U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

HYDROSTRUCTURAL MAPS OF THE DEATH VALLEY REGIONAL FLOW SYSTEM, NEVADA AND CALIFORNIA

By

C.J. Potter, D.S. Sweetkind, R.P. Dickerson, and M.L. Killgore

2002

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

Pamphlet to accompany
MISCELLANEOUS FIELD STUDIES MAP
MF–2372

CONTENTS

ABSTRACT

The locations of principal faults and structural zones that may influence ground-water flow were compiled in support of a three-dimensional ground-water model for the Death Valley regional flow system, which covers 80,000 km^2 in southwestern Nevada and southeastern California. Faults include Neogene extensional and strike-slip faults and pre-Tertiary thrust faults. Emphasis was given to characteristics of faults and deformed zones that may have a high potential for influencing hydraulic conductivity. These include: (1) faulting that results in the juxtaposition of stratigraphic units with contrasting hydrologic properties, which may cause ground-water discharge and other perturbations in the flow system; (2) special physical characteristics of the fault zones, such as brecciation and fracturing, that may cause specific parts of the zone to act either as conduits or as barriers to fluid flow; (3) the presence of a variety of lithologies whose physical and deformational characteristics may serve to impede or enhance flow in fault zones; (4) orientation of a fault with respect to the present-day stress field, possibly influencing hydraulic conductivity along the fault zone; and (5) faults that have been active in late Pleistocene or Holocene time and areas of contemporary seismicity, which may be associated with enhanced permeabilities.

INTRODUCTION

The Death Valley regional flow system (DVRFS; D'Agnese and others, 1997; Faunt and others, 1997) occupies a structurally complex region of approximately 80,000 km^2 in southwestern Nevada and southeastern California (maps A and B). In the DVRFS, agricultural areas and other environmentally sensitive areas near ground-water discharge sites in the Amargosa Desert, Death Valley, Oasis Valley, and the town of Tecopa lie downgradient of several potential sources of radionuclides at the Nevada Test Site and a potential repository for radioactive wastes at Yucca Mountain. Numerous studies of the hydrogeology of this region (cited in the "Previous Work" section) have been undertaken to gain insight into the regional transport of radionuclides through ground-water flow from these potentially contaminated sources toward sensitive discharge sites.

These maps (maps A and B) were prepared in support of a regional three-dimensional ground-water model currently being constructed by the U.S. Geological Survey (USGS) for the DVRFS (Faunt and others, 1999). The maps identify regional geologic structures whose possible hydrologic significance merits their inclusion in the hydrogeologic framework model (HFM) for the DVRFS. The HFM is the three-dimensional representation of the fundamental hydrogeologic characteristics that affect regional ground-water flow. At its simplest, the HFM can be represented with a simplified "hydrostratigraphy." In the structurally complex DVRFS, faults, fault systems, and areas of enhanced fracturing or brecciation affect regional flow significantly (Winograd and Thordarson, 1975; Faunt, 1997), so these structures should be superimposed on the hydrostratigraphy in the HFM. For this reason, a regional hydrogeologic map and a network of regional cross sections that incorporate the principal faults constitute the basic input to the HFM; the structural elements identified here and maps that document facies variation in the DVRFS are also fundamental components of the HFM (Faunt and others, 1999; Sweetkind and others, 1999).

The HFM provides input to the three-dimensional regional ground-water model that is being constructed using MODFLOW 2000 software developed by the USGS (Harbaugh and others, 2000; Hill and others, 2000). MODFLOW 2000 allows the adjustment of hydraulic properties of a cell and the definition of flow barriers between model cells; these barriers may be associated with specific structures, such as many of those identified on maps A and B. Special physical parameters may be explicitly associated with faults, fracture zones, and other specific volumes within MODFLOW. In this way, definition of relevant structures, and iterative assignment of hydrologic parameters to the specific structures or structural zones, facilitates geologically meaningful modeling of ground-water flow.

The hydrogeology of this region was originally addressed in detail by Winograd and Thordarson (1975) and has been the topic of numerous subsequent studies, as summarized in the "Previous Work" section. The DVRFS is underlain primarily by Paleozoic and Proterozoic miogeoclinal rocks, upon which major Miocene calderas and related thick ash-flow tuffs (for example, southwest Nevada volcanic field and central Death Valley volcanic field; Wright and others, 1991; Sawyer and others, 1994) have been superimposed in the north-central and south-central parts of the DVRFS. Major nonmarine sedimentary basins that formed during Neogene extension are also fundamental geologic elements. Regional ground-water flow is mainly northeast to southwest, and the most important regional aquifer is within the lower Paleozoic carbonate section (lower carbonate aquifer). Structurally controlled Tertiary and Quaternary basins contain important discontinuous aquifers (dominated by relatively coarse clastic sediments) over large parts of the DVRFS; facies variations within these basins produce lateral variation in hydrologic properties, so that other basin components (such as fine-grained lake beds) are relatively impermeable. Miocene densely welded tuffs, whose hydraulic conductivity is enhanced by fracture-controlled permeability, form locally important aquifers in the central and southern parts of the DVRFS (Nevada Test Site, Yucca Mountain, Greenwater Range). Metamorphic rocks and intrusive rocks of various ages, Proterozoic and Lower Cambrian clastic rocks (lower clastic confining unit), Mississippian clastic rocks (upper clastic confining unit), and Miocene lavas (volcanic confining unit) are among the poorly transmissive confining units that significantly affect flow. The spatial distribution of all of these confining units and aquifers in the subsurface has a fundamental effect on ground-water flow.

The faults shown on maps A and B are largely from Workman and others (in press), and fit one or more of the following criteria: (1) faults that are more than 10 km in map length; (2) faults with more than 500 m of displacement; and (3) faults in sets that define a significant structural fabric that characterizes a particular domain of the DVRFS. We have highlighted faults that have late Pleistocene to Holocene displacement (Piety, 1996).

Areas of thick Neogene basin-fill deposits (thicknesses 1–2 km, 2–3 km, and >3 km) are shown on map A, based on gravity anomalies and depth-to-basement modeling by Blakely and others (1999). Most basins are defined largely by normal faults; in Death Valley, pull-apart basins are controlled by extensive strike-slip faults. We have interpreted the positions of faults in the subsurface, generally following the interpretations of Blakely and others (1999). Where geophysical constraints are not present, the faults beneath late Tertiary and Quaternary cover have been extended based on geologic reasoning. Nearly all of these concealed faults are shown with continuous solid lines on maps A and B, in order to provide continuous structures for incorporation into the HFM.

An interpretation of the subsurface fault geometry in the DVRFS is portrayed on a network of cross sections (Sweetkind and others, 2001) that have also been constructed in support of the HFM. Maps A and B have been constructed to be consistent with, and complementary to, this cross section network.

This report was prepared in cooperation with the Nevada Operations Office, U.S. Department of Energy, under Interagency Agreement DE-AI08-96NV11967.

