusts in the western part of the DVRFS region in the Funeral, Cottonwood, and Grapevine Mountains are generally subparallel to the regional northeast-to-southwest flow direction and may not influence the flow field except to divert water locally (D'Agnese and others, 1997). To the west of the Spring Mountains, several smaller thrusts are exposed in the rotated range blocks (Burchfiel and others, 1982, 1983; Snow and Wernicke, 2000). These thrusts exist in a tract of LCCU that generally separates Pahrump Valley from the Amargosa Desert, but the thrust plates are, in general, broken by normal faults and may be too discontinuous to be regionally significant. The Spring Mountains preserve two major, regionally extensive thrust faults, the Keystone thrust to the east and the Wheeler Pass thrust to the west (Burchfiel and others, 1974). Although well exposed, these thrusts crop out in the highest part of the DVRFS region; therefore, the large amount of water available as potential recharge may overwhelm bedrock geologic controls from the thrusts (D'Agnese and others, 1998).

The Belted Range thrust is the most northwesterly thrust structure identified in the vicinity of the NTS and is almost completely buried beneath Cenozoic volcanic rocks (fig. B–32). Late Proterozoic to Cambrian siliciclastic rocks in the upper plate of the thrust, part of the LCCU, are exposed only locally at the NTS and are known from borehole data (Cole and Cashman, 1999). In a general sense, the Belted Range thrust and related imbricate thrusts in its footwall juxtapose siliciclastic-rock confining units of the LCCU and UCCU against the Paleozoic carbonate rocks of the LCA. The great permeability contrast between these units is thought to create an effective barrier to ground-water flow (Laczniak and others, 1996) and segregates flow systems in the volcanic rocks of the western part of the NTS from carbonate-rock flow systems of the eastern part of the NTS (fig. B–31). The steep hydraulic gradient along most of the western side of Yucca Flat appears to be related to the combined effects of the Belted Range thrust and its footwall imbricates (Winograd and Thordarson, 1975; D'Agnese and others, 1998). This thrust was not explicitly included in the geologic framework of the YMP/HRMP model (D'Agnese and others, 1997), and a zone of low hydraulic conductivity that approximated the trace of the thrust had to be added during model calibration. The Belted Range thrust was included explicitly in the geologic framework of the DOE/NV-UGTA model (IT Corporation, 1996b) but was generalized as a vertical barrier in this flow model (IT Corporation, 1996a).

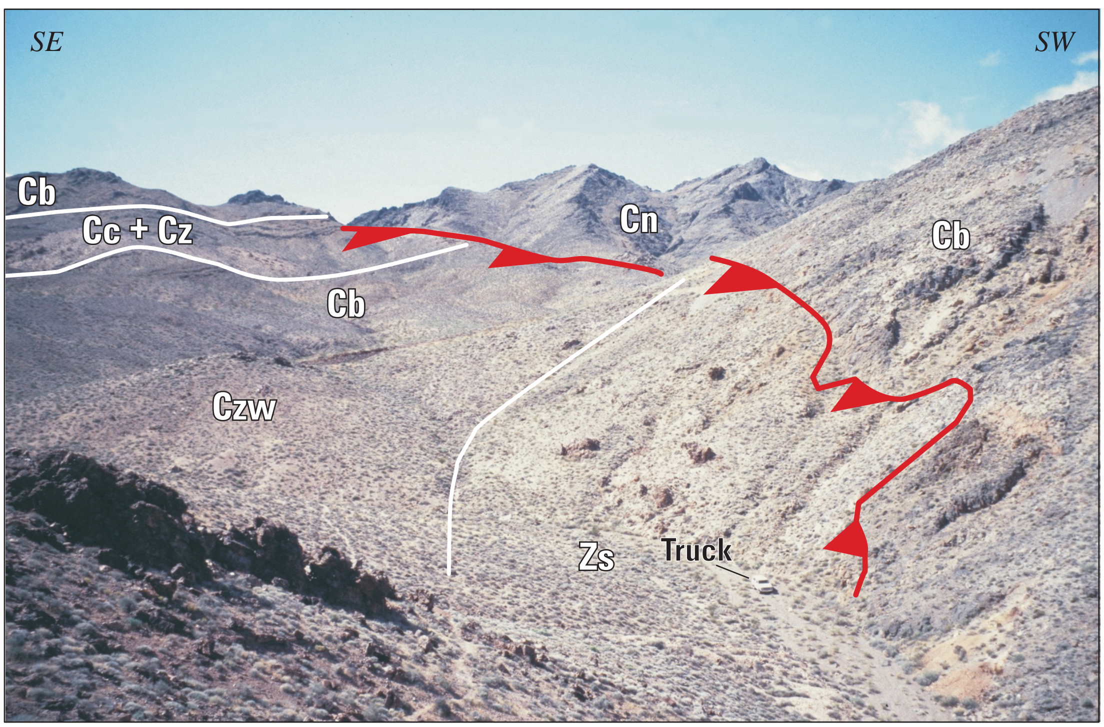
The Gass Peak thrust, along the eastern margin of the DVRFS region (fig. B–31), juxtaposes older siliciclastic Late Proterozoic Stirling Quartzite and Late Proterozoic to Lower Cambrian Wood Canyon Formation in its upper plate over highly folded and locally overturned younger Pennsylvanian and Permian carbonate-rock strata in the lower plate (Longwell and others, 1965; Guth, 1981). The thrust extends for at least 100 km along the eastern side of the Sheep Range and southward into the Las Vegas Range and may have greater than 30 km of horizontal displacement (Longwell and others, 1965; Guth, 1981). The siliciclastic rocks above the Gass Peak thrust may compartmentalize regional flow and

A View of north end of the Nopah Range, looking west-southwest



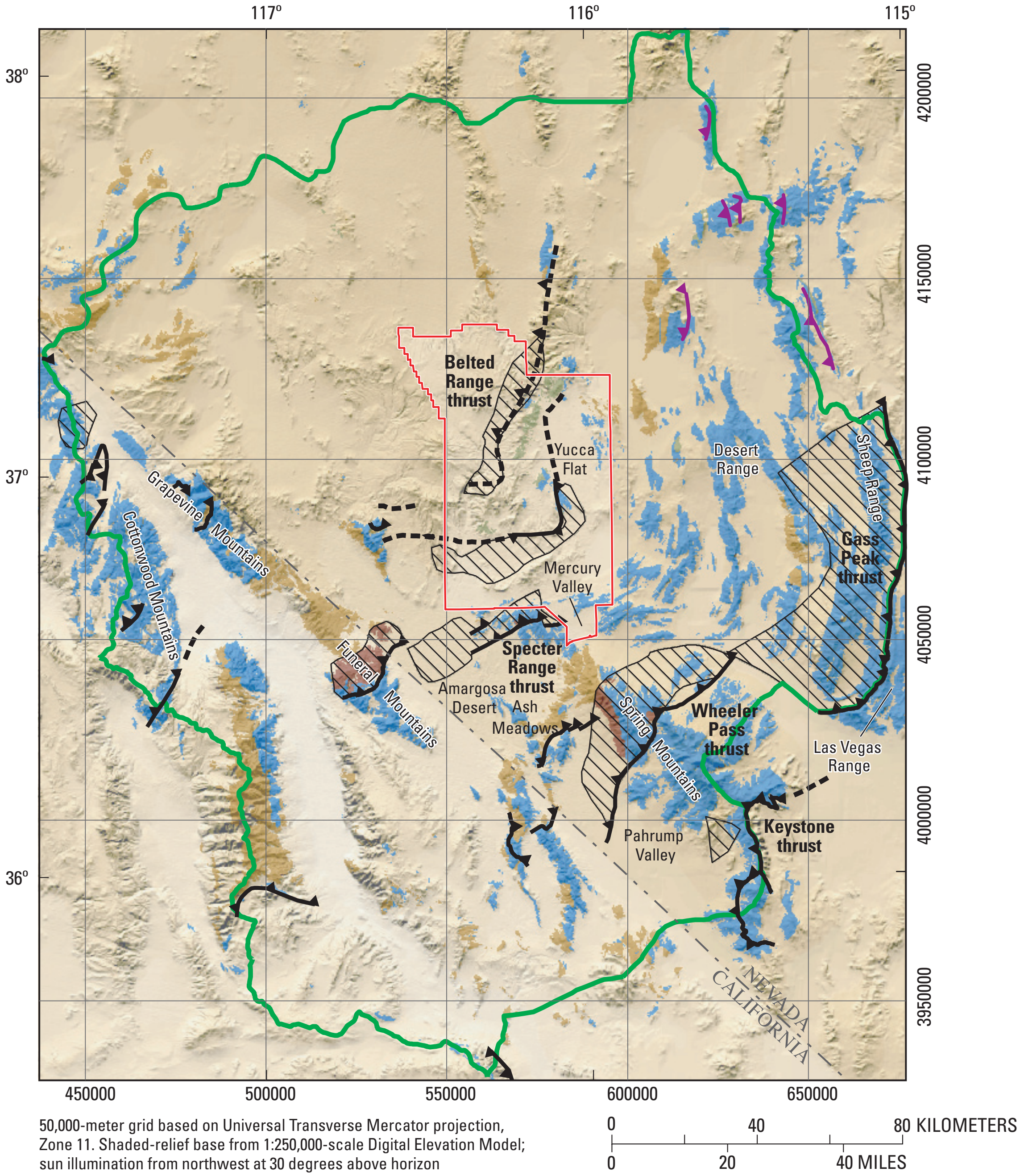
Late Proterozoic and Lower Cambrian siliciclastic rocks of hydrogeologic unit LCCU are thrust over lower Paleozoic carbonate rocks of hydrogeologic unit LCA, which are themselves thrust over younger carbonate rocks. Red lines denote thrust faults with arrow on the upper plate. Black lines portray general attitude of bedding. Geology after Burchfiel and others (1983). Photograph by D.S. Sweetkind, U.S. Geological Survey.

