aperture to one to two mm. Below about 10 m from the surface, the fractures are 40 to 50 percent filled, primarily with quartz and calcite (DOE95a).

Studies of surface fractures have led to the following general conclusions (DOE97c, SWE96):

- Fracture intensity is a function of lithology, variation in the degree of welding in the tuffs, and, to a lesser extent, proximity to faults
- Connectivity of the fracture network also depends largely on the degree of welding and the lithology
- Width and intensity of fractured zones vary around faults and are related to fault complexity

The degree of welding within the Paintbrush Group has the greatest effect on the overall character of the fracture network with fracture intensity and network connectivity being least in nonwelded or poorly-welded units.

Subsurface studies have indicated that correlation with surface features diminishes as the depth increases because:

- Some faults which displaced units in the Topopah Spring Tuff became inactive before the overlying Tiva Canyon Tuff was deposited
- Many faults are discontinuous so that the displacement may die out between observation points
- Faults commonly spread upward resulting in differing surface and subsurface geometries (DOE97c)

7.1.1.7 Volcanism (Adapted from DOE95a)

To assess the possibilities of disruptive volcanic events, the nature and history of volcanism in the area must be understood. Yucca Mountain consists of silicic volcanic rocks originating from the Timber Mountain caldera complex to the north. A resurgence of silicic volcanism is unlikely since the activity that formed the rocks at Yucca Mountain ceased millions of years ago. However, basaltic volcanism has taken place more recently. Basaltic volcanism is commonly accompanied by the intrusion of dikes into the surrounding rocks and could pose the potential for intrusion into the repository itself if such volcanism occurred close to the repository. Magmatic intrusions could mobilize waste and/or alter ground water pathways. The volcanic history of the Yucca Mountain area is discussed below.

Yucca Mountain is composed of Miocene volcanic rocks erupted from the overlapping Silent Canyon, Claim Canyon, and Timber Mountain calderas between 11 and 15 million years ago. The silicic volcanic tuffs that comprise Yucca Mountain are typical of mid-Tertiary basin and range extensional tectonics in southern Nevada. Yucca Mountain, at the depth of the proposed repository, is comprised of units of the Paintbrush Tuff, a major outflow ignimbrite of the Claim Canyon caldera segment of the Timber Mountain caldera complex (Figure 7-15). During the late Neogene (two to 10 Ma) and Quaternary (0 to two Ma) Periods, small-volume, mostly polygenetic, basaltic centers produced lava flows, air falls, and cinder cones in the area. The silicic and basaltic volcanism are described below.

Silicic Volcanism

The silicic volcanism in the Yucca Mountain area is part of an extensive, time transgressive pulse of mid-Cenozoic volcanism that occurred throughout much of the southwestern United States. Yucca Mountain is in the south-central part of the SNVF, a major Cenozoic volcanic field covering an area of over 11,000 km^2. Magmatism in the region was distributed in linear belts parallel to the convergent plate margin during the Mesozoic Era. In the southwestern United States, a pause or disruption in the belts about 80 Ma formed the Laramide magmatic gap or hiatus, which lasted until renewed silicic magmatism began in the northeastern part of the Great Basin about 50 Ma. Sites of eruptive activity migrated south and southwest across parts of Nevada and Utah, with eruptive centers distributed along arcuate east-west trending volcanic fronts. The most intensive eruptions were at the leading edge of the migrating front, with the most voluminous silicic volcanic activity in the Yucca Mountain area occurring between 11 and 15 Ma. Silicic magmatic activity in the area ceased about 7.5 to 9 Ma. The Yucca Mountain area marks the southern limit of time-transgressive volcanic activity.

Between 10 and 13 Ma, there were two significant changes in the regional volcanic and tectonic patterns: the southern migration of volcanism halted and the composition of the volcanic activity changed. Diminished silicic-eruptive activity migrated in less systematic patterns to the southwest and southeast, leaving a conspicuous amagmatic gap from the southern edge of the Nevada Test Site south to the latitude of Las Vegas.

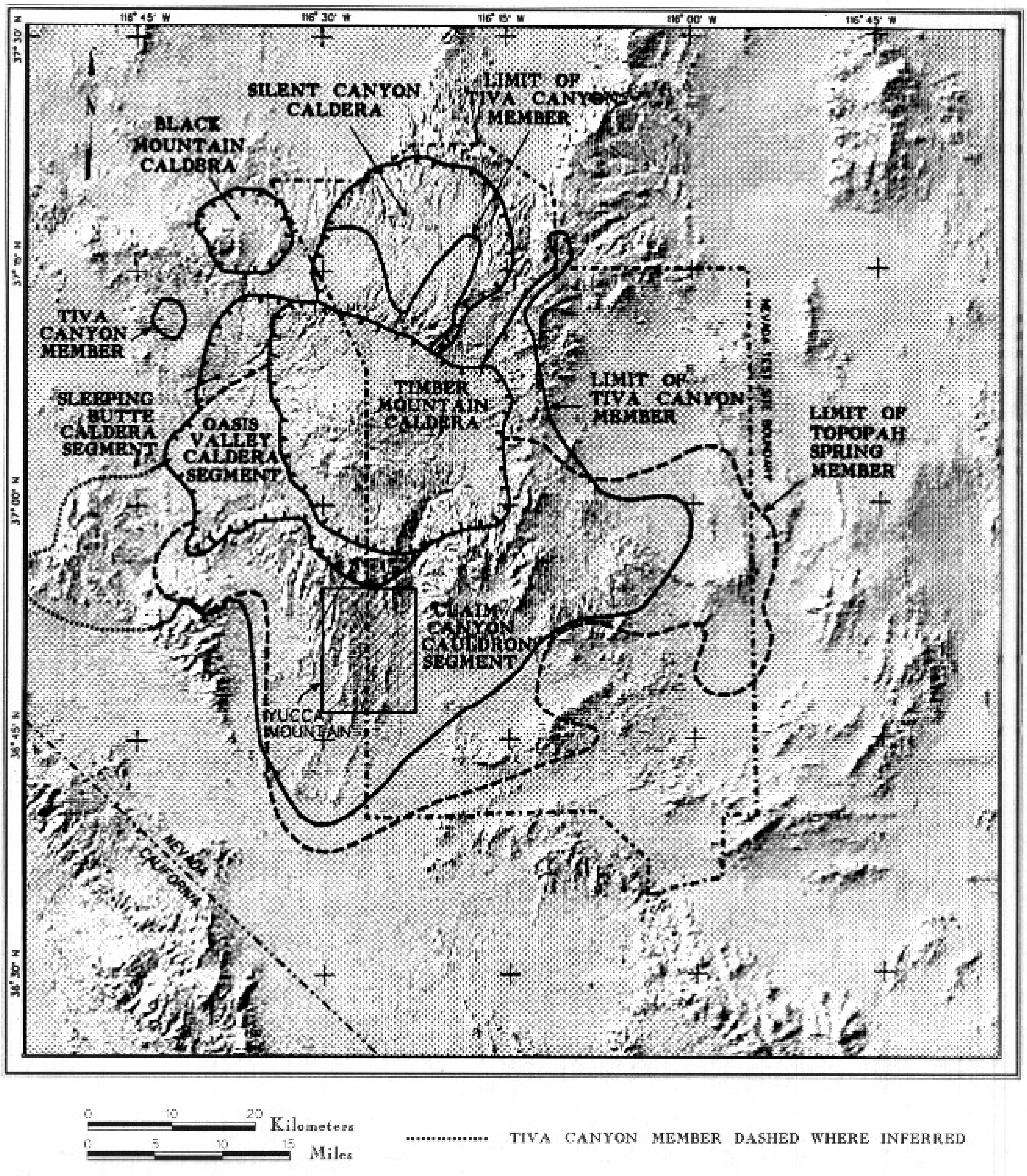

Figure 7-15. Index Map Showing Outlines of Calderas in the Southwestern Nevada Volcanic Field and the Extent of the Tiva Canyon and Topopah Spring Tuffs of the Paintbrush Group (Modified from DOE95a)

Should volcanism occur in the future, the type of volcanism (basaltic or silicic) is potentially significant, since silicic eruptions are more explosive. The DOE claims that there has been no silicic volcanism in the Yucca Mountain Region since about 7.5 Ma at the Stonewall Mountain caldera more than 100 km northwest of Crater Flat and since nine Ma at the closer Black Mountain caldera (60 km northwest of Crater Flat). Consequently, DOE has concluded that the potential for future silicic volcanism is negligible (DOE96e). However, work by NRC suggests that silicic pumice with an age of 6.3 ±0.8 Ma (based on zircon fission track data) existed beneath basalts in Crater Flat. This is at odds with the DOE position that post-caldera silicic eruptions had not occurred near the proposed repository site (NRC97a). Subsequently, NRC reported that, based on argon isotope dating, the age of the silicic material was 9.1 ±3 Ma, which correlates with the eruptions from the Black Mountain caldera (NRC97b). On the basis of this information, NRC concluded that silicic volcanism did not need to be considered in evaluating the probability and consequences of igneous activity at Yucca Mountain.