PREVIOUS WORK

The hydrogeology of the DVRFS has been the subject of a variety of investigations over the past several decades. Winograd and Thordarson (1975) provided a comprehensive hydrogeologic summary of a region of southwestern Nevada and southeastern California centered on the Nevada Test Site. They characterized ground-water flow, mainly in the "Ash Meadows ground-water basin," and also in the "Oasis Valley–Fortymile Canyon" and "Pahrump Valley" ground-water basins; together, these three basins correspond closely to the region now included within the DVRFS. Winograd and Thordarson (1975) synthesized hydrologic data and observations, hydrochemistry, regional stratigraphy, and regional geologic structure to produce many concepts that guided later work. They developed a strong case for regional interbasin flow within the lower carbonate aquifer, and this concept was further developed by Winograd and Pearson (1976), who used isotopic studies in ground water discharged at Ash Meadows (map A) to define possible fast pathways for regional flow in this aquifer. Dudley and Larsen (1976) studied the effects of agricultural water-well pumping on water levels at Devils Hole (a water-producing cavern in Paleozoic carbonates on the margin of Ash Meadows), and they proposed specific mechanisms and flow paths for ground-water discharge in the Ash Meadows area. Dettinger (1989) summarized regional characteristics and local variations in the lower carbonate aquifer.

Bedinger and others (1989b) coordinated a major synthesis of ground-water systems in the arid southwestern United States. As a part of this effort, an 80,000-km^2 "Death Valley Region" (similar to the DVRFS in the present study) was investigated in southwestern Nevada and adjacent parts of California. This is essentially a regional ground-water basin that comprises several smaller ground-water units (Bedinger and others, 1989a). Grose and Smith (1989) summarized the geology and constructed a set of regional cross sections in support of hydrologic characterization of the Death Valley region.

Since 1980, numerous studies have been undertaken to characterize the hydrology and hydrogeology at Yucca Mountain, the potential site of a geologic repository for high-level nuclear waste. These studies have included both unsaturated-zone and saturated-zone hydrology, stratigraphic studies, and geologic mapping (Office of Civilian Radioactive Waste Management, 1988). Hydrogeologic units were established, reflecting the variations in physical properties through the Tertiary volcanic and sedimentary section (U.S. Department of Energy, 1988). Luckey and others (1996) summarized the saturated-zone hydrology and hydrogeology of Yucca Mountain, including considerations of the effects of faulting. Scott and Bonk (1984), Day, Potter, and others (1998), Day, Dickerson, and others (1998), and Dickerson and Drake (1998) produced detailed geologic maps showing faults and fracture zones that may affect the hydrologic behavior of volcanic rocks in and near the potential repository. A three-dimensional numerical model of ground-water flow beneath Yucca Mountain was completed (C.C. Faunt, USGS, written commun., 2000); documentation for this model resides in the Yucca Mountain Project technical document data base.

Laczniak and others (1996) summarized the hydrogeologic controls on ground-water flow at the Nevada Test Site (boundary shown on maps A and B). They used hydrologic and geologic data to identify probable pathways for ground-water flow away from possible sources of radioactive contaminants. In so doing, they further developed concepts on stratigraphic and structural controls on flow in the Tertiary volcanic rocks and in the pre-Tertiary rocks, and identified areas where flow directions and rates are uncertain. Laczniak and others (1996, their plate 1) also produced a map that illustrates major controls on ground-water flow and directions of flow over much of the DVRFS.

To better understand ground-water flow in the vicinity of the Nevada Test Site and Yucca Mountain, the U.S. Department of Energy funded the development of three-dimensional numerical models of the regional ground-water system by the

IT Corporation (1996) and by the USGS (D'Agnese and others, 1997). Both efforts involved the construction of three-dimensional geologic framework models and assignment of hydrologic parameters to individual cells within these framework models, to allow modeling of ground-water recharge, flow, evapotranspiration, and discharge using an earlier version of MODFLOW software. In support of the USGS ground-water model, Faunt and others (1997) constructed a hydrogeologic map of the DVRFS, and summarized the approach for construction of the geologic framework. Of particular relevance to the present study, Faunt (1997) discussed the possible significance of faulting to regional ground-water flow, and the treatment of faults in the USGS flow model for the region. The present modeling effort has been undertaken to unify, reconcile and update these two (IT and USGS) three-dimensional numerical ground-water models.

REGIONAL STRUCTURAL FRAMEWORK

Regional faults shown on maps A and B include pre-Tertiary thrust faults, Neogene normal faults, and Neogene strike-slip faults. The fault distribution and style reflect the tectonic history of the region, wherein an early Paleozoic passive continental margin was subjected to late Paleozoic through Cretaceous(?) southeast-vergent thrusting, and the thrust-faulted and folded Paleozoic rocks were profoundly disrupted by Neogene extensional and strike-slip structures along the southwest margin of the Basin and Range province (Wernicke and others, 1988; Snow, 1992). This history has been summarized by Workman and others (in press), who have also summarized the nature of many of the principal structural features on maps A and B.

Thrust faulting in the region was either very protracted, or it occurred in more than one phase, with younger thrust faults situated south and east of older thrusts. In the western part of the DVRFS, the south- and southeast-directed thrusting (and associated folding) that affected the Paleozoic and Proterozoic section is as old as Permian (Snow, 1992). Latest movements on frontal thrusts in the vicinity of Las Vegas were late Early Cretaceous or younger, based on geologic relations observed along the Keystone thrust, where the Cambrian Bonanza King Formation is thrust over Jurassic nonmarine sedimentary rocks and late Early Cretaceous synorogenic strata (Fleck and Carr, 1990). Stratigraphic throws of several kilometers occurred along major thrusts, and offsets in regional facies trends indicate horizontal displacements as much as several tens of kilometers (Fleck, 1970; Snow, 1992).

Fourteen thrust faults are shown on maps A and B, but they may represent only a few regionally continuous Paleozoic and Mesozoic structures that were disrupted by Neogene extensional and strike-slip faulting. Beneath Cenozoic basins, the locations of buried thrust faults are inferred and projected based on regional geologic relations, and are consistent with the locations of thrust faults on the cross sections constructed for the DVRFS by Sweetkind and others (2001). In the Nevada Test Site area, structural studies by Cole and Cashman (1999) served as a guide for such projections.

In some cases, thrust faults have been largely reactivated by younger extensional faults; in these cases, the faults are shown as extensional faults rather than thrusts on maps A and B. Examples include the Bat Mountain extensional fault that reactivated the Clery thrust in the southern Funeral Mountains (Cemen and others, 1999), the low-angle detachment that reactivated the Panama thrust at Bare Mountain (Monsen and others, 1992), and the Marble Canyon thrust in the Cottonwood Mountains.

Neogene deformation in the DVRFS is characterized by a variety of structural patterns that overlap in space and time, including: (1) Basin and Range extension along high-angle and low-angle normal faults; (2) development of discrete strike-slip faults and transtensional basins within the Walker Lane belt and the Las Vegas Valley shear zone (LVVSZ); and (3) huge Miocene caldera complexes with thick infilling that both preceded and temporally overlapped regional extension.

The basin-and-range extensional style is most clearly expressed in the northeastern part of the DVRFS (maps A and B). There, the north-south trending basins generally have asymmetric cross sections, with a dominant normal fault producing a half-graben geometry. These normal faults generally dip 50°–65° and have accommodated as much as 3 km of displacement. Gravity data (Healey and others, 1981) strongly suggest that some of the larger faults are concealed beneath surficial deposits, basinward of the obvious range-front faults. At depth, several major west-side-down normal faults in the northeastern part of the DVRFS (west of and including the Sheep Basin normal fault) are inferred to flatten and converge at depth into a deep detachment zone, the Sheep Range detachment (Guth, 1981, 1990; Wernicke and others, 1984). In other parts of the DVRFS, such as at Yucca Mountain, closely spaced north-striking normal faults apparently do not sole into a gently dipping detachment at depth (Brocher and others, 1998).