B Baxter thrust fault, Resting Spring Range



In this photo, the Baxter thrust places older rocks included within hydrogeologic unit LCCU (units Zs, Czw, Cz, and Cc) over younger Paleozoic carbonate rocks of hydrogeologic unit LCA (units Cb and Cn). Red line denotes thrust fault, with barbs on upper plate. Cenozoic deformation has rotated the strata 25 to 40 degrees to the east, exposing the Paleozoic carbonate rocks that lie beneath the thrust. The thrust climbs upsection in both the hanging wall and the footwall, successively truncating younger units. Geology after Burchfiel and others (1983). White truck in wash at lower right for scale. Photograph by D.S. Sweetkind, U.S. Geological Survey.

Figure B–30. Examples of thrust fault relations in the Death Valley regional ground-water flow system region.



EXPLANATION

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

Mississippian dominantly siliciclastic rocks

Paleozoic carbonate rocks

Late Proterozoic to Cambrian siliciclastic rocks in upper plate of thrusts

Late Proterozoic to Cambrian siliciclastic rocks

Inferred subsurface extent of thrust plate (from Sweetkind, Dickerson, and others, 2001)

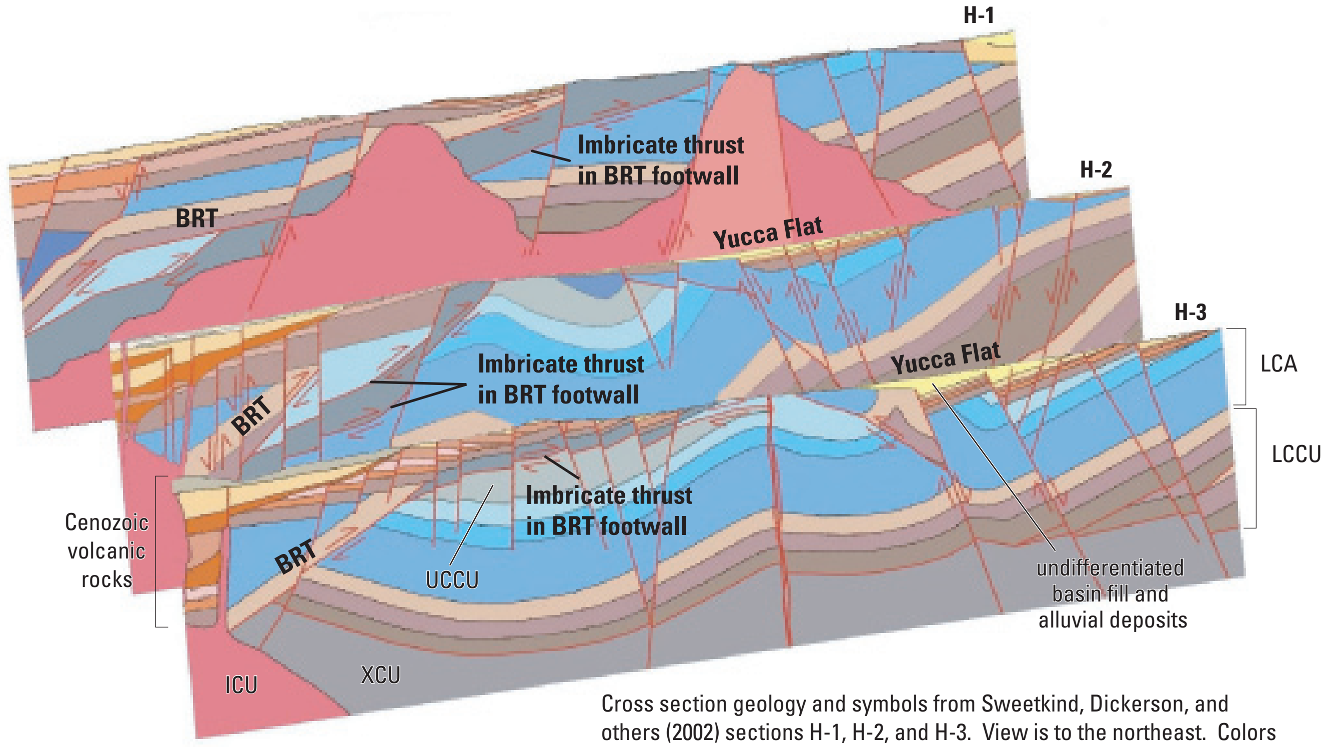
Thrust, dashed where inferred, arrow on upper plate (from Potter, Sweetkind, and others, 2002)

Mapped thrust (from Workman, Menges, Page, Taylor and others, 2000)

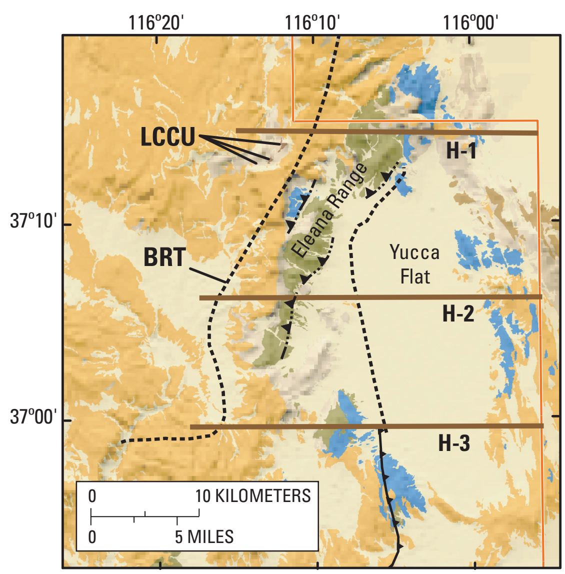
Death Valley regional ground-water flow system model boundary

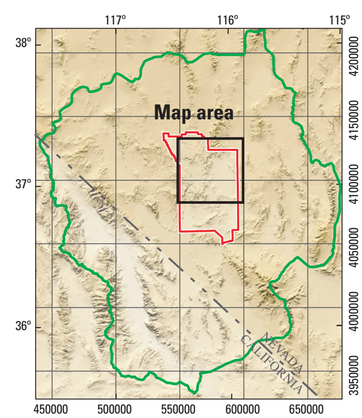
Nevada Test Site boundary

Figure B–31. Juxtaposition of hydrogeologic units by thrust faults in the Death Valley regional ground-water flow system region.



Cross section geology and symbols from Sweetkind, Dickerson, and others (2002) sections H-1, H-2, and H-3. View is to the northeast. Colors on the section correspond to hydrogeologic units as follows: Unit colored gray, XCU; units colored brown or tan, LCCU; units colored in shades of blue, LCA; gray, UCCU; red and pink, ICU; orange and light brown units at west (left) end of each section and beneath Yucca Flat are Cenozoic volcanic rocks; yellow color denotes undifferentiated basin fill and alluvial deposits. BRT, Belted Range thrust.





EXPLANATION

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

- Mississippian dominantly siliciclastic rocks (UCCU)
- Paleozoic carbonate rocks (LCA)
- Late Proterozoic to Cambrian siliciclastic rocks in upper plate of thrust (LCCU)
- Late Proterozoic to Cambrian siliciclastic rocks
- Undifferentiated Cenozoic volcanic rocks
- Undifferentiated Cenozoic basin fill
- Other rocks

- Nevada Test Site boundary
- Mapped thrust (from Potter, Sweetkind and others, 2002)
- Inferred thrust (from Potter, Sweetkind and others, 2002)
- Mapped thrust (after Cole and Cashman, 1999)
- Cross section line

Figure B–32. Interpreted subsurface geology, Belted Range thrust.