Basaltic Volcanism

Two episodes producing basaltic-volcanic rocks have been defined in the Yucca Mountain area, both occurring after the majority of the silicic volcanism ended. The first, marked by basalt of the silicic episode (BSE), consists of basalt-rhyolite volcanism postdating most silicic eruptions of the Timber Mountain-Oasis Valley (TM-OV) complex. The second episode is comprised of spatially-scattered, small-volume centers marked by scoria cones and lava flows of alkali basalt, ranging in age from about 10 Ma to less than 10,000 years. These post-caldera basalts of the Yucca Mountain Region are divided into older post-caldera basalts (OPB) and younger post-caldera basalts (YPB). The locations of basalts in the Yucca Mountain Region with ages of less than 12 Ma are shown in Figure 7-16 (NRC96). (The cited ages of some of the occurrences reported by NRC differ slightly from those reported by DOE. The differences are not substantive.)

The BSE crops out throughout the Yucca Mountain area and is identified by several characteristics: (1) a close association (in time and space) with activity of the TM-OV complex, (2) all centers of the BSE are large-volume eruptive units (<3km^3 dense-rock equivalent—the largest centers are in the ring-fracture zone of the Timber Mountain caldera), and (3) a wide range of geochemical composition. The BSE occurs in three major groups:

- **Mafic Lavas of Dome Mountain** (age 10.3 ±0.3 Ma) are exposed in the moat zone of the Timber Mountain caldera and comprise the largest volume of basaltic rocks

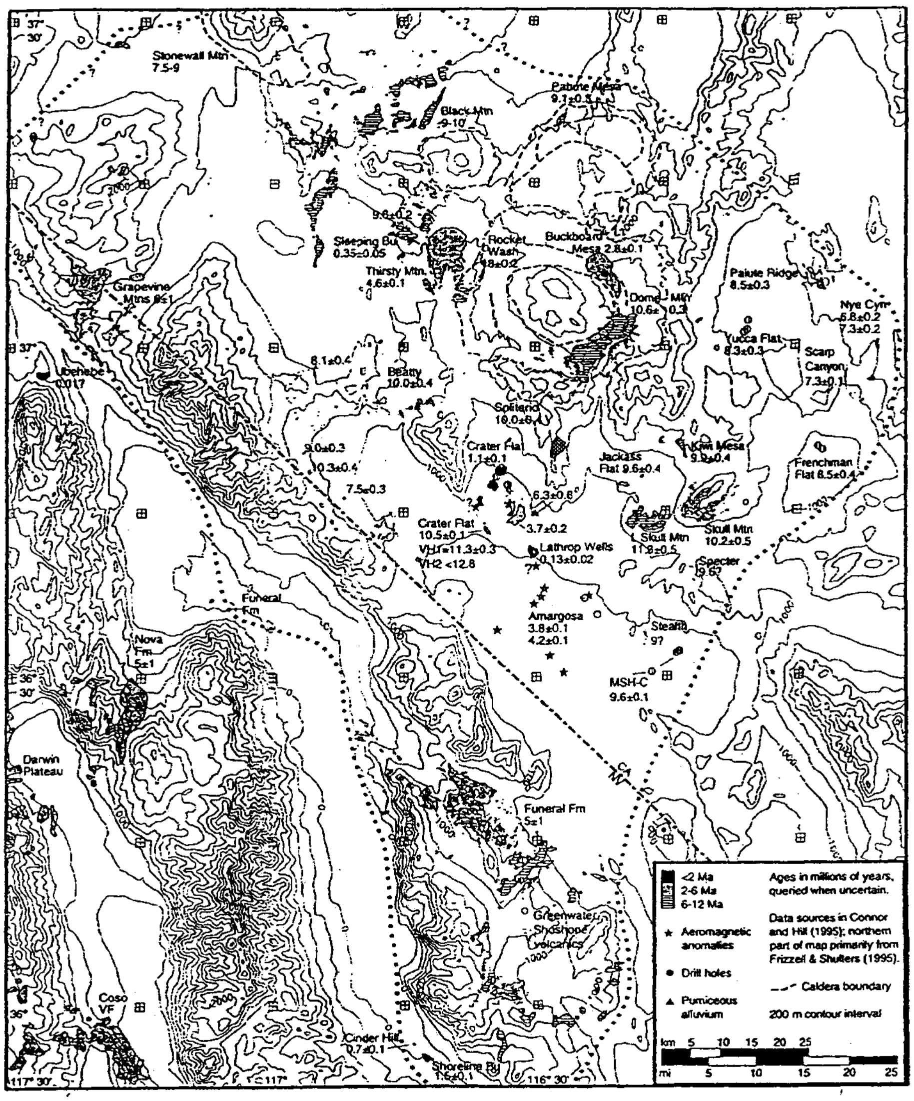

Figure 7-16. Distribution of Basalts in the Yucca Mountain Region with Ages of Less Than 12 MA (NRC96). Dotted line defines boundary of Yucca Mountain/Death Valley isotopic province where basalts have same relatively unique isotopic structure.

- **Basaltic Rocks of the Black Mountain Caldera** overlap some units of the caldera in age

- **Basaltic Volcanic Rocks, Yucca Mountain Area** include the basaltic andesite of Skull Mountain (dated 10.2 ±0.5 Ma), the basalts of Kiwi Mesa, and Jackass Flats

The second episode of basaltic volcanism, marked by the post-caldera basalt of the Yucca Mountain Region, occurred at sites either well removed from the eruptive centers of the TM-OV complex or younger than the silicic-magmatic activity. These sites generally consist of small volume (<1 km^3) centers marked by clusters of scoria cones and lava flows.

The OPB were produced along either north-northwest trending Basin and Range faults or at the intersection of Basin and Range faults with the ring-fracture zone of older calderas. These range in age from 10.4 to 6.3 Ma and are represented at four localities:

- **Rocket Wash**, thin, basalt lava flows (8.0 ±0.2 Ma) occur at the edge of the ring-fracture zone of the Timber Mountain caldera

- **Pahute Mesa**, three separate but related basalts (with ages ranging from 8.8 ±0.1 to 10.4 ±0.4 Ma) occur at the intersection of faults with the ring-fracture zone of the Silent Canyon caldera

- **Paiute Ridge**, dissected scoria cones and lava flows (8.5 ±0.3 Ma) are associated with intrusive bodies occurring at the interior of northwest-trending graben; the related Scarp Canyon basalt (8.7 ±0.3 Ma) crops out west of Nye Canyon

- **Nye Canyon**, three surface basalts (6.3 ±0.2 Ma, 6.8 ±0.2 Ma, and 7.2 ±0.2 Ma) and a buried basalt (8.6 Ma) occur in the Canyon.

The second eruptive cycle, resulting in the YPB, usually occurred at clusters of small-volume centers aligned along predominantly northeast structural trends. These eruptions occurred from 4.9 Ma to as recently as 0.004 Ma and are represented at the following localities (in decreasing age):

- **Thirsty Mesa**, a thick accumulation of fluidal lava and local feeder vents erupted onto a pre-existing Thirsty Canyon Group ignimbrite (welded tuff) plateau (ages of 4.6, 4.68 ±0.3, and 4.88 ±0.4 Ma are reported for various samples)

- **Amargosa Valley**, cuttings from a buried basalt gave ages of 3.85 ±0.05 and 4.4 ±0.07 Ma

- **Southeast Crater Flat** basalt lavas (4.27 to 3.64 Ma) are the most areal-extensive of the YPB

- **Buckboard Mesa** basaltic andesite (3.07 ±0.29 to 2.79 ±0.10 Ma) erupted from a scoria cone in the northeast part of the ring-fracture zone of the Timber Mountain caldera and from nearby fissures

- **Quaternary Basalt of Crater Flat** consists of a series of four northeast trending basalt centers extending along the axis of Crater Flat including the Little Cones (0.76 ±0.20 to 1.1 ±0.3 Ma), the Red and Black Cone centers (1.55 ±0.15 to 0.84 ±15 Ma and 1.09 ±0.3 to 0.80 ±0.06 Ma, respectively), and the Makani Cone (1.66 ±0.5[22] to 1.04 ±0.03 Ma)

- **Sleeping Butte Centers** are two small volume (<0.1 km^3) basaltic centers about 2.6 km apart with an estimated age of 0.38 Ma based on recent argon isotope dating measurements

- **Lathrop Wells Center**, the youngest and most thoroughly studied center of basaltic volcanism, involved multiple eruptions over more than 100,000 years

Three alternative models involving various chronologies of volcanic events have been proposed by DOE to explain the eruptive history of the Lathrop Wells volcanic center. These include a four-event eruption model (eruption at >0.13, 0.08 to 0.09, 0.065, and 0.004 to 0.009 Ma), a three-event eruption model (eruptions at 0.12 to 0.14, 0.065, and 0.004 to 0.009 Ma), and a two-event eruption model (eruptions at 0.12 to 0.14 and 0.004 to 0.009 Ma). Exact dating of the eruptions has been problematic and the exact number and timing of the eruptions is not certain, but the youngest eruption is believed to be less than 10,000 years old. This most recent activity was restricted to minor ash deposits (TRB95).