In the southwestern part of the DVRFS (Bare Mountain–Amargosa Desert–Death Valley area), there are several gently to moderately dipping, large-offset extensional detachment faults (maps A and B) with broadly domed metamorphic complexes in their lower plates. The upper plates are commonly highly extended and tilted along normal faults that sole into the detachment faults. Although these detachment faults generally have gentle dips, the fault surfaces locally have dips of 50°–60° (Badwater Turtleback fault, Black Mountains, Miller, 1991; Fluorspar Canyon detachment, Bare Mountain, Monsen and others, 1992). The major extensional fault systems represented by the large detachments likely worked in concert with major northwest-striking strike-slip faults (such as the Death Valley–

Furnace Creek system and the Stewart Valley–Pahrump fault zone) to accommodate Neogene transtension.

The large northwest-striking strike-slip faults, prominent in the southwest half of the DVRFS, are generally buried beneath Neogene basins, although the traces of some of the faults are defined by Quaternary fault scarps in the basins (Anderson, Bucknam, and others, 1995a; Anderson, Crone, and others, 1995b; Piety, 1996). Gravity data (Blakely and others, 1998, 1999) portray a structurally complex pre-Tertiary surface adjacent to these faults consisting of steep-sided local depressions and ridges that must be fault bounded and probably represent local contraction and extension within the overall strike-slip environment (Wright, 1989).

In addition to northwest-striking strike-slip faults, Carr (1984) emphasized the significance of northeast-trending fault zones, or series of fault zones, such as the Mine Mountain–Spotted Range structural zone, which essentially occupies the area between Yucca Mountain, Yucca Flat, and Mercury, including all of the Specter Range, Rock Valley, and adjacent areas. This structural zone is described as a broad zone of small northeast-striking faults and fractures, some of which have demonstrable sinistral strike-slip motion on them; it is also associated with numerous small seismic events (map B). Carr (1984, 1990) also emphasized a zone of minor northeast-striking faults, associated with active seismicity, in the Slate Ridge area northeast of the northern terminus of Death Valley.

The varying intensity of Neogene extension and strike-slip faulting in the DVRFS has produced considerable variation in the nature of the preservation of older thrust structures. For example, the Spring Mountains are a high-standing, relatively unextended block that preserves most of the geometry of the Sevier thrust belt. In contrast, discontinuous fragments of thrust faults are preserved in more highly extended and tilted ranges such as the Montgomery Mountains and the Resting Spring and Nopah Ranges to the west of the Spring Mountains.

Miocene caldera boundaries dominate the Neogene structure of the north-central part of the DVRFS (Byers and others, 1976; Sawyer and others, 1994). The arcuate structural boundaries of the nested calderas of the southwest Nevada volcanic field and other Miocene calderas in the region, as defined by Slate and others (2000), are shown on maps A and B. These boundaries are marked by faults that generally have arcuate map traces and dip inward toward the caldera's center. The greatly thickened tuff sections within the calderas attest to the collapse of major silicic volcanic centers along the arcuate structural boundaries. The Thirsty Canyon lineament (corresponding to feature 14 of Grauch and others, 1999; their figure 7 and table 4) is interpreted from geophysical data to be a pre-existing fault zone that was later exploited to form the straight northwestern boundaries of the Silent Canyon and Timber Mountain caldera complexes (Grauch and others, 1999).

The central Death Valley volcanic field (Greenwater Range and Black Mountains, southern part of the DVRFS) is not associated with large calderas. It is composed of a series of lava flows and nonwelded to densely welded tuffs that were derived from localized volcanic centers rather than climactic caldera-forming eruptions (Wright and others, 1991). This is expressed on map A as a yellow polygon (designating Cenozoic fill 1–2 km thick) with no associated faulting in the western part of the Greenwater Range.

HYDROGEOLOGIC ROLE OF FAULTS

Five hydrogeologic effects of faulting in the DVRFS were considered in this study: (1) fault juxtaposition of stratigraphic units with contrasting hydrologic properties, resulting in ground-water discharge and other perturbations in the regional flow system; (2) special physical characteristics of the fault zones themselves, as a result of brecciation, fracturing and other processes, that may cause specific parts of the fault zone to act as conduits or barriers to flow; (3) the influence of specific lithologies on the hydrologic behavior of faults; (4) the influence of the contemporary stress field on the hydrologic behavior of faults and fractures; and (5) the hydrologic behavior of active faults and seismically active areas.

SPRINGS LOCALIZED ALONG NEOGENE FAULTS

Juxtaposition of contrasting hydrostratigraphic units along Neogene normal faults has been instrumental in localizing significant ground-water discharge. The line of springs in Ash Meadows (map A), responsible for an aggregate discharge of 100,000 m^3 per day (D'Agnese and others, 1997), is localized along the gravity fault, which places the lowest part of the lower carbonate aquifer (to the east, on the footwall) against the Tertiary and Quaternary sediments (to the west, on the hanging wall). Regional northeast-to-southwest ground-water flow is likely diverted to the surface where the base of the lower carbonate aquifer (equals top of lower clastic confining unit) is juxtaposed against the low-permeability, basin-fill materials across the gravity fault (Winograd and Thordarson, 1975). Discontinuous local aquifers (coarse clastic material and travertine deposits) within the basin fill provide flow paths to discharge sites near the basin margin (Dudley and Larsen, 1976).

At Oasis Valley, northeast of Beatty, Nev., a cluster of springs (14,500 m^3/day aggregate discharge; D'Agnese and others, 1997) is localized just west of the Hogback normal fault (map A). Grauch and others (1999) proposed that these springs are localized by the juxtaposition of permeable volcanic rocks, on the east side (hanging wall) of the fault, against the lower clastic confining unit, which underlies the volcanic cover on the west side (footwall) of the fault. Westward-flowing ground water in the volcanic rocks is forced to the surface where it encounters the lower clastic confining unit across the Hogback fault (Grauch and others, 1999).

Near Furnace Creek Ranch in Death Valley, several clusters of springs (aggregate discharge 11,000 m^3/day; D'Agnese and others, 1997) appear to be localized by fault juxtaposition of contrasting hydrostratigraphic units. In this case, the strike-slip Furnace Creek fault zone has a significant component of down-to-the-southwest displacement, juxtaposing the lower carbonate aquifer (to the east) against Miocene sedimentary rocks (to the west). Several subsidiary faults, west of the main Furnace Creek fault, as well as the normal fault that bounds the western front of the Black Mountains, involve Miocene sediments and younger valley-fill and playa deposits. Southwest-flowing ground water that bears the chemical signature of regional flow in the lower carbonate aquifer (Winograd and Thordarson, 1975) is diverted to the surface, most likely because of contrasting hydraulic conductivities across these faults.