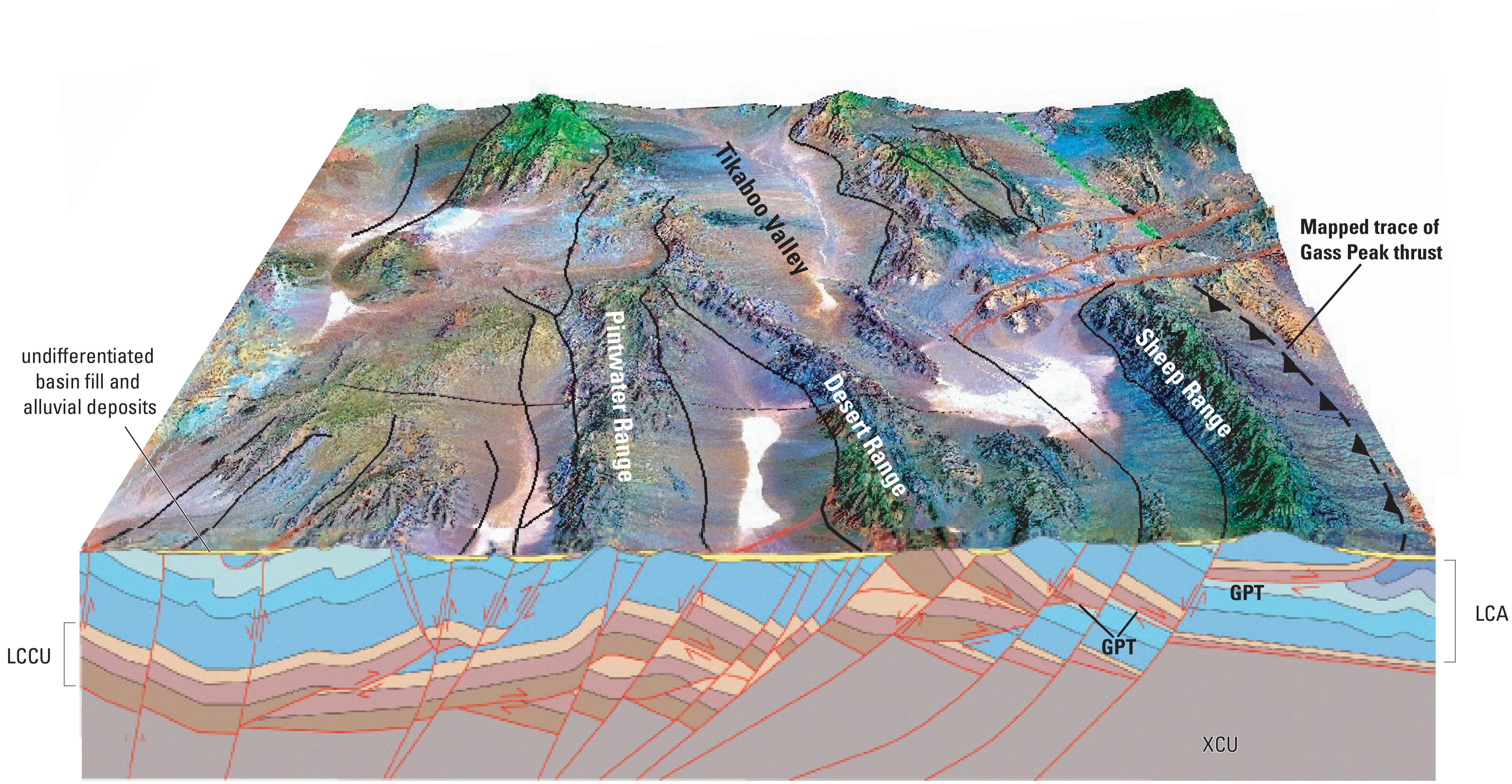
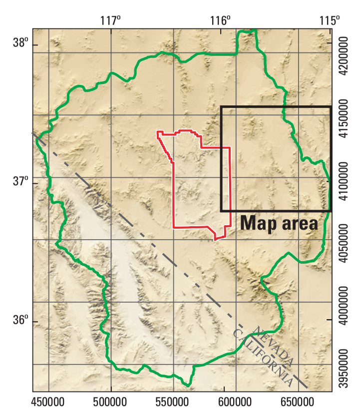


Image is false-color composite combining LANDSAT 6 spectral bands 2, 5, and 7 in RGB (Red-Green-Blue) space. Individual bands were processed to display their full dynamic range. The image was further processed in hue-saturation space to emphasize specific geologic features.

EXPLANATION

Mapped and inferred faults from surface geologic mapping
(from Potter, Sweetkind, and others, 2002)

- Strike-slip fault
- Normal fault
- Thrust fault



Cross section geology from Sweetkind, Dickerson, and others (2001) section H-5. View is to the north. GPT, Gass Peak thrust

Figure B–33. Interpreted subsurface geology, Gass Peak thrust.

separate the DVRFS from the Colorado River flow system to the east (Eakin, 1966). However, Cenozoic normal faults to the west of the Sheep Range have disrupted the continuity of the Gass Peak thrust (Guth, 1981, 1990; Wernicke and others, 1984) (fig. B–33). These faults are part of the Sheep Range detachment, a system of down-to-the-west normal faults that are inferred to flatten and converge at depth into a deep detachment zone, on the basis of significant rotation of bedding in the eastern part of the DVRFS region (Guth, 1981, 1990; Wernicke and others, 1984). These listric faults disrupt the continuity of the upper plate of the Gass Peak thrust and potentially allow connection of the two regional flow systems (fig. B–33). Guth (1981) presents an alternative view in which upper plate LCCU units thicken rapidly westward and effectively prohibit hydraulic connection of carbonate rocks of the upper and lower plate. Structurally elevated LCCU in the Desert Range (fig. B–33) is interpreted as a structural duplex of the Gass Peak thrust plate (Caskey and Schweikert, 1992) that has been subsequently disrupted by regional extension. This area forms a regional high of LCCU that diverts flow coming from the northeastern part of the DVRFS region (Dettinger and others, 1995; Dettinger and Schaefer, 1996).

The Specter Range thrust (fig. B–31) is a southeast-vergent thrust exposed in the Specter Range just south of the southern border of the NTS (Burchfiel, 1965; Sargent and Stewart, 1971). The thrust fault places older Late Proterozoic Stirling Quartzite and Late Proterozoic to Lower Cambrian Wood Canyon Formation (LCCU) over younger folded Ordovician, Silurian, and Devonian, strata (LCA) in the footwall (Burchfiel, 1965). The Specter Range thrust fault climbs upsection and loses stratigraphic throw to the northeast, where it appears to die out beneath Mercury Valley (McKee and others, 1998; Cole and Cashman, 1999). Interpretation of the subsurface extent of this thrust (McKee and others, 1998) indicates that it is a barrier to ground-water flow and channels flow in the regional carbonate aquifer southwestward toward discharge sites at Ash Meadows.

Juxtaposition of Hydrogeologic Units by Detachment and Normal Faults

Structurally high LCCU and XCU hydrogeologic units in the southwest part of the DVRFS region are associated with areas of highly disrupted surface rocks that are underlain by gently dipping extensional detachments that commonly expose a metamorphic core in their lower plates. The ranges bounding Death Valley (including the Panamint, Grapevine, Funeral, and Black Mountains) (fig. B–34) preserve major detachment faults that juxtapose lower plate, midcrustal, medium- and high-grade metamorphic rocks against unmetamorphosed upper-plate rocks across mylonite zones (Hamilton, 1988). The Grapevine and Funeral Mountains preserve the upper and lower plates, respectively, of the Boundary Canyon detachment, a gently dipping fault that juxtaposes amphibolite-grade metamorphic rocks of the lower plate against the unmetamorphosed rocks of the upper plate across a mylonitic zone only a few meters thick (Hamilton, 1988; Wright and Troxel, 1993). A major system of gently inclined normal faults exposes midcrustal metamorphic rocks in the Black Mountains, to the east of Death Valley. Overlying these major, low-angle detachment faults are Cenozoic sedimentary and volcanic rocks (fig. B–35*A*) that are cut by abundant listric normal faults (Greene, 1997). The Panamint Mountains (fig. B–34) are bounded on the east, north, and west sides by extensional structures known as the Tucki Mountain detachment system (Wernicke and others, 1986; McKenna and Hodges, 1990; Andrew, 2000). Exposures of Proterozoic metamorphic and siliciclastic rocks in the Funeral and Black Mountains are associated with a steep hydraulic gradient along the east side of Death Valley (D'Agnese and others, 1997). Regional springs are present in Death Valley only in the northern part of the Grapevine Mountains and the southern part of the Funeral Mountains (Steinkampf and Werrell, 2001), where more permeable rocks allow ground-water flow; no regional springs are present where the confining units are exposed.