Summary

The majority of the silicic volcanic rocks that form the most important units in the Yucca Mountain stratigraphic section were deposited about 11 to 15 Ma. This silicic volcanism ceased about 7.5 Ma. Silicic volcanism was followed by two subsequent episodes of basaltic volcanic rock formation. In the first episode, basalts of the silicic episode were deposited about 10 Ma. In the second or post-caldera episode, smaller eruptions occurred beginning 8 to 10 Ma and continuing to near present time. The youngest basaltic rocks at the Lathrop Well volcanic center have ages between 4,000 and 9,000 years.

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[22] This value appears to be an anomaly and will be investigated further.

Both DOE and NRC agree that a future occurrence of silicic volcanism is highly unlikely and therefore the consequences of such an event need not be considered in system performance assessment. However, DOE and NRC have not reached agreement on the treatment of igneous activity associated with possible future basaltic volcanic events.

Given the history of volcanism in the Yucca Mountain Region, there is some probability that a volcanic event can either intersect the repository footprint and directly affect the waste or that a nearby intrusive dike can indirectly affect the natural and engineered barriers. In TSPA-93 (DOE94a), DOE used available data to estimate the impact of indirect magmatic effects, such as heating or attack by aggressive volatiles on waste packages, when contact of the waste packages with magma does not occur. Assuming that the waste packages were vertically emplaced, such that the thermal loading they produced was 57 kW/acre, the magmatic effect on peak drinking water doses is virtually indistinguishable from a case in which magmatic effects are not considered.

In subsequent activities to address the stochastic uncertainty associated with the possibility that a future magmatic event may intersect the repository, DOE convened a panel of 10 experts and used a formal elicitation process to develop disruption[23] probability estimates (DOE96f). Results of the elicitation include (DOE97a):

- A mean annual disruption probability of 1.5×10^{-8}
- A 95 percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8}
- Upper and lower bounds of 10^{-10} to 10^{-7}

The NRC has taken a different tack in establishing the probabilities of volcanic disruption. The NRC approach considers spatial patterns of basaltic volcanism, regional recurrence rates of volcanic activity, and structural controls on volcanism in the Yucca Mountain Region (NRC96). Using two different measures to assess the impact of structural controls on volcanism (density of high dilation-tendency faults and horizontal gravity gradients), two methods to assess spatial-temporal distributions (near-neighbor and Epanechnikov kernel methods) and regional recurrence rates varying from two to 10 volcanoes per million years, calculated probabilities based on NRC's bounding approach ranged from 1×10^{-8} to 2×10^{-7} volcanic disruptions per year (NRC96).

[23] Disruption is the physical intersection of magma with the potential repository volume (DOE97a).

Based on a homogeneous Poisson model (i.e., with a time invariant rate), the probability of at least one volcanic disruption event occurring in 10,000 years, using DOE's estimated maximum (95 percent confidence) disruption rate of 4.9×10^{-8}/y, is 0.0005. Based on the maximum disruption rate estimated by NRC of 2×10^{-7}/y, the probability of at least one disruption is 0.002 in 10,000 years.

In its 1996 Phase 3, Yucca Mountain Total System Performance Assessment, EPRI did not include consideration of volcanism (EPR96). This position was based on an assessment made by one member of the expert panel — one of 10 volcanologists sponsored by DOE — who estimated that the annual probability of a magmatic intrusion into the proposed repository is 1.0×10^{-8}.

Scientists at UNLV, supported by the State of Nevada, have considered a number of alternative modeling approaches to volcanism. (See, for example, HO96 and HO95.) Using a non-homogeneous Poisson model (i.e., with a time varying rate), Ho estimated the probability of at least one disruption in 10,000 years to lie between 0.0014 and 0.03.

DOE investigated the significance to repository performance of basaltic igneous activity in the TSPA-VA (DOE98, Volume 3, Section 4.4.2). Scenarios evaluated included impact of an event where the waste package is breached by the magma and waste is transported to the surface; impact of a magmatic event where the repository footprint is not intercepted but groundwater pathways are altered; and impact of a magmatic event where 0 to 170 waste packages are breached resulting in an enhance source term but no direct transport of waste to the surface. The probability of direct surfaces releases was estimated to be essentially zero for the first 10,000 years due to the ability of the waste package to withstand magmatic attack over the assumed 5 to 40-day period of the intrusive event. Peak dose rates for direct surface releases are several orders of magnitude less than for the TSPA-VA base case after one million years. Peak dose rate CCDFs for the enhanced source term scenario are lower than the base case at both 100,000 and one million years but the scenario can result in spikes in the dose rate that are greater than the base case. DOE estimates that over 10,000 years, there is less than one chance in 1,000 that any igneous activity occurs. If an igneous event into the repository occurs, there is a 60 percent probability that the source term for groundwater transport of radionuclides would be enhanced. If the magmatic event does not intersect the repository footprint, the consequences are negligible.

7.1.1.8 Geologic Stability Issues

The NAS Committee report states that the Yucca Mountain site will exhibit long-term geologic stability on the order of one million years (NAS95). This implies that the contribution of geology to overall system performance can be assessed for that time period. The Committee therefore concludes that there is no need to arbitrarily select a shorter compliance evaluation period, such as 10,000 years. The Committee recommends "...that compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by long-term stability of the geologic environment."

This section examines the Committee's assertion of long-term geologic stability and related issues. Factors addressed include characteristics of the geologic and hydrologic systems implied by the Committee's concepts of "stable" and "boundable;" validity of the assertion of stability; and the significance of stability to the occurrence, magnitude, and evaluation of peak dose. Geologic stability does not imply absence of geologic activity or absence of changes in geologic processes, but rather that any changing characteristics of the system do not introduce uncertainties of sufficient magnitude to compromise the ability to perform credible analyses of future repository performance.

Characterization of Geologic Stability by the NAS Committee

The NAS report (NAS95) does not specifically define geologic stability. The existence of stability is discussed six times in the report, in different ways:

- *The geologic record suggests that [the time frame during which the geologic system is relatively stable or varies in a boundable manner] is on the order of one million years.* (Executive Summary, page 9)

- *...the long-term stability of the fundamental geologic regime [is] on the order of one million years at Yucca Mountain.* (page 55)

- *The long-term stability of the geologic environment at Yucca Mountain ... is on the order of one million years.* (page 67)

- *The time scales of long term geologic processes at Yucca Mountain are on the order of one million years.* (page 69)

- *The time scale for long-term geologic processes at Yucca Mountain is on the order of approximately one million years*. (page 72)

- *The geologic record suggests that [the time frame over which the geologic system is relatively stable or varies in a boundable manner] is on the order of about one million years.* (page 85)

These characterizations of geologic stability are quite similar, although some are expressed in terms of the geologic regime itself and others are described in terms of the processes that operate on or within that regime. These two assertions are not necessarily the same. For example, characteristics of the geologic regime that are important to peak dose evaluation might remain stable while tectonic and other natural processes and events continue in the future, even varying from past characteristics. Alternatively, natural processes and events may continue in the future as they have occurred in the past (i.e., the processes and events exhibit stability), while the effects they produce may change the features of the geologic regime that are important to peak dose evaluation. Conditions in which past and continuing tectonic movement produces differential movement of deep geologic structures might cause changes in the hydrologic regime important to the occurrence of the peak dose. The various expressions of stability used in the Committee's report imply no significant change in either the geologic regime or in the processes and events that affect the characteristics of that regime.

The Committee's report does not explicitly justify the assertion of million-year stability by providing a synopsis and interpretation of the geologic record. Some of the references cited in the report contain information about the geologic record (e.g., DOE's Site Characterization Plan for the Yucca Mountain site (DOE88)), but none of the cited references interprets the record to indicate a million-year stability of the geologic regime or the processes associated with it.

Existing Documentation Related to Stability

Existing documentation does not directly address long-term stability of the natural features of Yucca Mountain and its environs. Until revision of the EPA and NRC regulations for Yucca Mountain was initiated, the DOE documents containing information about the geologic features of the Yucca Mountain site anticipated that evaluations of site suitability would be made in accord with DOE's 10 CFR Part 960 Site Suitability Regulations and anticipated that safety performance of a repository at the site would be evaluated in terms of EPA's 40 CFR Part 191 regulations and NRC's 10 CFR Part 60 regulations. Under this regulatory framework, the time period of concern is 10,000 years. [The NRC's 10 CFR Part 63 regulations and EPA's 40 CFR

Part 197 standards retain this time period. See Section 7.3.11 for a discussion of EPA's rationale.