JUXTAPOSITION OF CONTRASTING UNITS ALONG THRUST FAULTS

The thrust faults included on maps A and B are those of regional extent that juxtapose lithologic units with contrasting hydraulic conductivities. For example, thrusts that place the lower clastic confining unit above the lower carbonate aquifer, such as the Specter Range and Schwaub Peak thrusts, are included. Although the outcrop traces of such thrust faults are not commonly associated with spring discharge (with one exception, discussed in the following paragraph) they are capable of causing significant regional diversion of ground-water flow. In general, because the Spring Mountains record little Neogene extension, the relatively continuous thrust faults that are shown there likely are the dominant hydrostructural elements. In other areas of the DVRFS, where thrust faults are disrupted by Neogene faults, these older geologic patterns have been segmented, and the overall hydrostructural framework is more complex.

Willow Spring and Cold Creek Spring, at the foot of the Spring Mountains about 17 km south of Indian Springs, may be examples of ground-water discharge controlled by thrust-fault juxtaposition of hydrostratigraphic units. These springs are essentially on the trace of the Wheeler Pass thrust, which places the lower clastic confining unit above upper Paleozoic carbonate rocks. Ground water flowing northwestward within the carbonate rocks from recharge areas in the Spring Mountains is forced to the surface where it encounters the lower clastic confining unit at the Wheeler Pass thrust.

SPECIAL PHYSICAL CHARACTERISTICS OF FAULT ZONES

At the depths included within the DVRFS ground-water model (the upper 2 km of the Earth's crust), the faults shown on maps A and B are brittle faults. Brittle faults (characterized by breakage of mineral grains rather than by crystal-plastic flow) can act either as barriers or as conduits to flow, depending on the architecture of the fault zone and specific rock types involved. For example, many brittle fault zones contain a narrow core of finely comminuted, relatively impermeable gouge, which is the locus of most of the actual fault displacement (Caine and others, 1996). The core zone is flanked by highly fractured "damage zones" along the margins of the fault zones that have high fracture permeabilities and large hydraulic conductivities parallel to the fault zones (Caine and others, 1996). Thus, there may be significant anisotropy associated with this type of fault zone. Contrasting water levels and water chemistry across faults in the Yucca Mountain–Crater Flat area provide evidence that some normal faults in volcanic rocks impede cross-fault flow (Luckey and others, 1996, p. 25–29), and thus help to compartmentalize the flow system.

Most of the faults shown on maps A and B have the core zone/damage zone architecture described by Caine and others (1996). The width of the relatively impermeable core zone is commonly 0.5–1.0 m for high-angle normal faults in volcanic rocks at Yucca Mountain and in carbonate rocks in the Specter Range, and for the Point of Rocks detachment (low-angle normal fault) in the northern Spring Mountains. For these normal faults, the surrounding more permeable damage zones vary in width from 10 to 100 m. Dettinger (1989) reported enhanced transmissivities in normal-faulted carbonate rocks, where measured in wells drilled for the U.S. Air Force's MX missile-siting program in Coyote Springs Valley, Nev.; these transmissivities are 20–40 times those measured in relatively undeformed carbonates in Army well 1 near Mercury, Nev., and they likely occur in a broad fault-related damage zone.

Major strike-slip faults occupy broad valleys in the DVRFS and have notoriously poor exposure, so we have no direct observations of the core zone of these structures. In general, large-displacement strike-slip faults are characterized by a continuous, relatively impermeable core zone (Chester and Logan, 1986). Flow barriers along strike-slip faults, though effective locally, may be regionally discontinuous. Chester and Logan (1986), for example, noted considerable variations in the thickness of the core zone (5 cm to 1 m) along an inactive strand of the San Andreas fault. Thus, it seems likely that core zones could become irregular and discontinuous locally; this may apply particularly in cases where strike-slip fault zones contain branching and anastamosing strands (such as the Pahrump area along the Stewart Valley–Pahrump fault system).

Within the DVRFS, flow barriers in the Indian Springs area may be caused by impermeable fault gouge along strands of the LVVSZ; spring discharge at Indian Springs may reflect upward flow of ground water against an impermeable fault barrier (Winograd and Thordarson, 1975). Springs in northern Death Valley may be localized for similar reasons along the Northern Death Valley–Furnace Creek fault zone.

The nature and width of damage zones associated with strike-slip faults may vary greatly, depending on whether it is an area of a releasing or restraining bend, or in the vicinity of a fault termination. Sibson (1986) associated broad zones of distributed crushing with restraining bends, and bodies of "implosion breccia" with releasing bends. [Implosion breccia is produced by implosion of rock fragments into void space created by rapid fault slip, commonly accompanied by hydrothermal mineralization; Sibson (1986).] In the Mercury–Indian Springs area, where there is a major restraining bend in the LVVSZ, Paleozoic rock is brecciated for a distance of several kilometers along the northeast side of the fault. This is probably an example of the distributed crushing predicted by Sibson (1986). Locations of significant releasing bends along strike-slip faults in the DVRFS include (1) the Death Valley fault zone along the west side of the Black Mountains; (2) the prominent southeasterly bend in the Furnace Creek fault as it merges into its breakaway zone along the western front of the Resting Springs Range; and (3) two places along the Stewart Valley–Pahrump fault zone, one near Stewart Valley, and the other southwest of Big Dune in the Amargosa Desert.

Around the margins of high-grade metamorphic bodies (metamorphic core complexes), such as those in the Black Mountains, Funeral Mountains, and Bare Mountain, moderately to gently dipping brittle detachment faults are superimposed on ductile fault zones. The core zone for the brittle detachment exposed around the turtlebacks in the Black Mountains is commonly less than 1 m wide; the fractured and faulted hanging-wall damage zone can exceed 100 m above these and similar metamorphic core complexes, whereas the footwall damage zone is commonly only one-tenth this thickness. These brittle detachments transmitted water in the past, as evidenced by veining and mineralization observed in present-day exposures; such processes occurred at depths of several kilometers and partially sealed these structures. The ductile extensional faults that formed at high temperatures in the middle crust lie in the footwalls beneath the brittle detachments. Although the ductile faults have great tectonic significance, they formed through high-strain crystal-plastic behavior rather than fracturing, and are considered to share the low permeabilities that characterize the metamorphic complexes.

The physical characteristics of thrust faults are variable. The core zone for the Specter Range thrust is several meters thick, and the development of the damage zone is highly variable, based on our observations in the Specter Range.

LITHOLOGIC CONTROL ON THE HYDROLOGIC BEHAVIOR OF FAULTS

The specific rock types involved in faulting may greatly influence the hydrologic properties of a fault. Where faults cut mudstones or shales, clay-rich materials may be smeared along the fault surface, producing a barrier to flow. Where low-angle normal faults that formed at shallow crustal levels cut sandstone and quartzite-rich units, "ball-bearing style" brecciation may greatly enhance local permeability. For example, the Point of Rocks low-angle normal fault in the northern Spring Mountains has Proterozoic quartzite-rich clastic rocks in its lower plate. These rocks, which regionally compose the lower clastic confining unit, locally have enhanced permeability where affected by the extensional faulting.