The Fluorspar Canyon–Bullfrog Hills detachment system (fig. B–35*B*) separates nonmetamorphosed Cenozoic volcanic strata in the upper plate from the pre-Cenozoic bedrock of the lower plate at Bare Mountain (Monsen and others, 1992; Fridrich and others, 1999). In the southern Bullfrog Hills, complexly faulted upper plate volcanic rocks are disrupted by listric normal faults that merge with the detachment zone, which consists of fault-bounded lenses of nonmetamorphosed Paleozoic strata (fig. B–35*B*) (Maldonado and Hausback, 1990; Maldonado, 1990), all of which overlie a lower plate of amphibolite-grade metamorphic rocks (Hoisch and others, 1997). This fault was not included in the geologic framework of the YMP/HRMP model, and a zone of low hydraulic conductivity that approximated the fault was added during flow-model calibration (D'Agnese and others, 1997). Inverse models of gravity data (fig. B–35*C*) (Ponce and others, 2001) and recent geologic mapping (Monsen and others, 1992; Fridrich and others, 1999) show that Cenozoic volcanic rocks are thin and that pre-Cenozoic rocks lie at shallow depths throughout most of the southern part of the Bullfrog Hills. These data substantiate the existence of the detachment fault in the Bullfrog Hills.

Juxtaposition of contrasting HGUs along large-offset normal faults localizes substantial ground-water discharge at several places in the DVRFS region. Regional northeast-to-southwest flowing ground water is likely diverted to the surface in the eastern Amargosa Desert, where the LCA is juxtaposed against the low-permeability basin-fill materials across the Gravity fault (Winograd and Thordarson, 1975; Dudley and Larsen, 1976). At Oasis Valley, a cluster of springs is localized along the Hogback normal fault (Potter, Sweetkind, and others, 2002). These springs appear to be localized by the juxtaposition of permeable volcanic rocks on the east against LCCU on the west (Grauch and others, 1999; Fridrich and others, 1999). As a result, westward-flowing ground water in the volcanic rocks is forced to the land surface when it contacts the LCCU. Several springs in the central part of the DVRFS region appear to be related to fault juxtaposition of contrasting

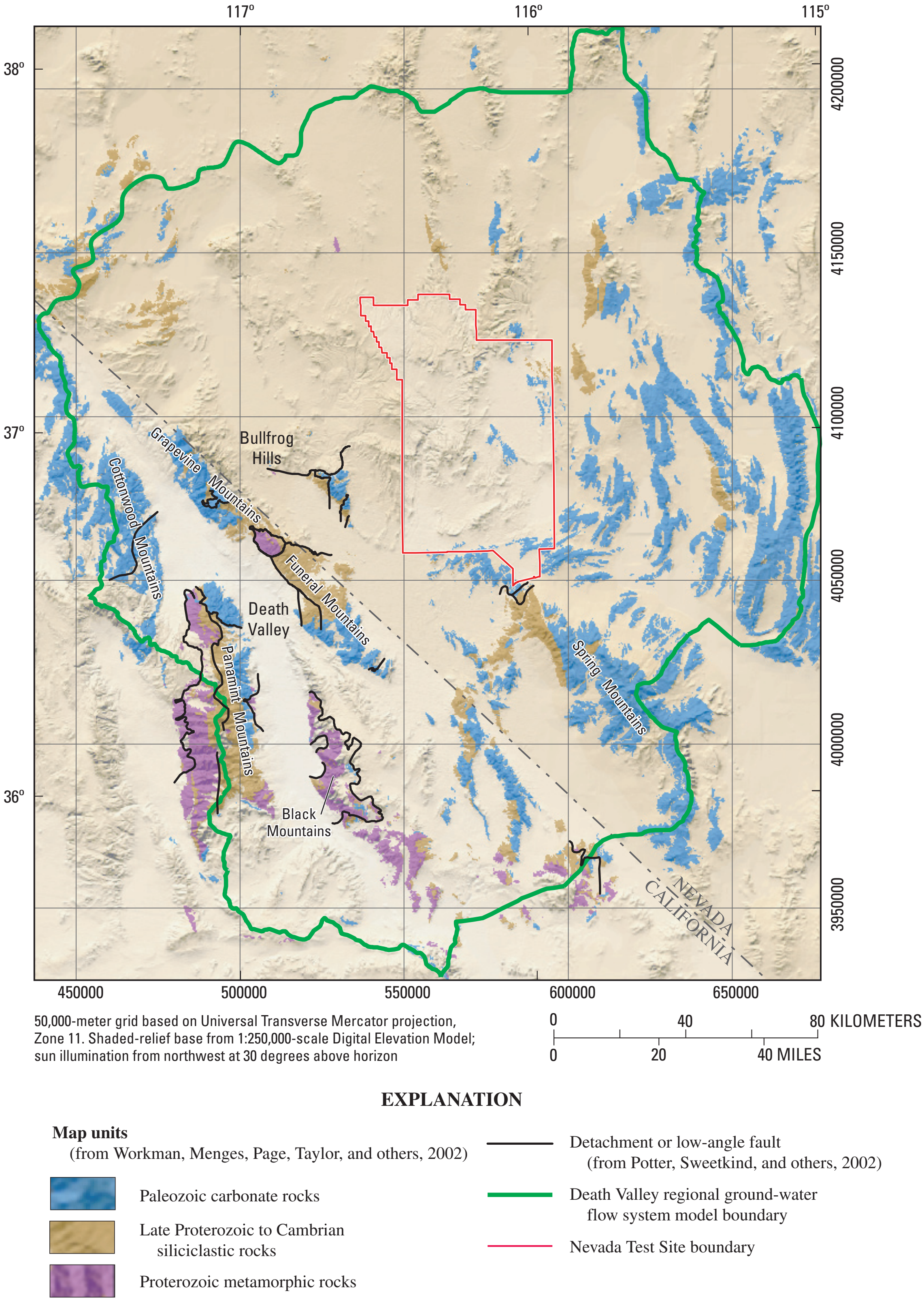
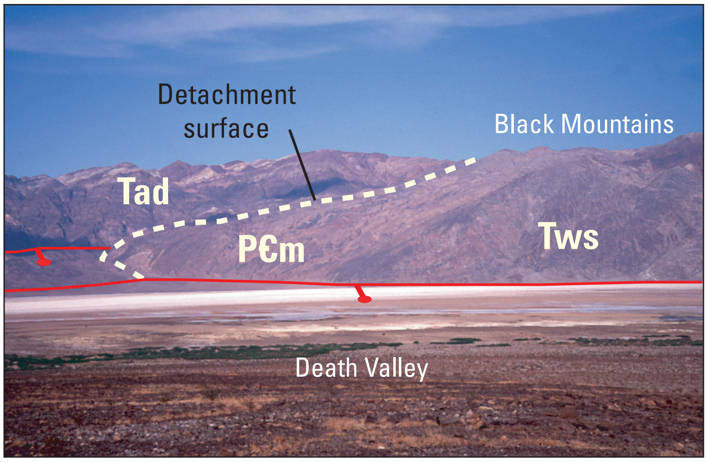


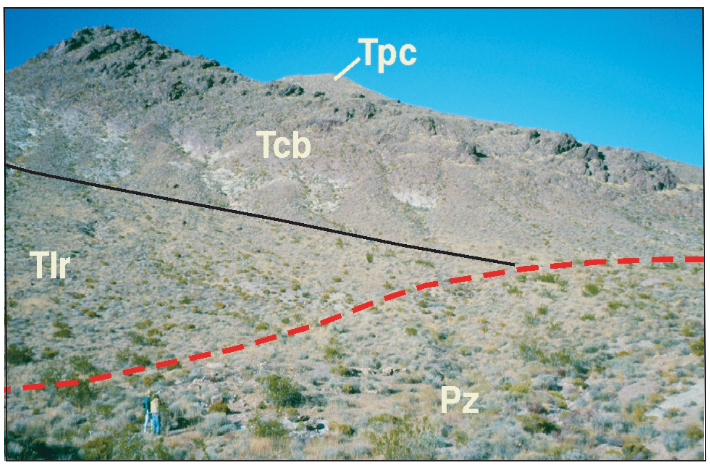
Figure B–34. Juxtaposition of hydrogeologic units by detachment faults in the Death Valley regional ground-water flow system region.

A



View is to the east from the western side of Death Valley. The crystalline core of the Black Mountains (P€m and Tws on the figure) lie beneath a gently northwest-dipping detachment fault. Upper plate rocks are Cenozoic sedimentary and volcanic rocks (Tad on figure; equivalent to hydrogeologic unit VSU) cut by abundant listric normal faults that flatten and merge with the detachment fault. Normal faults are shown by red lines, with ball and bar on downthrown side.

B



View of Fluorspar Canyon–Bullfrog Hills detachment. Tilted Cenozoic volcanic rocks (Tlr, Tcb, Tpc) are truncated against a subhorizontal detachment fault that locally has complexly faulted Paleozoic strata (Pz in figure) in its lower plate. Geology after Maldonado and Hausback (1990). Inverse models of gravity data (below) show that pre-Cenozoic rocks lie at shallow depths throughout most of the southern part of the Bullfrog Hills.

Photographs by D.S. Sweetkind, U.S. Geological Survey.