The 10,000-year time frame for compliance with EPA's 40 CFR Part 191 regulation was selected by the Agency because it was short compared to long-term factors, such as tectonic motion, that might affect and change in ways that could not be characterized, the natural environment conditions important to regulatory compliance evaluations. On the other hand, the time period was long enough to bring into consideration, at least in principle, factors such as seismicity that are important in geologic time scales and might affect repository performance.

The DOE has, in many Yucca Mountain project documents, implied geologic stability or the equivalent for time periods of 10,000 years. The State of Nevada believes, however, that the record does not justify such a conclusion. For example, the State asserted in its comments (NEV85) on DOE's draft Environmental Assessment (DOE84) for the Yucca Mountain site, that DOE's conclusion that "neither major tectonic activity nor the resumption of large-scale silicic volcanic activity in the area near Yucca Mountain is likely in the next 10,000 years" is premature, based on existing evidence. The State also asserted that "possible hydrovolcanic activity at Yucca Mountain has not been sufficiently evaluated" (NEV85, Volume II, page 125).

DOE and others have reported a variety of topical studies concerning geologic and hydrologic phenomena that are relevant to stability of the geohydrologic regime (potential for climate change and its effects are discussed in Section 7.1.3). Topics addressed include:

- Potential for water table rise (SZY89, ARN96, KEM92, NAS92, DOE98)
- Tectonic movement and its potential effects (BAR96)
- Seismicity and its potential effects (CAR91, ARN96)
- Volcanism and its potential effects (DOE96e, DOE96f, HO95, HO96, BAR93)
- Potential for rockfall in drifts and its effects (CRW96, DOW98)
- Potential for changes in the fracture network and fracture flow (MAT97)

Work was recently initiated, and is ongoing, that attempts to use data from fluid inclusions to estimate the potential for heated, ascending fluids to reach the repository horizon in the future (DOE00). Fluid inclusions are small droplets of the solutions that form minerals that are trapped as defects in the growing crystal.

As discussed in Section 7.3.10, information from the studies cited above and other sources will be used in DOE's integrated consideration of features, events, and processes that can affect repository performance in the TSPA evaluations for the Site Recommendation Considerations Report (SRCR) and the Site Recommendation (SR).

The effect of these phenomena on uncertainty in performance assessment results and on the potential to evaluate compliance with regulatory standards at far-future times when peak dose is predicted to occur is discussed in Section 7.3.11.

In general, the documents of record show controversy concerning the stability of the geologic regime and associated natural processes and events at the Yucca Mountain site and the effect of natural processes and events on repository performance. The controversy stems both from opposing interpretations of the available data by DOE and the State of Nevada and by differing definitions of geologic stability. To some extent, the opposing viewpoints reflect the institutional positions of the parties involved; nonetheless, the uncertainties in the data permit alternative interpretations to be made and controversy to persist.

Interpretation of the Geologic Record Related to Stability

The geologic history of the area provides the basis for assertions concerning the stability of the geologic regime for Yucca Mountain and its vicinity. Site characterization activities for DOE's Yucca Mountain project, and other activities unrelated to the Yucca Mountain project (e.g., commercial characterization of natural resource potential), have yielded an extensive data base concerning geologic features and the geologic record of the region. The most comprehensive data available for assessing the geologic stability of the Yucca Mountain site are contained in the Yucca Mountain Site Description (CRW98a).

Such data do not, however, definitively resolve the question of the long-term stability of the geologic regime and its impact on projections of repository system performance. Such issues can be resolved only in context, through the expert judgment of the involved parties. The NAS Committee's assertion of long-term geologic stability at Yucca Mountain for the next million years is an example of expert judgment.

The basis for the Committee's judgment of the geologic stability of Yucca Mountain over the next one million years is the conclusion that the properties and processes of the geologic regime important to repository performance "...are sufficiently understood and stable over the long time scales of interest to make calculations [of repository performance] possible and meaningful"

(NAS95, page 68). The relevant properties and processes include the radionuclide inventory of the waste, the influx of water to the repository, migration of the water and its contained waste materials from the repository to the ground water, and subsequent dispersion and migration of contaminated ground water to the regional biosphere. The Committee considers it possible, for example, to estimate, with acceptable uncertainty, concentrations of wastes in ground water at various locations and times for the purpose of a bounding safety assessment.

The assertion of geologic stability implies a judgment that the basic features of the geologic regime that affect waste release and transport will remain as they are, or change in a limited and reasonably predictable fashion, over the next million years. In other words, phenomena that would substantially and unpredictably change the current, relevant geohydrologic regime are not expected. Such phenomena would include tectonic motion, seismicity, and volcanism sufficient to change the features of the geologic regime that govern radionuclide release and transport.

The Committee's assertions also imply that the geologic and hydrologic features of the site and region can and will be characterized in a way that allows repository performance to be reliably projected on the basis of current conditions. Two of the parameters cited by the Committee as important to predicting the performance of the repository—water influx to the repository and dispersion and migration of ground water in the biosphere—have been demonstrated by DOE modeling studies (e.g., those for the Total System Performance Assessment for the Viability Assessment; TSPA-VA, DOE98) to be highly important to estimating potential health effects from the repository. However, these two parameters are currently among the least well-known of the parameters related to repository performance.

The DOE performance assessment reports indicate that these hydrologic parameters will be extremely difficult to evaluate reliably. As DOE notes in the TSPA-VA, direct observation of water infiltration rates is not possible. Consequently, the TSPA-VA treats the infiltration rate to the repository as an uncertain parameter. Bounding values, consistent with the NAS Committee's concept of bounding, can be established, but the bounds may have to be narrowed considerably from present ranges to be meaningful to the process of determining compliance.

This situation raises an issue not addressed directly by the NAS Committee: Can key performance-related parameters be adequately characterized? The long-term geologic stability of the Yucca Mountain site may be less important to evaluating repository performance than the actual values of those parameters most significant to its performance. As the example given above demonstrates, the variability of a parameter such as infiltration rate presents an obstacle to characterizing reliably the long-term risks to the critical group. In addressing the overall question of long-term repository performance, the uncertainty associated with these factors may be much more significant than the uncertainty associated with the long-term geologic stability of the site.

Summary of Evidence for Stability

The information presented in this chapter generally supports the NAS Committee's assertion that the fundamental geologic regime at Yucca Mountain will remain stable over the next one million years. The overall picture that emerges from the data is that the site and region had a highly dynamic period of volcanism, seismicity, and tectonic adjustment in the past, but these processes and events have matured into a system in which the magnitudes, frequencies, locations, and consequences of such phenomena can be bounded with reasonable confidence relative to assessing the long-term repository performance.

The possible exception to this finding is the chance that on-going processes and events are producing differential changes to the geologic and hydrologic regimes that are currently unrecognized but could affect repository performance and potential radiation risks for affected populations in the future. For example, on-going tectonic processes and movements could potentially have different effects on the geologic and hydrologic regimes near the surface and at depth, and the at-depth changes may not be readily recognizable. At present, tectonic movement in the area varies by location but falls generally within the range of four to 10 mm/year (DOE95a). Over one million years, an annual tectonic movement of 10 mm/year will produce a total translation of location of about 5 miles. If all of the elements of the geologic and hydrologic regime important to repository performance and dose estimation do not move together in space and time, the differential movement could invalidate the results of performance and exposure assessments. The potential for differential movement and its consequences are not yet addressed.

Perspective on the Significance of Stability of the Geologic Regime

A judgment that the geologic regime at Yucca Mountain will be stable for one million years enhances confidence in the results of model-based assessments of the effects of natural processes and events over that time frame on repository performance. Long-term natural phenomena may not, however, control repository performance or uncertainties in performance assessment results. Uncertainties in other factors involved in performance projections may ultimately control the reliability of the projections.

The existence of long-term geologic stability can assure reliable estimation of long-term peak doses only if stability-related issues are confirmed to dominate repository performance and numerical values of relevant parameters have been established with confidence. As discussed subsequently in Section 7.3, DOE's total system performance assessments indicate that the rate of infiltration of water to the repository and the dilution and dispersion characteristics of ground water containing radioactive contamination released from the repository are among the dominant factors in repository performance and dose assessment. The finding that these are among the most important performance parameters has been sustained throughout the evolution of TSPA evaluations and the repository design (see Sections 7.3.1 through 7.3.10).