Normal-faulted carbonates may possess high-permeability fracture networks in damage zones, as discussed in the previous subsection. Where this fracture-controlled flow produces preferential dissolution of carbonate rock, significant ground-water flow pathways are produced. Dettinger (1989, p. 16) cited USGS geologists' descriptions of "flow tubes" along major fault zones in the Muddy River Springs area (east of the DVRFS), as resembling "long, narrow caves—that evidently formed during transmission of large volumes of water…". During reconnaissance field investigations, we observed an orifice associated with the Point of Rocks Spring on the normal-faulted bedrock margin of Ash Meadows (map A), where ground water issues from a hillside through a 10- to 20-cm-diameter void in the Cambrian Bonanza King Formation; this void appears to be tube-like, extending back into the bedrock beneath the hillside. Devils Hole, also on the margin of Ash Meadows (map A), is a much larger example of a fault-controlled dissolution feature in carbonate rock. Winograd and Thordarson (1975, p. C16) characterized Devils Hole as a "water-filled funnel-shaped cavern" that is controlled by a steeply dipping, northeast-striking fault. Dudley and Larsen (1976, p. 10) noted that "Devils Hole has resulted from solution enlargement of a fault zone and from subsequent collapse of the roof and walls into the cavern." Solution passages extend more than 111 m (365 ft) below the land surface (Winograd and Thordarson, 1975). These examples demonstrate local dissolution of carbonate rock along faults, rather than widespread karstic development throughout the DVRFS. Considering the latter possibility, Winograd and Thordarson (1975) noted that the numerous small isolated caves in carbonate rocks in the region are not interconnected and are absent on dip slopes, supporting a conclusion that the caves most likely originated subaerially as weathered-out blocks isolated by joints or faults.

INFLUENCE OF THE CONTEMPORARY STRESS FIELD

Faunt (1997) developed the concept that faults in the DVRFS may be conduits or barriers to flow depending on their orientation relative to the present-day stress field; faults in relative tension (north to northeast striking) would be transmissive, and those in relative compression (northwest striking) would be barriers to flow. She showed how the contemporary stress field varies locally within the DVRFS, based on in situ stress measurements, earthquake focal mechanisms, and geologic evidence, and used this analysis to determine the relative conductivities along the various mapped faults (Faunt, 1997). This approach is supported by the work of Barton and others (1995), who used downhole analyses at Cajon Pass and Long Valley, Calif., and at Yucca Mountain, Nev., to show that critically stressed fractures and faults have much higher permeabilities than those not optimally oriented for failure in the current stress field. Ferrill and others (1999) proposed that the closely spaced, dominantly north-northeast-striking faults at Yucca Mountain should produce a strong anisotropy in the hydraulic conductivity; ground-water flow should be enhanced in a north-northeasterly direction, parallel to faults and fractures that are nearly perpendicular to the minimum horizontal stress direction. Given the presence of fracture-filling mineralization (dominantly calcite and quartz) and a variety of faulting styles, it is not clear that the orientation of faults in the present-day stress field would be the governing factor in fault-zone permeability, but it is a contributing factor that should be considered.

ACTIVE FAULTS AND CONTEMPORARY SEISMICITY

Seismically active faults and potentially active faults have been shown to be important hydraulic conduits in other areas, based on monitoring of in situ stresses and fluid flow in fractured and faulted rock (Barton and others, 1995) and on geologic evidence for syntectonic fluid flow in exposures of ancient fault zones. Accordingly, zones of active seismicity and very young faults may be of special interest from a hydrologic standpoint. Sibson (1994) emphasized that freshly ruptured faults should become highly permeable, if tortuous channel-ways, but that rupture-zone permeability is likely to be short lived. This is because hydrothermal flow along fractures rapidly leads to precipitation and self-sealing (within100 yr for initial fracture widths of 0.01–1 mm; Bruhn and others, 1990). Thus, it is likely that recurrently active fault zones should have an important effect in any flow system, and that inactive faults may be comparatively less significant as ground-water flow paths.

In applying these concepts to the DVRFS, it is important to recognize that the USGS ground-water flow model is confined to the upper 5 km (or less) of the Earth's crust in a carbonate-dominated province, and that earthquake foci in the region are commonly at considerably greater depths (as much as 15 km). Ruptures that propagate to shallow depths along active faults may be pathways for warm, deeply derived fluids. However, it is not immediately evident how the concepts of transient permeability structure along active faults at seismogenic depths would apply to physical, geochemical, and hydrochemical processes along active fault ruptures in the shallow crust.

The eastern California shear zone, which encompasses Death Valley, Owens Valley, and the intervening part of southeastern California, has accommodated a significant component of the distributed right-lateral displacement between the Pacific and North American plates in Neogene time (Bennett and others, 1999). Within this broad zone, regional seismicity patterns and geodetic and geologic studies indicate that the locus of major tectonic activity has shifted to the southwest since Miocene time, from Death Valley into Owens Valley (McKenna and Hodges, 1990; Dixon and others, 1995; Bennett and others, 1999). For this reason, the laterally extensive strike-slip faults through Death Valley proper may no longer be significant hydrologic pathways, even though they record late Pleistocene to Holocene slip (map B).

The DVRFS contains several swarms of minor recurrent seismicity that may be hydrologically important. Map B shows computed epicenter locations, based on seismic monitoring in the 1970's and 1980's (Rogers and others, 1987; Harmsen and Rogers, 1988). Although nuclear explosions on the Nevada Test Site have been removed from the data, many aftershocks triggered by nuclear events remain in the record, particularly in the northern part of the Nevada Test Site (Carr, 1984). Because no seismic events were recorded in that area prior to 1959, the cluster of epicenters in the northern Nevada Test Site is not considered to represent natural seismicity (Carr, 1984).

Young faults and clusters of natural seismicity are highlighted on maps A and B to emphasize their potential hydrologic importance. Faults that have measurable late Pleistocene or younger displacement (Piety, 1996) are designated with a black stipple pattern on maps A and B. Areas of recurrent natural seismicity, which may or may not be related to discrete faults present on the map, are included within the blue-outlined polygons designated with Roman numerals I through V on map B. As described in the section entitled "Zones with potentially large hydraulic conductivities," polygons I–V are zones that have special geologic characteristics, as well as seismicity clusters, that may be consistent with relatively large hydraulic conductivities.

ZONES WITH POTENTIALLY LARGE HYDRAULIC CONDUCTIVITIES

In addition to the hydrologic effects of individual faults, rock deformation affecting broader areas may influence regional ground-water flow. Such subregional deformation might include widespread brecciation and fracturing, either of which could strongly influence the hydraulic conductivity of bedrock. On map B, five specific zones are inferred to have potentially large hydraulic conductivities as a result of special geologic characteristics that result from rock deformation. In addition, all of these zones are characterized by clusters of epicenters that record low-magnitude seismicity not specifically associated with discrete major faults.

Zones I through III are located northeast of the northern part of Death Valley proper. Zone I, in the Slate Ridge–northern Death Valley–Last

Chance Range area, encompasses the intersection between a terrane underlain by highly jointed Jurassic granite (northeast of northern Death Valley) and the northern Death Valley–Furnace Creek strike-slip fault zone (Weiss and others, 1993). The broad zone of steeply dipping, northeast-striking, closely spaced jointing in the granitic rocks at Slate Ridge may have originated during oroclinal bending of the Slate Ridge area (Albers, 1967). Zone II, in the eastern Slate Ridge area, is also largely underlain by the highly jointed Jurassic granite, as well as Proterozoic and Cambrian sedimentary rocks and Tertiary volcanic rocks. Zone III, in the Gold Mountain area adjacent to the northern Death Valley fault zone, is characterized by closely spaced normal faults with a dominant east-west strike that cut both Tertiary volcanic rocks and the underlying Paleozoic carbonate rocks. Faunt (1997) and D'Agnese and others (1997) identified northeast-trending zones, northeast of Death Valley, that may possess enhanced permeabilities, based on geologic concepts developed and illustrated by Carr (1984, 1990). Parts of these zones correspond to zones I through III.