C

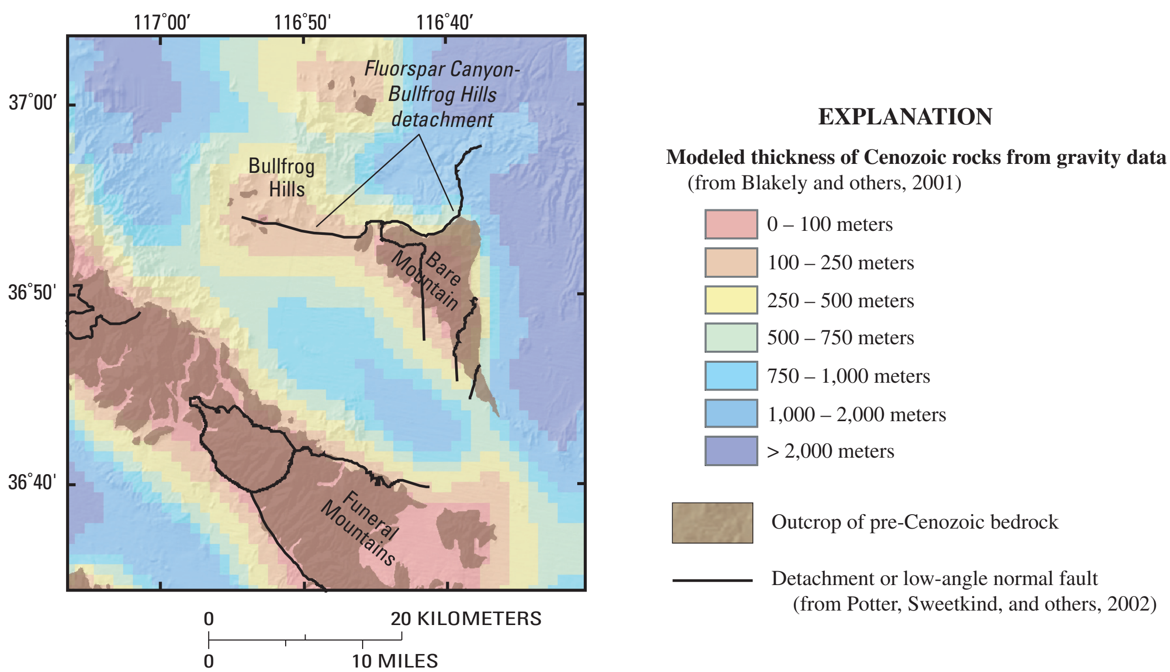


Figure B–35. Examples of detachment fault relations in the Death Valley regional ground-water flow system region.

HGUs near the Furnace Creek fault zone (D'Agnese and others, 1997; Steinkampf and Werrell, 2001). This strike-slip fault zone has a significant component of down-to-the-southwest displacement, juxtaposing the LCA (to the east) against the VSU units (to the west). Southwestward-flowing ground water that bears the chemical signature of regional flow in the LCA (Winograd and Thordarson, 1975; Steinkampf and Werrell, 2001) is diverted to the land surface, most likely because of contrasting hydraulic conductivities across the fault zone. Contrasting water levels and water-chemistry data across faults in the Yucca Mountain–Crater Flat area provide evidence that some normal faults in the volcanic rocks impede ground-water flow (Luckey and others, 1996) and thus compartmentalize the flow system.

Implication of Alternative Interpretations on Magnitude of Regional Extension

Ground-water investigations of the DVRFS region have assumed a relatively continuous Paleozoic carbonate aquifer throughout at least the eastern one-half of the DVRFS region (Winograd and Thordarson, 1975; Prudic and others, 1995; Thomas and others, 1996; Laczniak and others, 1996; D'Agnese and others, 1997, 2002). The Paleozoic carbonate-rock aquifer crops out extensively in the ranges throughout most of the eastern one-half of the DVRFS region; its presence beneath basin-fill sediments in the valleys, however, is subject to interpretation. Regional models of extension (Wernicke, 1992; Snow and Wernicke, 2000) imply discontinuity between range blocks in the carbonate-rock section. Regional estimates of extension based on correlation of thrust faults indicate that many of the carbonate-rock mountain ranges of the DVRFS region lie in a zone of extreme crustal extension, implying that these ranges are thin slivers of crust that detached above a migrating flexure in highly thinned crust (Holm and others, 1992; Wernicke, 1992). In this view, Proterozoic siliciclastic or crystalline rocks might be expected beneath basin-fill sediments in the valleys. In contrast, a number of interpretive geologic cross sections of the region portray a relatively continuous carbonate aquifer beneath basin-fill sediments throughout much of the DVRFS region (Grose, 1983; Grose and Smith, 1989; Laczniak and others, 1996; Sweetkind, Dickerson, and others, 2001).

Pre-Cenozoic bedrock has been identified in boreholes in areas of the DVRFS region that have been interpreted to have been greatly extended (fig. B–36), although the bedrock beneath most of the basins has not been reached by drill holes. Paleozoic carbonate rocks have been identified in borehole UE–25 p#1 (USGS Site ID 364938116252101) to the east of Yucca Mountain (Carr and others, 1986) and in the northern part of the Amargosa Desert (Carr and others, 1995; R.W Spengler, U.S. Geological Survey, written commun., 2002). Boreholes of Paleozoic bedrock in Yucca Flat are numerous enough to construct subsurface geologic maps of specific formations (Cole and others, 1997). Furthermore, hydrochemical data indicate that a number of the major springs in the DVRFS region (fig. B–36) are probably sourced from water that flowed through the carbonate-rock aquifer (Winograd and Thordarson, 1975; Steinkampf and Werrell, 2001). These data indicate at a minimum that some, if not all, of the water from regional springs is flowing through a continuous carbonate-rock aquifer (Winograd and Pearson, 1976). More information on the hydrochemistry and its implications for regional ground-water flow can be found in Chapter D (this volume).

Juxtaposition of Hydrogeologic Units at Caldera Boundaries

The structural and topographic margins of calderas in the SWNVF juxtapose intracaldera and outflow-facies volcanic rocks. Intracaldera rocks differ in their geometry and material properties from equivalent outflow facies in having greater thicknesses of welded material and more complex welding zonation, greater lithologic diversity including megabreccia and thick lava accumulations, and a greater degree of alteration. Fracture patterns in intracaldera rocks tend to be more irregular than those of outflow tuffs (Blankennagel and Weir, 1973), leading to a smaller number of connected flow paths. Outflow tuff sheets, although thinner than intracaldera tuff accumulations, have better connected fracture networks and there is less likelihood of significant alteration (Blankennagel and Weir, 1973). Few boreholes in the SWNVF are located such that the hydraulic significance of juxtaposition at caldera boundaries can be defined.

A caldera model with gently inwardly sloping topographic walls along with near-vertical ring faults defining the structural boundary of caldera subsidence (Lipman, 1984; Lipman 1997) was used as a conceptual basis for simulating all calderas within the SWNVF in the YMP/HRMP model (D'Agnese and others, 1997, p. 15). An alternative conceptual model for the buried calderas of the SCCC and TMCC was used in the geologic framework of the DOE/NV-UGTA model (IT Corporation, 1996b). The alternative model envisions a group of rectilinear fault-block basins formed by caldera collapse localized by preexisting linear normal faults (Ferguson and others, 1994; Warren and others, 2000). An example of such a fault is the Thirsty Canyon lineament (corresponding to feature 14 of Grauch and others, 1999; their figure B–7 and table B–4) that is interpreted from geophysical data to be a preexisting fault zone that was later exploited to form the straight northwestern boundaries (fig. B–13) of the SCCC and TMCC (Grauch and others, 1999). Numerous local fault blocks proposed for this alternative model (Ferguson and others, 1994; Warren and others, 2000) were not used in recent 3D geologic framework models of the Pahute Mesa area (McKee and others, 1999; McKee and others, 2001) because (1) the geophysical data are insufficient to detect the high-angle fault-block basins and (2) the geologic data from boreholes in the upper 900 m define small-offset, high-angle faults (McKee and others, 1999, 2001).