The DOE's performance assessments to date for Yucca Mountain have emphasized release of nuclides from the repository over a 10,000-year time frame, in response to the requirements of EPA's 40 CFR Part 191 regulations, which were applicable until enactment of the WIPP Land Withdrawal Act. Experience in evaluating repository performance over a 10,000-year time frame (DOE94a, DOE95b) has shown that repository conditions must be assessed at, or near, the time when key performance parameters, such as temperature, may be at their peak values. The 10,000-year time frame encompasses the time of highest uncertainty in the effect of repository design factors important to waste isolation and safety performance. These uncertainties may have a greater effect on predicting long-term repository performance and regulatory compliance than a natural process or event, such as an earthquake or a volcanic eruption. This is due to the high degree of uncertainty in the "nominal" dynamics and performance of the repository's barriers and the low probability of a major natural process or event occurring.

Beyond 10,000 years, however, the technical factors associated with repository design features that dominate performance issues earlier may become less important to determining regulatory compliance at the time of peak dose. If the engineered barrier system is likely to have failed in the long term, radionuclides will be available for transport to the environment. The DOE performance assessment report by Intera, Inc. (DOE94b) states that variations in assumptions and conditions for waste package degradation produce less than a 20 percent variation in results for a 10,000 year assessment period and less than a 10 percent variation in results for a 100,000 year period. Supplemental calculations in DOE94c show that peak doses and releases at the accessible environment boundary over a one million-year period are generally unaffected by waste package lifetimes up to 100,000 years. As discussed in Section 7.3.11, it is in the time period beyond 10,000 years that the issue of long-term geologic stability becomes more important to repository performance.

7.1.2 Hydrologic Features

7.1.2.1 Unsaturated Zone Hydrology

The region beneath the surface of Yucca Mountain in the vicinity of the proposed repository is characterized by a very thick unsaturated zone, ranging in thickness from about 500 to 750 m. The variable thickness is produced by the combined effects of rugged topography and a sloping water table. The presence of a thick unsaturated zone is desirable for siting an underground waste repository because ground water, and any contaminants it might carry, generally travels more slowly through the unsaturated zone than through the saturated zone. The thicker the unsaturated zone, the longer contaminants will take to reach the water table.

In this document, and in the literature generally, the term unsaturated flow actually means partially-saturated flow, since by definition there can be no water flow through a totally dry medium. Unsaturated ground water flow is more complex than fully-saturated flow because it involves the simultaneous movement of water, air and water vapor. For unsaturated media, the measure of permeability is called the effective hydraulic conductivity. The effective hydraulic conductivity, and hence the rate of fluid flow, through any given partially-saturated porous medium depends on the degree of saturation of that medium. The higher the saturation, the greater the quantity of water that can flow through it, all other factors (saturated hydraulic conductivity, hydraulic gradient, etc.) being equal. As the degree of saturation reaches 100 percent, the effective hydraulic conductivity approaches fully-saturated hydraulic conductivity. The dependency between degree of saturation and effective hydraulic conductivity is complex, due to the nonlinearity of the relationship.

The dependence of unsaturated flow on the degree of saturation is important to understand when reading the following sections of this document because some of the phenomena described are not intuitively obvious. An example of this is described later, where it is stated that water moving downward in the partially-saturated zone encounters zones of increased effective porosity, which may act as barriers to further downward flow. It may at first seem counterintuitive that a zone of increased porosity could act as a flow barrier until one considers that a geological zone with a high porosity possesses a low capillary suction potential. If this zone is overlain by a zone which has a lower porosity and thus a higher capillary potential, water entering the upper zone will be retained there as a result of capillary equilibration. These conditions will prevail until the gravitational force overcomes the capillary force in the upper zone as more water enters, which usually happens when the bottom of the upper zone becomes nearly saturated, allowing water to flow into the lower zone.

A sequence of nonwelded porous tuffs that overlies the Topopah Spring Member (Section 7.1.1) may act as a natural capillary barrier to retard the entrance of water into the fractured tuffs. A similar sequence of nonwelded tuffs underlies the Topopah Spring Member. These underlying nonwelded tuffs locally contain sorptive zeolites and clays that could be an additional barrier to the downward transport of some radionuclides from a repository to the water table.

The proposed repository is surrounded by and crossed by numerous strike-slip and normal faults with varying amounts of offset (LBL96). The repository would be located largely, if not entirely, within what is known as the "central block" as described below (see Figure 7-8). The structural geology of this block is less complex than in the surrounding area, although one extensive, nearly vertical normal fault has been mapped in the block (Ghost Dance Fault). The central block of Yucca Mountain is a large block beneath the center of the Yucca Mountain ridge and is bounded on its west side by the Solitario Canyon fault, a major north-striking normal fault with greater than 100 m of offset. West of this fault is a chaotic, brecciated and faulted west-dipping zone caused by drag on the fault. A zone of imbricate normal faults forms the eastern boundary of the central block. These faults are west-dipping and have vertical offsets of about two to five m. Northwest striking strike-slip faults also occur in the area, such as the one forming the northern boundary of the central block, beneath Drill Hole Wash. The concept of a central block should not, however, be taken to imply that the central block or the proposed repository area is free of faults (USG84a).

Unsaturated Zone Hydrogeologic Units

The detail of the layered volcanic rock sequence beneath Yucca Mountain is very complex. The various rock units can be separated into a small or large number of units depending upon the scale and aims of a particular study. For the purposes of this document, the unsaturated zone is considered to consist of six hydrogeologic units, based on their physical properties. This grouping and the description of the six units are based primarily on USG84a, except where otherwise referenced. Additional data regarding matrix and fracture properties are presented in the hydrogeologic database developed in DOE95c.

The physical properties within each formation vary considerably, largely due to variation in the degree of welding of the tuffs. In most cases, physical property boundaries do not correspond to rock-stratigraphic boundaries. However, it is the physical properties that largely control water occurrence and flow; the hydrogeologic subunits into which the volcanic sequence is separated are different than the lithological units outlined in Section 7.1.1.3. The hydro-geologic units are,

Stratigraphic unit		Tuff lithology	Hydrogeologic unit	Approximate range of thickness (meters)[1]	Fracture density (fractures/m³)[2]	Generalized permeability[3]	
						Matrix	Fracture
Alluvium		- - - -	Alluvium	0 - 30	- - - -	Generally substantial	- - - -
Paintbrush Tuff	Tiva Canyon Member	MD	Tiva Canyon welded unit	0 - 150	10 - 20	Negligible	Substantial
Paintbrush Tuff	Yucca Mountain Member; Pah Canyon Member	NP, B	Paintbrush nonwelded unit	20 - 100	1	Moderate	Small ?
Paintbrush Tuff	Topopah Spring Member	MD	Topopah Spring welded unit	290 - 360	8 - 40	Negligible	Substantial
Tuffaceous beds of Calico Hills		NP, B (V) / (D) (in part zeolithic)	Calico Hills nonwelded unit (Water table; Saturated Zone)	100 - 400	2 - 3	(V) Substantial / (D) Small to negligible	Small ?
Crater Flat Tuff	Prow Pass Member						
Crater Flat Tuff	Bullfrog Member	MD, NP, B (undifferentiated)	Crater Flat unit	0 - 200	8 - 25	Variable	Variable

[1] Thicknesses from geologic sections of Scott and Bonk (1984).
[2] Scott and others (1983).
[3] Inferred from physical properties.

in descending order, Quaternary Alluvium (Qal), the Tiva Canyon welded unit (TCw), the

Figure 7-17. Unsaturated Zone Hydrogeologic Units (USG84a)

Paintbrush nonwelded unit (PTn), the Topopah Spring welded unit (TSw), the Calico Hills nonwelded unit (CHn), and the Crater Flat unit (CFu). Figure 7-17 illustrates these hydrogeologic units and some of their characteristics. They are described in detail in the following paragraphs.

Structural features, although they are not hydrogeologic units in the same sense as stratigraphic units, are mappable, have certain measurable hydraulic characteristics, and may have a significant effect on unsaturated zone flow. Because these structural features are regarded as important components of the unsaturated hydrologic system, they are described later in this section.

Qal. Unconsolidated alluvium underlies the washes that dissect Yucca Mountain and forms the surficial deposit in broad inter-ridge areas and flats nearby. Thickness, lithology, sorting, and permeability of the alluvium are quite variable; particles range in size from clay to boulders, and in places the unit is moderately indurated by caliche. Alluvial and colluvial deposits generally have small effective hydraulic conductivity, large specific retention, and large effective porosity as compared to the fractured rocks. Therefore, a large proportion of the water infiltrated into the alluvial and colluvial material is stored in the first few meters of the soils and is lost to evaporation during dry periods. The saturated permeability of alluvium generally is substantial compared to the tuff units.