Zone IV, which encompasses the south-central part of the Nevada Test Site, the Specter Range, the large basin south of the Specter Range, and the eastern part of the Amargosa Desert, is underlain principally by the lower carbonate aquifer, as well as by Tertiary volcanic rocks and Proterozoic clastic rocks that are cut by (1) prominent northeast-striking left-lateral faults (such as the Rock Valley and Cane Spring faults); (2) north-striking normal faults such as the "gravity fault" (Winograd and Thordarson, 1975); and (3) myriad minor normal faults in the Specter Range (Sargent and Stewart, 1971). These Neogene faults are superimposed on pre-Tertiary thrust faults including the CP thrust (Cole and Cashman, 1999), the Specter Range thrust (Sargent and Stewart, 1971), and probable higher, steeply dipping thrust splays beneath the Striped Hills (Potter and others, 1999, in press).

Previous workers assigned special second-order hydraulic characteristics to a large tract of ground that corresponds mainly to zone IV. Winograd and Thordarson (1975) and D'Agnese and others (1997) interpreted the broad potentiometric trough (map A), within which the Specter Range and the Spotted Range lie, to be a highly fractured domain in the lower carbonate aquifer. D'Agnese and others (1997) and Faunt (1997) specifically correlated this potentiometric trough with the Spotted Range–Mine Mountain structural zone of Carr (1984). The highly productive line of springs on the margin of Ash Meadows represents discharge of ground water that has passed through this presumed zone of elevated hydraulic conductivity. Within the potentiometric trough, Winograd and Pearson (1976) have hypothesized "megascale channeling" through a highly transmissive corridor that is less than 5 km wide, extending from Mercury Valley southwest to Ash Meadows. This hypothesis is based on the presence of strongly elevated ^{14}C values in Crystal Pool, relative to all other springs in the Ash Meadows area. Winograd and Pearson (1976) suggested that this is evidence for strongly heterogeneous flow in the lower carbonate aquifer, involving northeast-southwest oriented structurally controlled channeling. Elevated $^{87}Sr/^{86}Sr$ values in springs at the south end of the Ash Meadows spring line are probably the signature of ground-water flow from recharge areas underlain by the lower clastic confining unit in the northwestern Spring Mountains (Peterman and Stuckless, 1993). Waters discharging at these southernmost springs may have followed flow paths on the margin of the potentiometric trough, where their isotopic compositions were not fully homogenized relative to the regional ground-water flow in the lower carbonate aquifer. This relation may be further evidence for strongly heterogeneous flow.

Zone V is the broad domain just north of the Las Vegas Valley that appears on geologic maps and satellite images to have been "dragged" into an abrupt oroclinal bend against the right-lateral LVVSZ. A prominent set of northeast-striking, left-lateral strike-slip faults are present in and near the Spotted Range and Indian Springs Valley; the displacement on these faults is consistent with shear imposed by the oroclinal bending. In zone V, early Miocene and older rocks (principally Paleozoic rocks of the lower carbonate aquifer) have undergone strong vertical-axis rotations in a 20- to 30-km-wide zone. Paleomagnetic studies by Nelson and Jones (1987) and Sonder and others (1994) demonstrate that oroclinal bending in the ranges north of the LVVSZ was accommodated by vertical-axis rotation of myriad small blocks, 2–4 km or less in diameter, with the magnitude of vertical-axis rotation increasing toward the LVVSZ. The apparent folding in zone V was accomplished by brittle deformation mechanisms—essentially by myriad minor faults and distributed deformation that are expressed in outcrops as broad zones of tectonic brecciation. Accordingly, zone V is a 30-km-wide zone of distributed brittle shear north of the LVVSZ, accommodated by an irregular array of small faults whose spacing may range from a few meters to a few kilometers. Our reconnaissance investigations show that these rocks contain lenses and tabular bodies that are pervasively brecciated in zones that presumably formed at shallow crustal levels (in the upper several kilometers) during middle Miocene motion on the LVVSZ. The present northeasterly strikes of the stratigraphic units and of the range-bounding faults are favorable for continuing extensional deformation in the present-day stress field. Map B shows a diffuse band of earthquake epicenters crossing the Spotted Range, Indian Springs Valley, and Pintwater Range within zone V. These are predominantly low-magnitude events that may be recording extensional deformation or shear along mid-Miocene zones of weakness within the orocline. The seismicity and the distributed brittle deformation in zone V both suggest that relatively large hydraulic conductivities characterize this sub-region.

SUMMARY

Maps A and B are principally designed to show: (1) regionally significant faults that may influence ground-water flow in the DVRFS; and (2) areas that have special deformational characteristics that may result in enhanced hydraulic conductivities for particular volumes of the hydrogeologic framework for the regional flow model. These faults and deformed areas are shown along with annotation of late Pleistocene to Holocene fault displacement, earthquake epicenters, late Tertiary to Quaternary basins, locations of springs, and the potentiometric surface. This allows users to consider the potential interactions among these features, and their collective impact on ground-water flow in the region.

REFERENCES CITED

Albers, J.P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geological Society of America Bulletin, v. 78, p. 143–156.

Anderson, R.E., Bucknam, R.C., Crone, A.J., Haller, K.M., Machette, M.N., Personius, S.F., Barnhard, T.P., Cecil, M.J., and Dart, R.L., 1995a, Characterization of Quaternary and suspected Quaternary faults, regional studies, Nevada and California: U.S. Geological Survey Open-File Report 95–599, 56 p.

Anderson, R.E., Crone, A.J., Machette, M.N., Bradley, L.A., and Diehl, S.F., 1995b, Characterization of Quaternary and suspected Quaternary faults, Amargosa area, Nevada and California: U.S. Geological Survey Open-File Report 95–613, 41 p.

Barton, C.A., Zoback, M.D., and Moos, Daniel, 1995, Fluid flow along potentially active faults in crystalline rock: Geology, v. 23, p. 683–686.

Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., 1989a, Studies of geology and hydrogeology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste—Characterization of the Death Valley region, Nevada and California: U.S. Geological Survey Professional Paper 1370–F, 49 p., 8 plates.

Bedinger, M.S., Sargent, K.A., Langer, W.H., Sherman, F.B, Reed, J.E., and Brady, B.T., 1989b, Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste; basis of characterization and evaluation: U.S. Geological Survey Professional Paper 1370–A, 41 p., 1 plate.

Bennett, R.A., Davis, J.L., and Wernicke, B.P., 1999, Present-day pattern of Cordilleran deformation in the western United States: Geology, v. 27, p. 371–374.

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

Blakely, R.J., Langenheim, V.E., Ponce, D.A., and Dixon, G.L., 2000, Aeromagnetic survey of the Amargosa Desert, Nevada and California—A tool for understanding near-surface geology and hydrology: U.S. Geological Survey Open-File Report 00–188, 35 p., 2 plates.