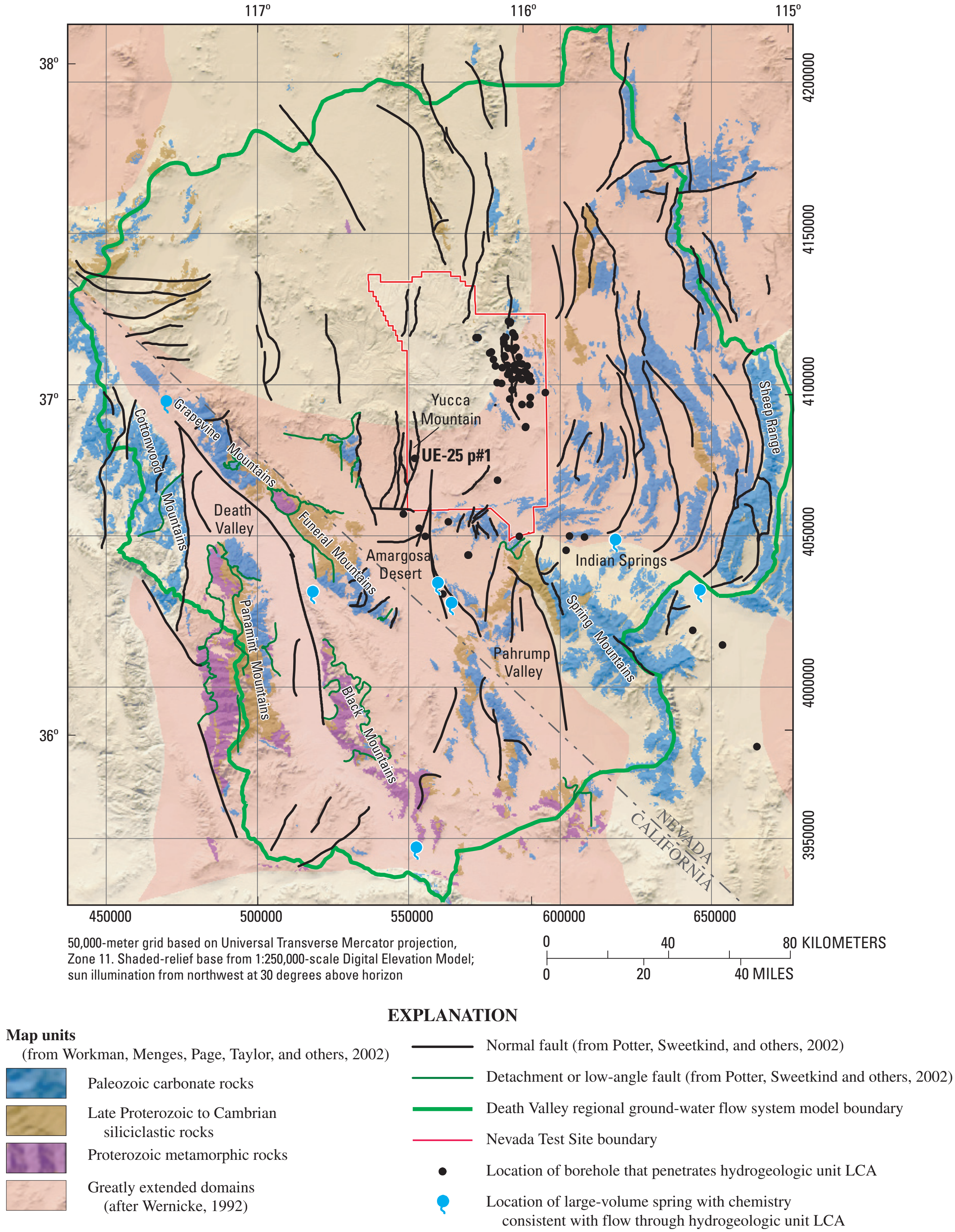


Figure B–36. Greatly extended domains, faults, boreholes, and regional springs associated with the Paleozoic carbonate-rock aquifer.

Faults as Hydrogeologic Features

Many brittle fault zones contain a narrow core of fine-grained, relatively low-permeability gouge that is the locus of fault displacement (Caine and others, 1996). In many cases, the core will have reduced permeability, relative to that of the original rock or the surrounding damage zone, as a result of progressive grain-size reduction, dissolution, reaction, and mineral precipitation (Caine and others, 1996). The core zone can be flanked by damage zones, a network of subsidiary small faults and fractures that enhance secondary permeability (Caine and others, 1996; Caine and Forster, 1999). Fault cores typically restrict fluid flow across the fault, while the damage zone may conduct ground-water flow parallel to the fault zone. In general, large-displacement faults are characterized by a continuous, relatively low permeability core zone (Chester and Logan, 1986).

Hydraulic Barriers

On the basis of characteristics of the potentiometric surface, the location of springs, and the location of the fault with respect to predominant northeast-to-southwest ground-water flow in the DVRFS region, several of the large strike-slip faults in the DVRFS region, including the LVVSZ, the Pahrump–Stewart Valley fault zone, and the Death Valley–Furnace Creek fault system (fig. B–7), are thought to be potential barriers to ground-water flow. The large strike-slip faults in the southwestern part of the DVRFS region are generally buried beneath Cenozoic sediments, although traces of the faults are commonly defined by Quaternary fault scarps (Anderson and others, 1995; Piety, 1996). Geophysical investigations of the LVVSZ (Langenheim and others, 2001) and the Pahrump–Stewart Valley fault zone (Blakely and others, 1998, 1999) portray a structurally complex pre-Cenozoic surface adjacent to these faults consisting of steep-sided local depressions and ridges that likely are fault-bounded (fig. B–37) and probably represent local compression and extension in the overall strike-slip environment (Wright, 1989).

The LVVSZ extends more than 100 km northwestward from its eastern end near Frenchman Mountain, on the east side of Las Vegas Valley (fig. B–7). The LVVSZ is a complex system of right-lateral faults with several fault strands and associated steep-sided pull-apart subbasins (Langenheim and others, 2001). Right-lateral offset of correlative features across the LVVSZ is estimated to be from 40 to 66 km (Stewart and others, 1968; Longwell, 1974); displacement is thought to have occurred between 14 and 8.5 Ma (Bohannon, 1984; Duebendorfer and Black, 1992). The LVVSZ appears to form a hydraulic barrier in the Indian Springs, Nev., area; spring discharge at Indian Springs (fig. B–36) may reflect upward flow of ground water against a low-permeability fault barrier (Winograd and Thordarson, 1975). The Pahrump–Stewart Valley fault zone (Stewart and others, 1968; Burchfiel and others, 1983; Stewart and Crowell, 1992) is a regionally extensive, right-lateral, strike-slip fault zone that roughly parallels the California-Nevada border through the Stewart and Pahrump Valleys. The fault zone may be as long as 150 km (Schweickert and Lahren, 1997; Blakely and others, 1998) and is estimated to have between 20 and 30 km of right-lateral offset based on offset of Proterozoic and Paleozoic rocks (Stewart and others, 1968), interpreted correlations of thrust sheets, and offsets in regional facies trends (Stevens and others, 1991). The faults are almost everywhere buried by Cenozoic rocks; part of the zone is exposed in the southern Montgomery Mountains (fig. B–38) (as defined by Burchfiel and others, 1983).

The 250-km-long Death Valley–Furnace Creek fault system consists of right-lateral strike-slip and normal faults that cross the entire western part of the DVRFS region (fig. B–7) (Stewart, 1988; Piety, 1996). The southern part of the system is a 50-km-long set of northwest-striking, predominantly right-lateral faults that underlie southern Death Valley (Workman, Menges, Page, Ekren, and others, 2002). The central part of the system is a 60-km-long, north-northwest-trending, primarily oblique normal-slip fault zone that forms the western range front of the Black Mountains (fig. B–6) (Piety, 1996). The northern part of this fault system is an active right-lateral fault zone (Piety, 1996) with a total cumulative right-lateral offset estimated at about 65 to 80 km (Stewart, 1967; Stewart and others, 1968; Snow and Wernicke, 1989). Springs in the northern part of Death Valley may be localized along the northern Death Valley–Furnace Creek fault zone where upward flow of ground water is localized against a low-permeability fault barrier (Winograd and Thordarson, 1975; Potter, Sweetkind, and others, 2002).

Potter, Sweetkind, and others (2002) compiled the locations of principal faults and structural zones in the DVRFS region that may influence ground-water flow. A subset of the mapped faults in DVRFS region was chosen for possible inclusion as hydraulic barriers in the ground-water flow model (fig. B–39). Faults were chosen on the basis of their length, offset, type of slip, orientation, characteristics of the potentiometric surface, and the location of springs. The emphasis was on faults that may have special hydraulic characteristics that may require them to be treated as separate entities in the flow model. Juxtaposition of HGUs with different hydraulic properties was not a primary consideration as these relations are incorporated in the HFM (Chapter E, this volume). Structural features were classified based on a hierarchical approach for possible sequential inclusion into the flow model (table B–8). Initially, northwest-striking faults were separated from faults of other (primarily north-south) orientation (table B–8; fig. B–39). The northwest-striking faults typically are the large-offset strike-slip faults that are oriented approximately perpendicular to the flow direction. These faults are interpreted as being the most likely structural barriers to regional ground-water flow. Second-level subdivision of these faults consists of dividing the northwest-striking faults that involve the regional carbonate-rock aquifer from those that involve other, primarily confining, units. Finally, local segments of strike-slip faults are subdivided; these segments of different orientation from the main fault trace correspond to releasing or restraining bends