TCw. Lying immediately beneath the Qal is the Tiva Canyon welded unit, consisting of devitrified ash-flow tuffs ranging from 0 to 150 m in thickness across the site. The TCw is the densely to moderately-welded part of the Tiva Canyon Member of the Paintbrush Tuff. This unit is the uppermost stratigraphic layer that underlies much of Yucca Mountain; it dips 5° to 10° eastward within the central block, resulting in a relatively planar eastward-sloping, dissected land surface. The unit is absent in some washes and is about 150 m thick beneath Yucca Crest. This unit has a fracture density of 10 to 20 fractures/m^3 and small matrix permeability. Saturated matrix hydraulic conductivity has been estimated at about 2×10^{-6} m per day (m/d); the effective hydraulic conductivity is thought to be lower, as saturation is estimated to range from 60 - 90 percent. Neither bulk rock nor fracture hydraulic conductivities are well characterized for this unit.

PTn. The Paintbrush nonwelded unit is situated below the TCw unit and consists of the nonwelded and partially welded base of the Tiva Canyon Member, the Yucca Mountain Member, the Pah Canyon Member, the nonwelded and partially-welded upper part of the Topopah Spring Member, and associated bedded tuffs. All are part of the Paintbrush Tuff. The unit consists of thin, nonwelded ash-flow sheets and bedded tuffs that thin to the southeast from a maximum thickness of 100 m to a minimum thickness of about 20 m. The unit dips to the east at 5 to 25 ; the dip at any location depends on the tilt of the faulted block at that site. In the central block, the dip rarely exceeds 10 . In the vicinity of the central block, this unit crops out in a narrow band along the steep west-facing scarp along Solitario Canyon.

Tuffs of this unit are vitric, nonwelded, very porous, slightly indurated, and in part, bedded. The unit has a fracture density of about one fracture/m^3. Saturated hydraulic conductivities of five core samples of the matrix have a geometric mean of about 9.0×10^{-3} m/d. Porosities average about 46 percent, but some porosities are as much as 60 percent. The rocks of this unit are moderately saturated, with an average value of about 61 percent. However, water contents are relatively large; the mean volumetric water content is about 27 percent and the mean water content by weight is about 19 percent. The maximum values reported are: saturation, 80 percent; volumetric water content, 42 percent; and water content by weight, 36 percent.

TSw. The Topopah Spring welded unit consists of a very thin upper vitrophyre, a thick central zone consisting of several densely welded devitrified ash-flow sheets and a thin lower vitrophyre of the Topopah Spring Member of the Paintbrush Tuff. The unit, which varies from 290-360 m in thickness, is densely- to moderately-welded and devitrified throughout its central part. The TSw contains several lithophysal cavity zones that generally are continuous, but vary appreciably in thickness and stratigraphic position. The TSw is also intensely fractured.

The Topopah Spring Member is the thickest and most extensive ash-flow tuff of the Paintbrush Tuff. The central and lower densely-welded, devitrified parts of the Topopah Spring welded unit are the candidate host rock for a repository. This part of the unit contains distinctive subunits that have abundant lithophysal gas cavities within the central block. The saturated hydraulic conductivity of the matrix of this unit generally is small and has a mean of about 3.0×10^{-6} m/d.

Because of the densely fractured nature of this unit, bulk hydraulic conductivity is substantially greater than matrix hydraulic conductivity. Saturated horizontal hydraulic conductivity of the rock mass is about one m/d for a 120-meter interval of the TSw that was packed off and tested at Well J-13 (see Figure 7-18 for bore hole locations), about six km east of Yucca Mountain. Because of the marked contrast between the matrix and the bulk hydraulic conductivities in this unit, values of the bulk hydraulic conductivity from Well J-13 (USG83) and borehole UE-25a#4 probably represent the hydraulic conductivity of the fractures in this unit. The large bulk hydraulic conductivity of this unit probably promotes rapid drainage of water. The amount of flow carried in the fractures with respect to the matrix has been estimated to range between 10 - 95 percent (GEO97).

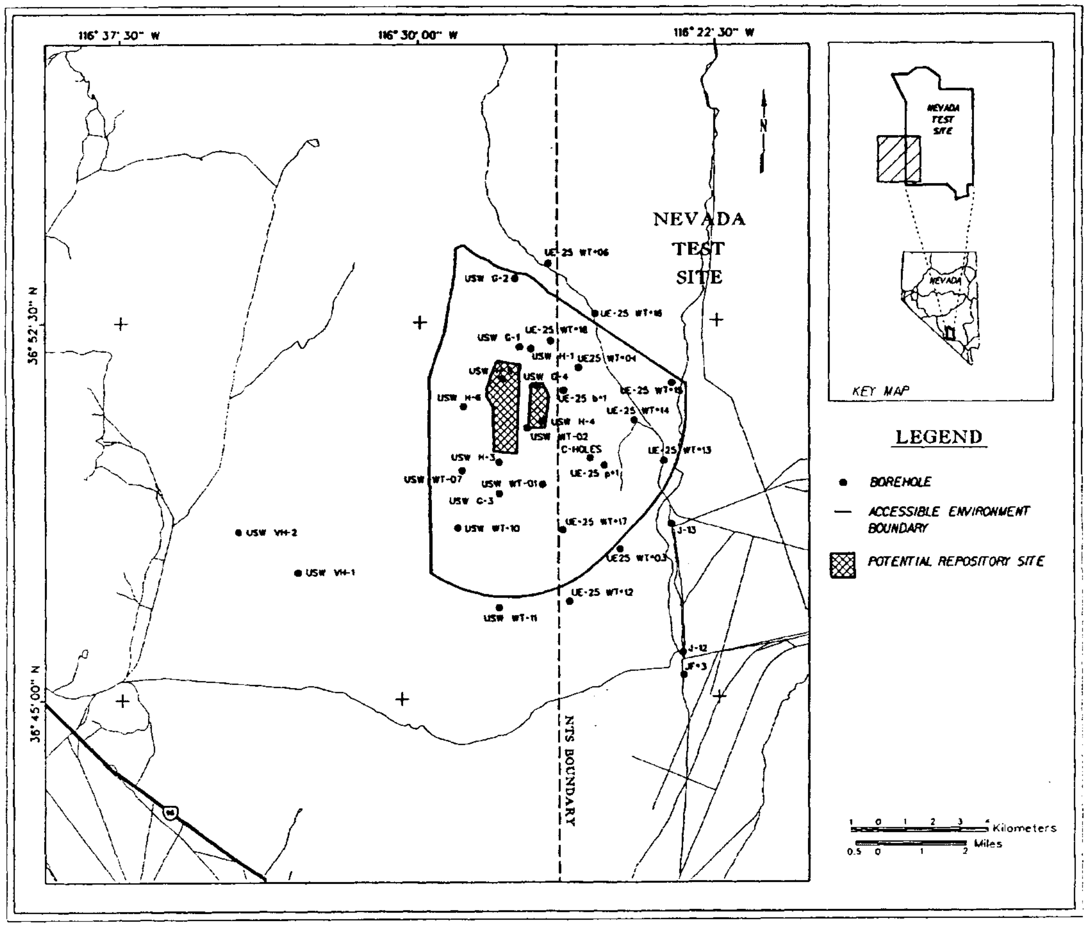


Figure 7-18. Locations of Deep Boreholes in the Vicinity of Yucca Mountain (USG96a)

The effect of lithophysal cavities on the hydrologic properties of the TSw is not well understood. Total porosity is much greater where lithophysal cavities are more abundant than in those sections that are free of these cavities. Overall unsaturated hydraulic conductivity probably is decreased by the presence of these cavities. These cavities commonly are several centimeters in diameter, filled with air, and form capillary barriers with the fine grained matrix. In effect, the cavities decrease the transmissive cross-sectional area, decrease effective porosity, and consequently, decrease the effective hydraulic conductivity.

CHn. Beneath the TSw unit is a series of non- to partially-welded ash-flow tuffs called the Calico Hills nonwelded unit. Locally, these may be vitric (CHnv) or zeolitized (CHnz). The CHn includes the following components, in descending order:

1. A nonwelded to partially-welded vitric layer, locally zeolitic, that is the lowermost part of the Topopah Spring Member of the Paintbrush Tuff.

2. Tuffaceous beds of Calico Hills.

3. The Prow Pass Member of the Crater Flat Tuff, which is nonwelded to partially-welded where it occurs in the unsaturated zone beneath the central block.

4. The nonwelded to partially-welded upper part of the Bullfrog Member of the Crater Flat Tuff where it is above the water table.

In the vicinity of the central block, this unit crops out in a narrow band along the steep west-facing scarp along Solitario Canyon. Both vitric and devitrified facies occur within the CHn. As described below, the permeability of the vitric facies is substantially greater than that of the devitrified facies. Alteration products in the devitrified facies include zeolites (most abundant), clay, and calcite (rare). Because this facies is mostly zeolitic, it is hereafter referred to as the zeolitic facies. Thickness of the zeolitic facies generally increases from the southwest to the northeast beneath Yucca Mountain. Beneath the northern and northeastern parts of the central block, the entire unit is devitrified and altered.