Blakely, R.J., Morin, R.L., McKee, E.H., Schmidt, K.M., Langenheim, V.E., and Dixon, G.L., 1998, Three-dimensional model of pre-Cenozoic basement beneath Amargosa Desert and Pahrump Valley, California and Nevada—Implications for tectonic evolution and water resources: U.S. Geological Survey Open-File Report 98–496, 29 p.

Brocher, T.M., Hunter, W.C., and Langenheim, V.E., 1998, Implications of seismic reflection and potential field geophysical data on the structural framework of the Yucca Mountain–Crater Flat region, Nevada: Geological Society of America Bulletin, v. 110, p. 947–971.

Bruhn, R.L., Yonkee, W.A., and Parry, W.T., 1990, Structural and fluid-chemical properties of seismogenic normal faults: Tectonophysics, v. 175, p. 139–157.

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

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025–1028.

Carr, W.J., 1984, Regional structural setting of Yucca Mountain, southeastern Nevada, and late Cenozoic rates of tectonic activity in part of the southwestern Great Basin, Nevada and California: U.S. Geological Survey Open-File Report 84–854, 98 p.

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

Cemen, Ibrahim, Wright, L.A., and Prave, A.R., 1999, Stratigraphy, and tectonic implications of the latest Oligocene and early Miocene sedimentary succession, southernmost Funeral Mountains, Death Valley region, *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic Basins of the Death Valley Region: Geological Society of America Special Paper 333, p. 65–86.

Chester, F.M., and Logan, J.M., 1986, Implications for mechanical properties of brittle faults from observations of the Punchbowl fault zones, California: PAGEOPH, v. 124, p. 79–106.

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

D'Agnese, F.A., Faunt, C.C., and Turner, A.K., 1998, An estimated potentiometric surface of the Death Valley region, Nevada and California, developed using Geographic Information System and automated interpolation techniques: U.S. Geological Survey Water-Resources Investigations Report 97–4052, 15 p., 1 plate.

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

Day, W.C., Dickerson, R.P., Potter, C.J., Sweetkind, D.S., San Juan, C.A., Drake, R.M. II, and Fridrich, C.J., 1998, Bedrock geologic map of the Yucca Mountain area, Nye County, Nevada: U.S. Geological Survey Geologic Investigations Series Map I–2627, scale 1:24,000, 21-p pamphlet.

Day, W.C., Potter, C.J., Sweetkind, D.S., Dickerson, R.P., and San Juan, C.A., 1998, Bedrock geologic map of the central block area, Yucca Mountain, Nye County, Nevada: U.S. Geologic Survey Miscellaneous Investigations Series Map I–2601, scale 1:6,000, 15-p pamphlet.

Dettinger, M.D., 1989, Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development—Summary of findings, 1985–88: Program for the study and testing of carbonate-rock aquifers in eastern and southern Nevada, Summary report 1, State of Nevada, Carson City, Nev., 37 p.

Dickerson, R.P., and Drake II, R.M., 1998, Geologic map of the Paintbrush Canyon area, Yucca Mountain, Nevada: U.S. Geological Survey Open-File Report 97–783, scale 1:6,000, 25-p text.

Dixon, T.H., Robaudo, Stefano, Lee, Jeffrey, and Reheis, M.C., 1995, Constraints on present-day Basin and Range deformation from space geodesy: Tectonics, v. 14, p. 755–772.

Dudley, W.W., Jr., and Larsen, J.D., 1976, Effect of irrigation pumping on desert pupfish habitats in Ash Meadows, Nye County, Nevada: U.S. Geological Survey Professional Paper 927, p. 1–52.

Faunt, C.C., 1997, Effect of faulting on ground-water movement in the Death Valley region, Nevada and California: U.S. Geological Survey Water-Resources Investigations Report 95–4132, 42 p., 1 plate.

Faunt, C.C., Belcher, W.C., D'Agnese, F.A., Sweetkind, D.S., Hill, M.C., and Potter, C.J., 1999, Geologic detail appropriate for modeling the Death Valley regional flow system (DVRFS), Nevada and California: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A–288.

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

Ferrill, D.A., Winterle, James, Wittmeyer, Gordon, Sims, Darrell, Colton, Shannon, Armstrong, Amit, and Morris, A.P., 1999, Stressed rock strains groundwater at Yucca Mountain, Nevada: GSA Today, v.9, no. 5, p. 1–8.

Fleck, R.J., 1970, Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California: Geological Society of America Bulletin, v. 81, p. 1705–1720.

Fleck, R.J., and Carr, M.D., 1990, The age of the Keystone thrust; laser-fusion $^{40}Ar/^{39}Ar$ dating of foreland basin deposits, southern Spring Mountains, Nevada: Tectonics, v. 9, p. 467–476.

Grauch, V.J.S., Sawyer, D.A., Fridrich, C.J., and Hudson, M.R., 1999, Geophysical framework of the southwestern Nevada volcanic field and hydrogeologic implications: U.S. Geological Survey Professional Paper 1608, 39 p.

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

Guth, P.L., 1981, Tertiary extension north of the Las Vegas Valley shear zone, Sheep and Desert Ranges, Clark County, Nevada: Geological Society of America Bulletin, v. 92, p. 763–771.

——1990, Superposed Mesozoic and Cenozoic deformation, Indian Springs quadrangle, southern Nevada, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 237–249.

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

Harmsen, S.C., and Rogers, A.M., 1988, Earthquake location data for the southern Great Basin of Nevada and California—1984 through 1986: U.S. Geological Survey Open-File Report 87–596, 92 p.

Healey, D.L., Snyder, D.B., Wahl, R.R., and Currey, F.E., 1981, Bouguer gravity map of Nevada, Caliente sheet: Nevada Bureau of Mines and Geology Map 70, scale 1:250,000.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00–184, 210 p.

IT Corporation, 1996, Underground Test Area subproject phase I data analysis task (Vol. I)—Regional geologic model data documentation package: ITLV/10972-81.

Laczniak, R.J., Cole, J.C., Sawyer, D.A., and Trudeau, D.A., 1996, Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 96–4109, 59 p., 4 plates.

Luckey, R.R., Tucci, Patrick, Faunt, C.C., Ervin, E.M., Steinkampf, W.C., D'Agnese, F.A., and Patterson, G.L., 1996, Status of understanding of the saturated-zone ground-water flow system at Yucca Mountain, Nevada, as of 1995: U.S. Geological Survey Water-Resources Investigations Report 96–4077, 71 p.

McKenna, L.W., and Hodges, K.V., 1990, Constraints on the kinematics and timing of late Miocene–Recent extension between the Panamint and Black Mountains, southeastern California, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 363–376, 1 plate, map scale 1:5,840.

Miller, M.G., 1991, High-angle origin of the currently low-angle Badwater Turtleback fault, Death Valley, California: Geology, v. 19, p. 372–375.

Monsen, S.A., Carr, M.D., Reheis, M.C., and Orkild, P.P., 1992, Geologic map of Bare Mountain, Nye County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I–2201, scale 1:24,000, 6-p. pamphlet.

Nelson, M.R., and Jones, C.H., 1987, Paleomagnetism and crustal rotations along a shear zone, Las Vegas Range, southern Nevada: Tectonics, v. 6, p. 13–33.