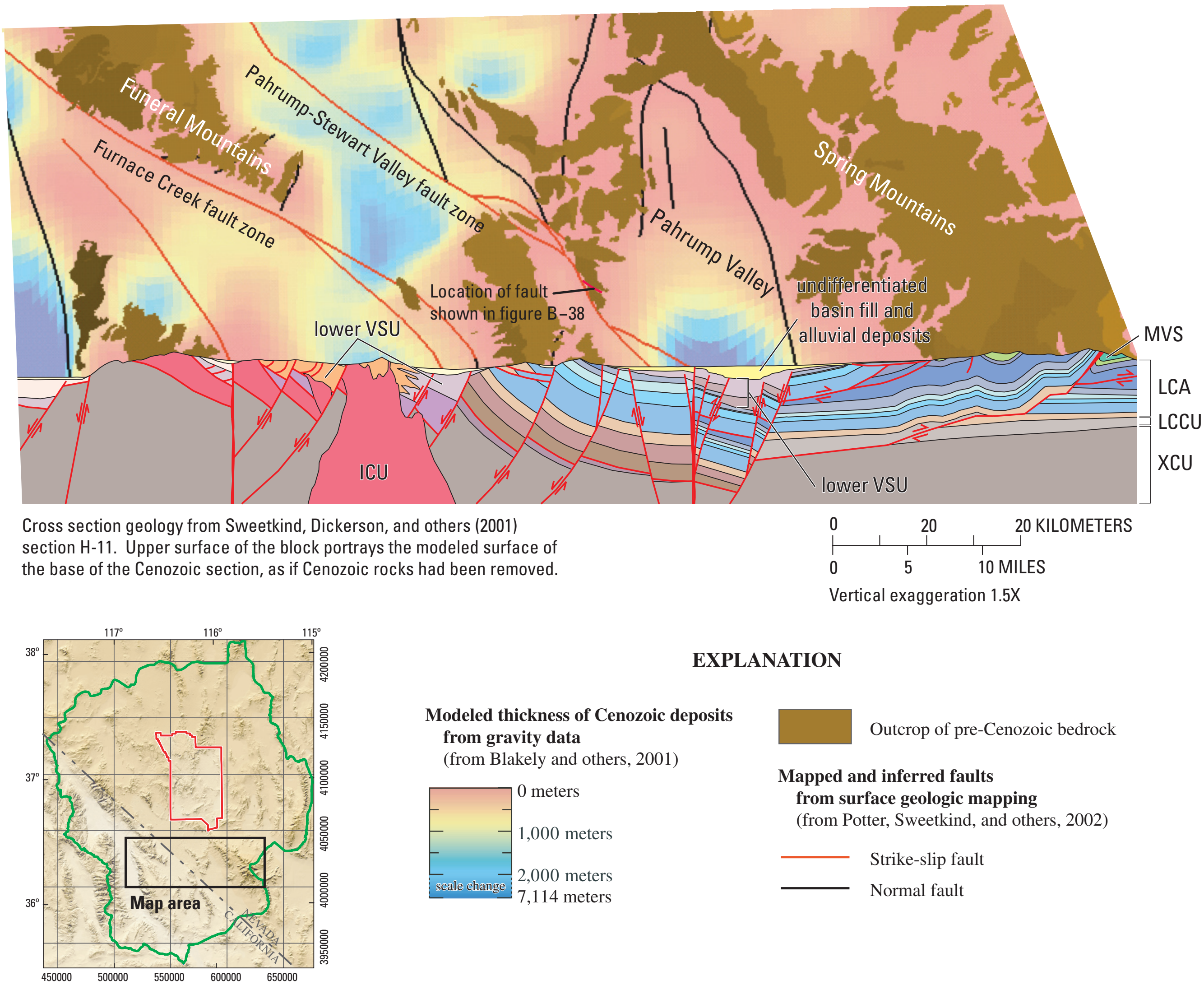


Figure B–37. Interpreted geometry of strike-slip faults, Death Valley regional ground-water flow system region.

that may differ significantly in hydraulic conductivity from other parts of the fault (Potter, Sweetkind and others, 2002). North-south-striking normal faults were subdivided primarily on magnitude of offset, and then by distribution in the DVRFS region (table B–8; fig. B–39).

Hydraulic Conduits

Comparison of the location of large-offset structures with the regional potentiometric surface (Winograd and Thordarson, 1975; D'Agnese and others, 1998) and the results of recent ground-water flow models (IT Corporation, 1996a; D'Agnese and others, 1997) indicates that few of the individual structures are hydraulic conduits on the regional scale. Rather than being associated with single faults, hydraulic conduits in the DVRFS region appear to be spatially associated with broad, northeast-striking zones that are transverse to the main trend of the Walker Lane belt (fig. B–7) (Carr, 1984; Stewart, 1988; Stewart and Crowell, 1992). These zones are characterized by active seismicity associated with subparallel, northeast-striking faults that accommodate relatively small amounts of sinistral and normal offset across a broad zone (Carr, 1984; Potter, Sweetkind, and others, 2002).

In the southern part of the NTS, the Spotted Range–Mine Mountain shear zone (Carr, 1984; Stewart, 1988) includes the Rock Valley, Cane Spring, and Mine Mountain faults (fig. B–7). These faults generally strike north-northeast, have demonstrated left-lateral offset of a few kilometers, have variable sense and amount of normal displacement (Frizzell and Shulters, 1990), and are associated with minor seismic events (Piety, 1996; Potter, Sweetkind, and others, 2002). These strike-slip faults are linked by north-striking normal faults that form local pull-apart basins and create complex map patterns in the south-central part of the Nevada Test Site (Maldonado, 1985; Frizzell and Shulters, 1990). Winograd and Pearson (1976) described a transmissive pathway or "megachannel" between Mercury

A

(A) Outcrop of a splay of the Pahrump–Stewart Valley fault zone exposed east of Stewart Valley. Fault is in Late Proterozoic Sterling Quartzite, part of hydrogeologic unit LCCU. Fault core consists of 10 centimeters of foliated clay-rich fault gouge, surrounded by a zone of brecciated wall rock. Hammer is about 30 centimeters in length.

(B) Looking west from near locality shown in (A) across splay of the Pahrump–Stewart Valley fault zone to Stewart Valley. Fault zone has a northwest strike and is about 250 meters wide. Fault zone consists of fault-bounded lenses of Late Proterozoic Stirling Quartzite; fault contacts are shown as black dashed lines.

Photographs by D.S. Sweetkind, U.S. Geological Survey.

B

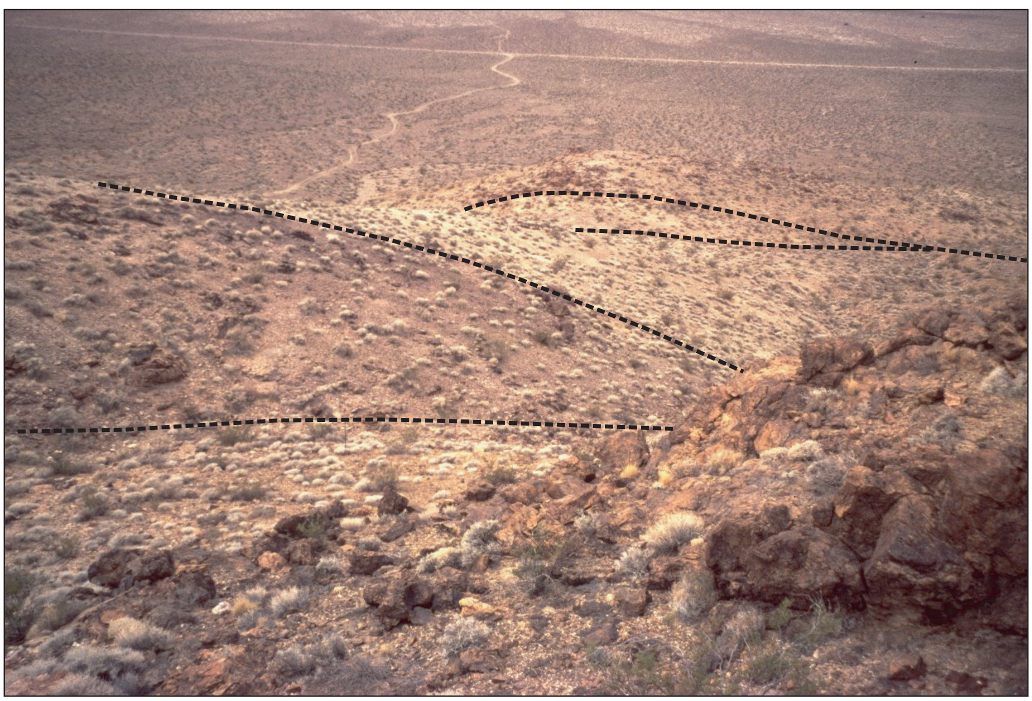


Figure B–38. Examples of strike-slip faults east of Stewart Valley, Death Valley regional ground-water flow system region.