Both the vitric and zeolitic facies of the CHn are very porous, with a mean porosity of about 37 percent for the vitric facies and 31 percent for the zeolitic facies. Saturations in this unit generally are greater than 85 percent, with a mean value for the zeolitic facies of about 91 percent.

A significant difference exists in values of vertical hydraulic conductivity of the matrix between the vitric and zeolitic facies of the CHn. The mean vertical hydraulic conductivity of the matrix of the vitric facies is 4.0×10^{-3} m/d. The geometric mean of the vertical hydraulic conductivity of the matrix of the zeolitic facies is about 8.0×10^{-6} m/d. The marked contrast in vertical hydraulic conductivities of the two facies probably is the result of extensive argillization in the zeolitic facies, which tends to decrease permeability.

CFu. In approximately the southern half of the central block, the lowermost unit in the unsaturated zone is the Crater Flat unit. This unit consists of the unsaturated welded and underlying nonwelded parts of the Bullfrog Member of the Crater Flat Tuff. No differentiation is made between the welded and nonwelded components of the Crater Flat unit because of the limited extent of the unit in the unsaturated zone beneath the central block, and therefore, its probable limited effect on the unsaturated flow system. Beneath the central block, the thickness of the CFu ranges from 0 to 160 m. Little is known about the unsaturated hydrologic properties of the unit, but it is assumed that the properties are similar to those of the nonwelded and welded counterparts higher in the section.

Structural Features

As previously described, the central block of Yucca Mountain is bounded on three sides by faults. Because these major faults and fault zones transect the full thickness of the unsaturated zone, they may by hydrologically significant either as flow barriers or as flow pathways. The variation in unsaturated hydraulic properties of these features have in most cases not been measured. However, some inferences can be made, based on the physical properties of the welded and nonwelded tuff units and on observations of drill cores.

The welded units are relatively brittle. Open faults have been observed in cores even from below the water table. Conversely, the nonwelded units generally are more ductile than the welded units and more readily produce a sealing gouge material. Fault zones are less common in the Calico Hills nonwelded unit. In general, hydraulic conductivity varies greatly along the faults and is greater in welded units than in nonwelded units (USG84a).

Knowledge of the permeability of the numerous faults which cross Yucca Mountain is important because some faults may act as conduits for rapid vertical flow in the unsaturated zone. This possibility is especially critical in areas in which such faults may intercept large amounts of lateral flow and divert this flow downward, potentially into the repository. Evidence for the permeability of the faults in and around the proposed repository area is mixed. Studies performed to date indicate that particular faults are barriers, while other faults are more permeable (LBL96). It is also possible that a particular fault may be relatively impermeable in some areas of the fault plane, and relatively permeable in others. Factors which may reduce permeability of faults include development and alteration of fault gouge, deposition of fracture coating materials on fault surfaces, and the juxtaposition of permeable and nonpermeable units by movement along the fault plane. Faulting can also create zones of enhanced permeability where the rock around the faults is highly fractured or brecciated.

Studies in the Exploratory Studies Facility (ESF) indicate that the permeability of the Bow Ridge fault is about the same as measured with air permeability testing of highly permeable bedded tuff formations or highly fractured welded units. Also, the geothermal profile in borehole ONC#1 shows that the geothermal profile is offset by several degrees as the borehole passes through the Bow Ridge fault zone. This indicates that the fault may be highly permeable to gas or moisture flow which decreases the temperature in that region (LBL96).

Evidence from other faults indicates that they may act as low permeability barriers. For instance, the water body observed at borehole SD-7 is thought to be perched over a zeolitic layer and prevented from moving laterally by the presence of the Ghost Dance fault. A similar hypothesis has been invoked to explain perched water in a borehole intersected by a splay of the Solitario Canyon fault. This conclusion is corroborated by pneumatic pressure data taken in borehole UZ-7a, which appear to show a degree of anisotropy in the fault which is consistent with a permeability barrier, at least in the horizontal direction (LBL96).

Another indication that some faults at the site may act as permeability barriers is obtained from potentiometric surface measurements. For instance, the potentiometric surface elevation on the western side of the Solitario Canyon fault is approximately 40 m higher than on the eastern side of the fault. This gradient could only be maintained if the Solitario Canyon fault is somehow a permeability barrier to flow (LBL96).

The ESF has provided data and observations regarding the structural features within Yucca Mountain. Prior to the construction of the ESF, detailed geological and structural cross-sections were prepared. As-built cross sections prepared from data and observations from the ESF show that geologic sections drawn prior to construction compare favorably with results from tunneling. These findings indicate that the lithostratigraphy, and to a lesser extent structure, of this are well-characterized and predictable. Detailed information on the results of ESF geological mapping is available in BOR96 and BOR96a. These publications provide detailed fracture pattern analysis including measurements of trace length, orientation, continuity, roughness, aperture, and mineral infilling. From ESF studies, three main fracture sets are reported; two are approximately vertical and strike north-south, and east-west, while the third fracture set is close to horizontal. BOR96 reports that the open distance between fracture faces averages 2.3 mm over the entire fracture population. The largest aperture is 91 mm, although this is anomalously large in this population; 67 percent of the fractures are closed (0 mm). For fractures with an aperture greater than zero, the average is 7.2 mm. The fracture population includes measurements from the Tiva Canyon Tuff, the Paintbrush Tuff, and the Topopah Spring Tuff. The repository horizon is generally more fractured, containing an average of about four fractures per meter, but typically ranges from about two to six fractures per meter (LLNL96).

A common feature in some horizons in the volcanic rocks are lithophysal cavities, which are voids in the rock presumably created by gases exsolved from cooling lavas and pyroclastic deposits. In the Tiva Canyon and Topopah Spring Tuffs, lithophysae are mostly concentrated into stratiform zones, but they also occur adjacent to lithophysal zones and sporadically in nonlithophysal zones. The cavities range in size from less than one centimeter (cm) to greater than 1.4 m. Fractures demonstrate several different relationships with lithophysal cavities. Fractures that intersect and terminate in lithophysal cavities are common. This, and other evidence, suggest that lithophysal cavities may locally influence fracture propagation (BOR96, BOR96a).

Ground Water Flow In The Unsaturated Zone

Water flow and storage in the unsaturated zone is three-dimensional and is controlled by the structural, stratigraphic, thermal, and climatological setting. The dynamics of water-air-vapor flow in the layered, fractured rock unsaturated zone beneath Yucca Mountain are complex and highly uncertain at this time. In the unsaturated zone, water is present both in liquid and vapor phases within the interstitial, fracture, and lithophysal openings. Hydrogeologic features that probably affect flow significantly in the unsaturated zone include the presence of fractured porous media, layered units with contrasting properties, dipping units, bounding major faults, and a deep water table. These features probably result in the occurrence of phenomena such as flow in both fractures and matrix, diversion of flow by capillary barriers, lateral flow, perched ground water zones, and vapor movement.

Infiltration Rates

The ultimate source of water in the unsaturated zone at Yucca Mountain is precipitation on the mountain. The spatial and temporal relationships between infiltration and recharge are complex, because of the hydrogeologic variability of Yucca Mountain. Some water that infiltrates returns to the surface by interflow; another part is returned to the atmosphere by evapotranspiration. A small quantity that is not evaporated, or discharged as interflow, percolates deep into the unsaturated zone and becomes net infiltration or percolation. The terms “infiltration” and “percolation” are used frequently, sometimes interchangeably, in literature about the Yucca Mountain unsaturated zone. For the purposes of this report, “infiltration” is used to describe the amount of water which enters Yucca Mountain at the ground surface, while “percolation” is used to describe the amount of water which actually penetrates deep enough into the mountain to reach the repository horizon and below. The difference between the two terms lies mainly in the partitioning of part of the infiltration flux into the vapor phase, which may then be recirculated to the atmosphere.

At Yucca Mountain, the infiltration rate is both spatially and temporally variable. Because the quantity of net infiltration that percolates through different paths is quite variable, estimated average recharge rates do not represent percolation rates through specific flow paths. Spatial variations of infiltration depend mostly on variations in the properties of surficial units, topography, the intersection of faults with the surface, and the presence of local fracturing. Temporal variations in infiltration rate are related to the seasonality and relatively infrequent precipitation events in the arid climate of Yucca Mountain. Temporal variations in the infiltration rate have also occurred over a much larger time span, reflecting long term climate changes.

Knowing the temporal and spatial variability of the percolation rates is crucial to modeling efforts because of the importance of the relationship of infiltration rate to horizontal and vertical permeabilities of the various units and the effect this has on whether or not significant lateral flow occurs in the unsaturated zone. The higher the actual infiltration rate, the greater the likelihood of significant lateral flow. Such lateral flow could result from a combination of two factors. The first factor is that infiltrating water may encounter zones of lower relative permeability as it moves downward. The second factor is that in many of the units, the relative permeability is far greater in the direction parallel to bedding than the direction perpendicular to it. The anisotropic permeability may cause lateral flow of mounded water away from the area in which it accumulates. Lateral flow is important because it could transmit water to structural features which would then move the water downward, possibly acting as a conduit to divert large amounts of water flowing downward through a small area. Such flow paths could direct water into and through the repository or away from it.