Peterman, Z.E., and Stuckless, J.S., 1993, Isotopic evidence of complex ground-water flow at Yucca Mountain, Nevada, USA, *in* High level radioactive waste management, Proceedings of the Fourth Annual International Conference, Las Vegas, Nev., April 26–30, 1993: LaGrange Park, Ill., American Nuclear Society, v. 2, p. 1559–1566.

Piety, L.A., 1996, Compilation of known or suspected Quaternary faults within 100 km of Yucca Mountain, Nevada and California: U.S. Geological Survey Open-File Report 94–112, 404 p., 2 plates.

Potter, C.J., Sweetkind, D.S., and Dickerson, R.P., 1999, A stacked thrust-ramp interpretation for the Striped Hills, Nye County, Nevada: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A–295.

Potter, C.J., Dickerson, R.P., Sweetkind, D.S., Drake, R.M. II, Taylor, E.M., Fridrich, C.J., San Juan, C.A., and Day, W.C., in press, Geologic map of the Yucca Mountain Region, Nye County, Nevada: U.S. Geological Survey Geologic Investigations Series Map I–2755, scale 1:50,000, pamphlet.

Rogers, A.M., Harmsen, S.C., and Meremonte, M.E., 1987, Evaluation of the seismicity of the southern Great Basin and its relationship to the tectonic framework of the region: U.S. Geological Survey Open-File Report 87–408, 196 p., 1 plate.

Sargent, K.A., and Stewart, J.H., 1971, Geologic map of the Specter Range NW quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ–884, scale 1:24,000.

Sawyer, D.A., Fleck, R.J., Lanphere, M.A., Warren, R.G., Broxton, D.E., and Hudson, M.R., 1994, Episodic caldera volcanism in the Miocene southwestern Nevada volcanic field—revised stratigraphic framework, $^{40}Ar/^{39}Ar$ geochronology, and implications for magmatism and extension: Geological Society of America Bulletin, v. 106, p.1304–1318.

Scott, R.B., and Bonk, Jerry, 1984, Preliminary geologic map of Yucca Mountain, Nye County, Nevada, with geologic sections: U.S. Geological Survey Open-File Report 84–494, scale 1:12,000, 9-p. text.

Sibson, R.H., 1986, Brecciation processes in fault zones—inferences form earthquake rupturing: PAGEOPH, v. 124, p. 159–175.

——1994, Crustal stress, faulting, and fluid flow, *in* Parnell, J., ed., Geofluids—origin, migration and evolution of fluids in sedimentary basins: Royal Society of London, Special Publication 78, p. 69–84.

Slate, J.L., Berry, M.E., Rowley, P.D., Fridrich, C.J., Morgan, K.S., Workman, J.B., Young, O.D., Dixon, G.L., Williams, V.S., McKee, E.H., Ponce, D.A., Hildenbrand, T.G., Swadley, WC, Lundstrom, S.C., Ekren, E.B., Warren, R.G., Cole, J.C., Fleck, R.J., Lanphere, M.A., Sawyer, D.A., Minor, S.A., Grunwald, D.J., Laczniak, R.J., Menges, C.M., Yount, J.C., and Jayko, A.S., 2000, Digital geologic map of the Nevada Test Site and vicinity, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California: U.S. Geological Survey Open-File Report 99–554A, scale 1:120,000, 53-p. text.

Snow, J.K., 1992, Large-magnitude Permian shortening and continental-margin tectonics in the southern Cordillera: Geological Society of America Bulletin, v. 104, p. 80–105.

Sonder, L.J., Jones, C.H., Salyards, S.L., and Murphy, K.M., 1994, Vertical axis rotations in the Las Vegas Valley shear zone, southern Nevada—Paleomagnetic constraints on kinematics and dynamics of block rotations: Tectonics, v. 13, p. 769–788.

Sweetkind, D.S., Dickerson, R.P., Blakely, R.J., and Denning, P.D., 2001, Interpretive geologic cross sections for the Death Valley regional flow system and surrounding areas, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2370, 3 plates, 35 p.

Sweetkind, D.S., Faunt, C.C., Belcher, W.C., D'Agnese, F.A., and Potter, C.J., 1999, Complex geology and hydrology demand a complex flow model—The Death Valley regional flow system (DVRFS), Nevada and California: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A–288.

Turner, A.K., D'Agnese, F.A., and Faunt, C.C., 1996, Digital hydrographic, land use/land cover, and hydrologic unit boundary files for the Death Valley region of southern Nevada and southeastern California processed from U.S. Geological Survey 1:100,000- and 1:250,000-scale digital data files: U.S. Geological Survey Open-File Report 95–362, 21 p.

U.S. Department of Energy, 1988, Site characterization plan, Yucca Mountain site, Nevada Research and Development Area, Nevada: Office of Civilian Radioactive Waste Management, DOE/RW-0199, vol. II, part A, chapter 3 (Hydrology), 241 p. with 18-p. reference list.

Weiss, S.I., Noble, D.C., Worthington IV, J.E., and McKee, E.H., 1993, Neogene tectonism from the southwestern Nevada volcanic field to the White Mountains, California—Part I. Miocene volcanic stratigraphy, paleotopography, extensional faulting and uplift between northern Death Valley and Pahute Mesa, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds., Crustal evolution of the Great Basin and Sierra Nevada: Department of Geological Sciences, University of Nevada, Reno, Nev., Geological Society of America Fieldtrip Guidebook, p. 353–369.

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

Wernicke, B.P., Guth, P.L, and Axen, G.J., 1984, Tertiary extensional tectonics in the Sevier thrust belt of southern Nevada, *in* Lintz, J.P., ed., Western geological excursions: Mackay School of Mines, University of Nevada, Reno, Nev., Geological Society of America, Cordilleran Section, Field Trip Guidebook, p. 473–510.

Winograd, I.J., and Pearson F.J., Jr., 1976, Major carbon 14 anomaly in a regional carbonate aquifer—Possible evidence for megascale channeling, south-central Great Basin: Water Resources Research, v. 12, p. 1125–1143.

Winograd, I.J., and Thordarson, W., 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712–C, 126 p., 3 plates.

Workman, J.B., Menges, C.M., Page, W.R., Ekren, E.B., Rowley, P.D., and Dixon, G.L., in press, Tectonic map of the Death Valley ground-water model area, Nevada and California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2381–B, scale 1:250,000.

Wright, L.A., 1989, Overview of the role of strike-slip and normal faulting in the Neogene history of the region northeast of Death Valley, California–Nevada, *in* Ellis, M.A., ed., Late Cenozoic evolution of the southern Great Basin: Nevada Bureau of Mines and Geology Open–File Report 89–1, Selected papers from a workshop at University of Nevada, Reno, Nev., November 10–13, 1987, p. 1–11.

Wright, L.A., Thompson, R.A., Troxel, B.W., Pavlis, T.L., DeWitt, E., Otton, J.K., Ellis, M.A., Miller, M.G., and Serpa, L.F., 1991, Cenozoic magmatic and tectonic evolution of the east-central Death Valley region, California, *in* Walawender, M.J., and Hanan, B.B., eds., Geological excursions in southern California and Mexico: Geological Society of America Annual Meeting Guidebook 1991, p. 93–127.