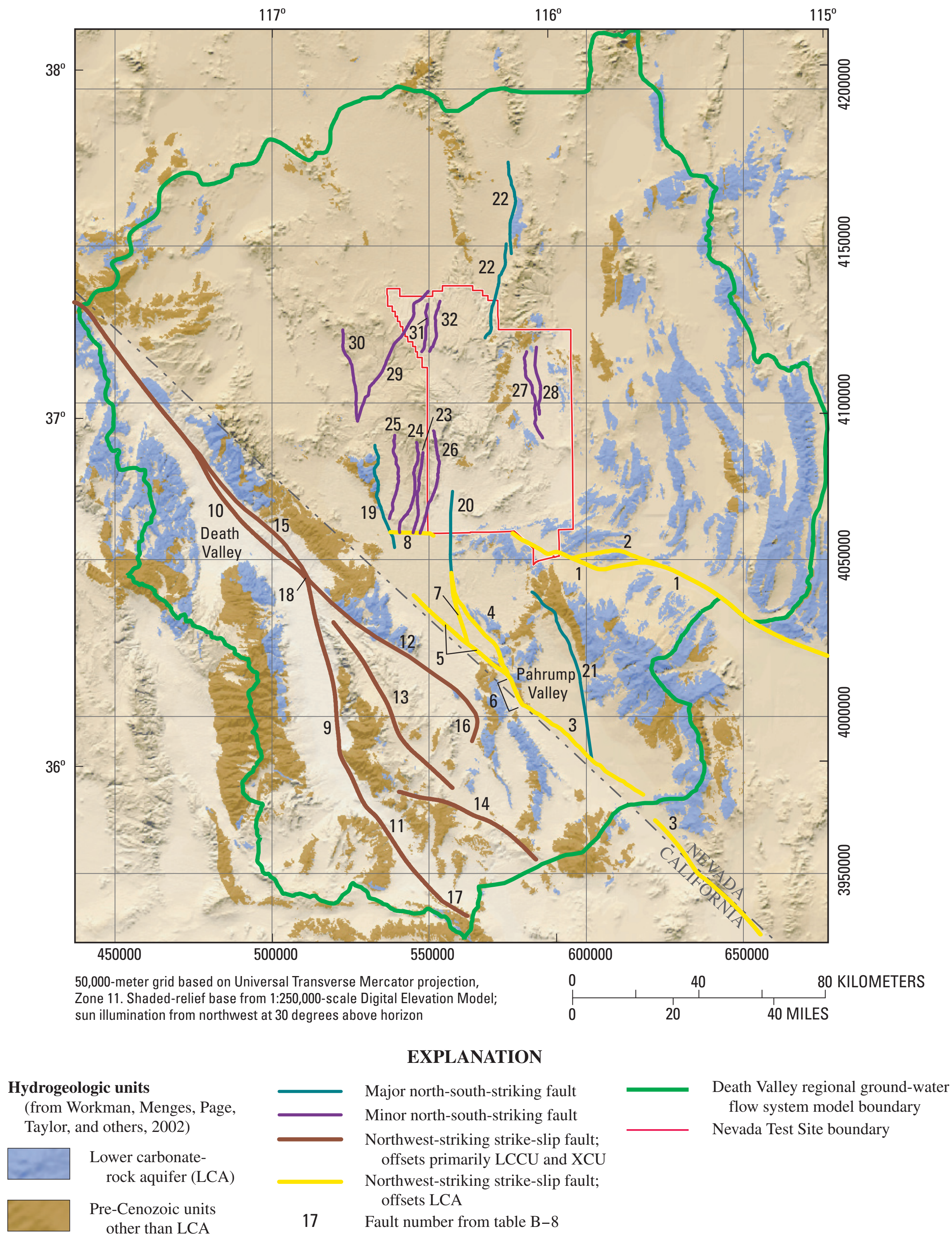


Figure B–39. Structures designated as potential flow barriers in the Death Valley regional ground-water flow system region.

Table B–8. Hierarchical subdivision of faults designated as potential flow barriers in the DVRFS model.

[LCA, lower carbonate-rock aquifer; LVVSZ, Las Vegas Valley shear zone. Numbers in parentheses refer to locations shown on figure B–39]

Northwest-striking structures

- Faults mainly in LCA
  - LVVSZ
    - Main trace of LVVSZ (1)
    - Indian Spring splay (2)
  - Pahrump–Stewart Valley and Highway 95 faults
    - Pahrump–Stewart Valley fault
      - Northwest-striking segments
        - Pahrump Valley area (3)
        - Ash Meadows area (4)
        - Amargosa Desert area (5)
      - North-striking segments
        - Stewart Valley (6)
        - Southern Gravity fault (7)
    - Highway 95 fault (8)
- Faults in hydrogeologic unit other than LCA
  - Death Valley–Furnace Creek fault zone, main trace
    - North-striking sections (central Death Valley) (9)
    - Northwest-striking sections
      - Death Valley sections
        - Northern Death Valley section (10)
        - Southern Death Valley section (11)
        - Furnace Creek fault (12)
      - Grandview fault (13)
      - Sheephead fault (14)
      - Keane Wonder fault (15)
  - Death Valley–Furnace Creek fault zone, transition zones and bends
    - Eagle Mountain area (16)
    - Saratoga Springs area (17)
    - Furnace Creek Ranch area (18)
- Major faults
  - Major faults near Yucca Mountain
    - Bare Mountain fault (19)
    - Northern Gravity fault (20)
  - Other major north-striking faults
    - Western Spring Mountains fault (21)
    - Belted Range fault (22)
- Minor faults
  - Yucca Mountain or Yucca Flat areas
    - Minor faults near Yucca Mountain
      - Western Yucca Mountain faults
        - Solitario Canyon fault (23)
        - Windy Wash fault (24)
      - Crater Flat fault (25)
      - Paintbrush Canyon fault (26)
    - Minor faults near Yucca Flat
      - Carpetbag fault (27)
      - Yucca fault (28)
  - Pahute Mesa–Oasis Valley features
    - Thirsty Canyon lineament (29)
    - Hogback fault (30)
    - East Box Car fault (31)
    - Almendro fault (32)

Valley and Ash Meadows to explain the carbon-14 content of spring water at Ash Meadows. The Spotted Range–Mine Mountain shear zone (Carr, 1984; Stewart, 1988) is associated with a trough in the regional potentiometric surface, potentially indicating high transmissivity in the Paleozoic carbonate rocks (D'Agnese and others, 1998), and corresponds in part to the "megachannel" defined by Winograd and Pearson (1976). Previous work (Winograd and Thordarson, 1975; D'Agnese and others, 1997; Faunt, 1997) indicates this area has greater permeability associated with highly fractured LCA.

Another zone of minor northeast-striking faults associated with active seismicity, has been inferred to exist in the Gold Mountain area (fig. B-7) northeast of the northern terminus of Death Valley (Albers and Stewart, 1972; Carr, 1984; Potter, Sweetkind, and others, 2002). This region is characterized by highly jointed granite adjacent to the northern Death Valley–Furnace Creek strike-slip fault zone and, to the south, by closely spaced normal faults that cut both the Cenozoic volcanic rocks and the underlying Paleozoic carbonate rocks (Potter, Sweetkind, and others, 2002). This zone corresponds spatially with spring discharge in the northern part of Death Valley; a region of greater transmissivity was added to the YMP/HRMP flow model during calibration (D'Agnese and others, 1997) to simulate this zone.

Although not part of the Walker Lane belt, the Pahranagat shear zone is another northeast-trending system of left-lateral strike-slip faults at the northern end of the Sheep Range (fig. B–7) (Tschanz and Pampeyan, 1970; Jayko, 1990). The fault zone is about 13 km wide, extends for at least 40 km along strike, and consists of several steeply dipping fault strands with oblique left-lateral strike-slip displacement.

Summary

Decades of study in the southern Great Basin have shown that the geologic framework, which is stratigraphically and structurally complex, is important in controlling ground-water flow. Flow within the regional carbonate-rock aquifer and in more localized basin-fill and volcanic-rock aquifers reflects structural and lithologic conditions that produce permeability variations. The hydrogeologic units (HGUs) in the Death Valley regional ground-water flow system (DVRFS) region generally include: Cenozoic basin-fill and playa deposits; as much as 2,000-m-thick sequence of Cenozoic lava flows, welded and nonwelded tuffs; Cenozoic and Mesozoic intrusive rocks; Mesozoic sedimentary and volcanic rocks; as much as 8,000-m-thick Paleozoic carbonate and siliciclastic rocks that are the principal aquifer, and Paleozoic to Late Proterozoic siliclastic rocks and Proterozoic igneous and metamorphic rocks that are the primary regional confining units.

Ground-water flow is affected by faults with kilometers of offset that cause juxtaposition of aquifers and confining units; structural deformation; degree of welding; and facies transitions, lithologic features, and hydrothermal alteration that produce variations in permeability.

Based on characteristics of the potentiometric surface, the location of springs, and the location with respect to predominant northeast-to-southwest ground-water flow in the DVRFS region, the LVVSZ, the Pahrump–Stewart Valley fault zone, and the Death Valley–Furnace Creek fault system strike-slip faults are potential barriers to ground-water flow; broad, northeast-striking zones that are transverse to the main trend of the Walker Lane belt, but not individual faults, are hydraulic conduits.

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