The actual quantity of net infiltration or percolation beneath the surface of Yucca Mountain has not been accurately determined. The percolation flux is a difficult parameter to determine for low flux regions such as Yucca Mountain. There are currently no reliable direct measurements that can be made to determine this important parameter (LBL96). Existing estimates have been obtained from a mixture of indirect methods involving field testing and modeling of various processes at different scales. Data exist to suggest that the flux reaching the repository horizon through the matrix is relatively small. Relatively low matrix saturations measured in the upper portion of the TSw suggest that much of the moisture which infiltrates into the TCw does not reach the TSw (LBL96). Data from the ESF show that no weeping fractures were found, even in the region where perched water is found in boreholes. (Note, however, that because of ventilation equipment inside the ESF, much of any such moisture might be removed from the ESF as water vapor). Furthermore, no moisture was observed infiltrating into the radial boreholes of Alcove 1 of the ESF after storm events, even though the boreholes are located close to the land surface in the highly fractured and broken TCw formation (LBL96). However, other data suggest that the percolation flux may reach the repository level mainly through episodic fracture flow. These data include observation and testing of extensive bodies of perched water located below the repository horizon, as well as measurements of bomb-pulse isotope levels from atmospheric nuclear testing which show that some water in the unsaturated zone is relatively young (LBL96).

Estimates of net infiltration vary from slightly negative (net loss of moisture from the mountain) to about 10 mm/yr (LBL96). USG84a reports that net infiltration flux probably ranges from 0.5 to 4.5 mm/year, based on estimates of earlier workers for various localities in the Yucca Mountain area. Flint and Flint (FLI94) provide preliminary estimates of spatial infiltration rates that range from 0.02 mm/yr, where the welded Tiva Canyon unit outcrops, to 13.4 mm/yr in areas where the Paintbrush nonwelded unit outcrops. The bulk of the area above the repository block is underlain principally by the Tiva Canyon member. The DOE's 1995 Total System Performance Assessment (DOE95b) concludes that, if the predominant flow direction is vertical, then the average infiltration through the repository block, using the average infiltration rates of Flint and Flint (FLI94), would be 0.02 mm/yr. If, on the other hand, the predominant flow direction has a significant lateral component due to material property heterogeneity and/or anisotropy and the sloping nature of the hydrostratigraphic unit contacts, then the average net infiltration rate over the repository block could be as high as some weighted average of the infiltration rates inferred from FLI94. The 1995 TSPA (DOE95b) also reports that the average, spatially-integrated infiltration rate is about 1.2 mm/yr; most of this infiltration occurs along the Paintbrush outcrop in the washes north of the repository block.

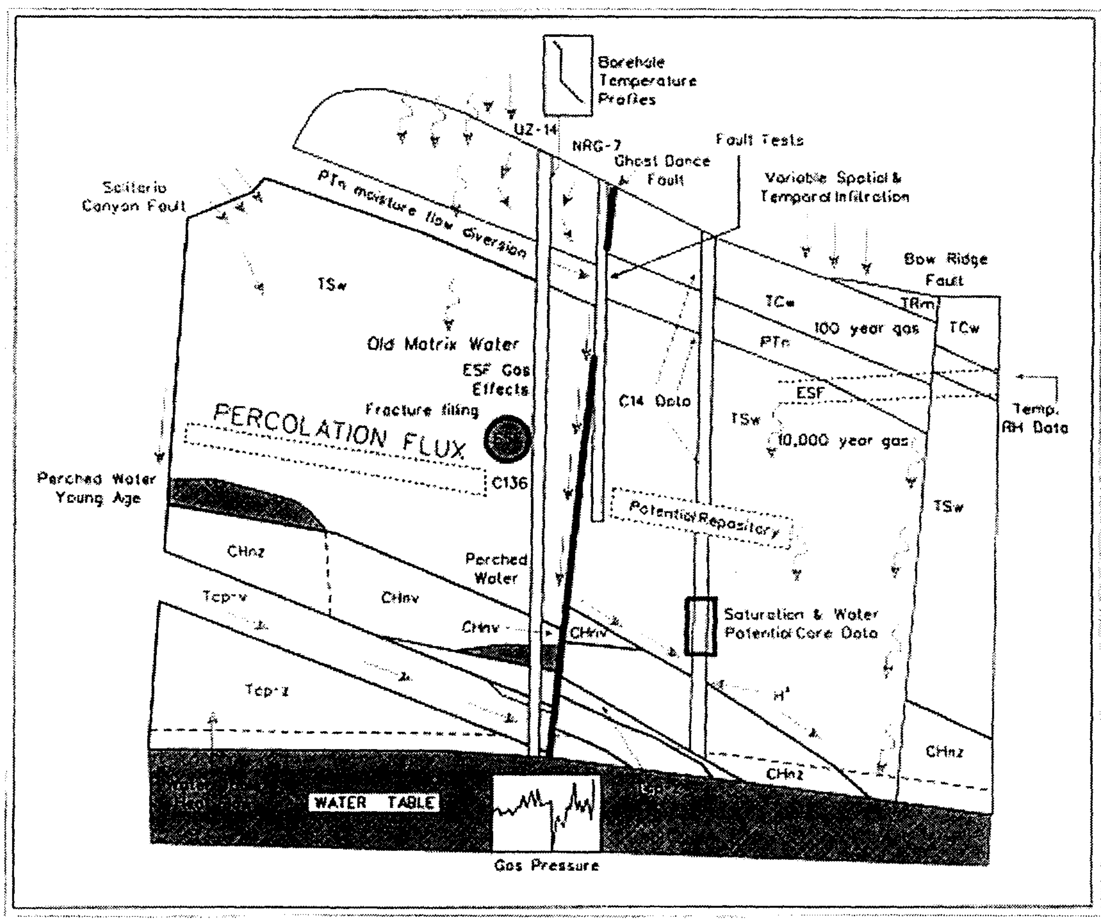
Recently, several lines of evidence have converged to alter the prevailing view regarding the magnitude of infiltration/percolation rates beneath Yucca Mountain, with the most recent estimates being revised upward from previous work. The newer estimates of percolation are around five mm/yr, with a range of one to 10 mm/yr (LANL96, LBL96). Recent isotopic analyses of rock samples from the ESF are consistent with a percolation rate of five mm/yr (LANL96, LBL96). Profiles of temperature vs. depth of water in boreholes are consistent with a range of infiltration rates from one to 10 mm/yr (LBL96). Three-dimensional modeling results of percolation flux at the repository horizon using the latest available spatially varying infiltration map indicate percolation fluxes on the order of five to 10 mm/yr. The expert elicitation panel estimates for mean infiltration rates range from 3.9 to 12.7 mm/y (GEO97). The effect of uncertainty in infiltration and percolation flux rates is examined in the discussion of the unsaturated zone conceptual model.

Conceptual Model(s)

The first detailed conceptual model of unsaturated zone flow at Yucca Mountain was proposed in USG84a. Since then, the majority of the data collected has been in general agreement with these ideas and concepts (LBL96). Most subsequent conceptualizations of unsaturated zone behavior are largely refinements of this model, revised to accommodate newly-acquired data (Figures 7-19 and 7-20). Newly-acquired data include isotopic analyses, concentration ratios of ions dissolved in matrix rocks and perched water zones, calcite fracture fillings, and thermal modeling of vertical temperature gradients. Perhaps the most significant change from early conceptual models has been the recent acquisition of new isotopic data which indicate the presence of “fast paths” for water moving through the unsaturated zone. This topic is discussed in more detail in a subsequent section.

The following presentation of the unsaturated zone flow conceptual model is taken primarily from USG84a. Where appropriate, the published literature is referenced when describing refinements or revisions that have been made to the USG84a model. The following conceptual model is presented as if it were an established physical reality. Bear in mind, however, that the proposed model is probably not the only reasonable description that could be made of the system. Following the description of the conceptual model is a discussion of critical unknowns, their effects on unsaturated zone flow, and results of numerical modeling studies.

Percolation of infiltrated water through the exposed fractures of the Tiva Canyon welded unit is relatively rapid because of the large fracture permeability and small effective porosity of this unit compared to the alluvial material. Therefore, a large proportion of the infiltrated water normally is percolated sufficiently deep within the fractured tuff to be unaffected by the evaporation potential that exists near the surface. Depending on the intensity of the infiltration, percolation downward through the Tiva Canyon welded unit may occur without a significant change in rate.



Figu
re 7-19. Early Conceptual Model of Ground Water Flow in the Unsaturated Zone at Yucca Mountain (USG84a)

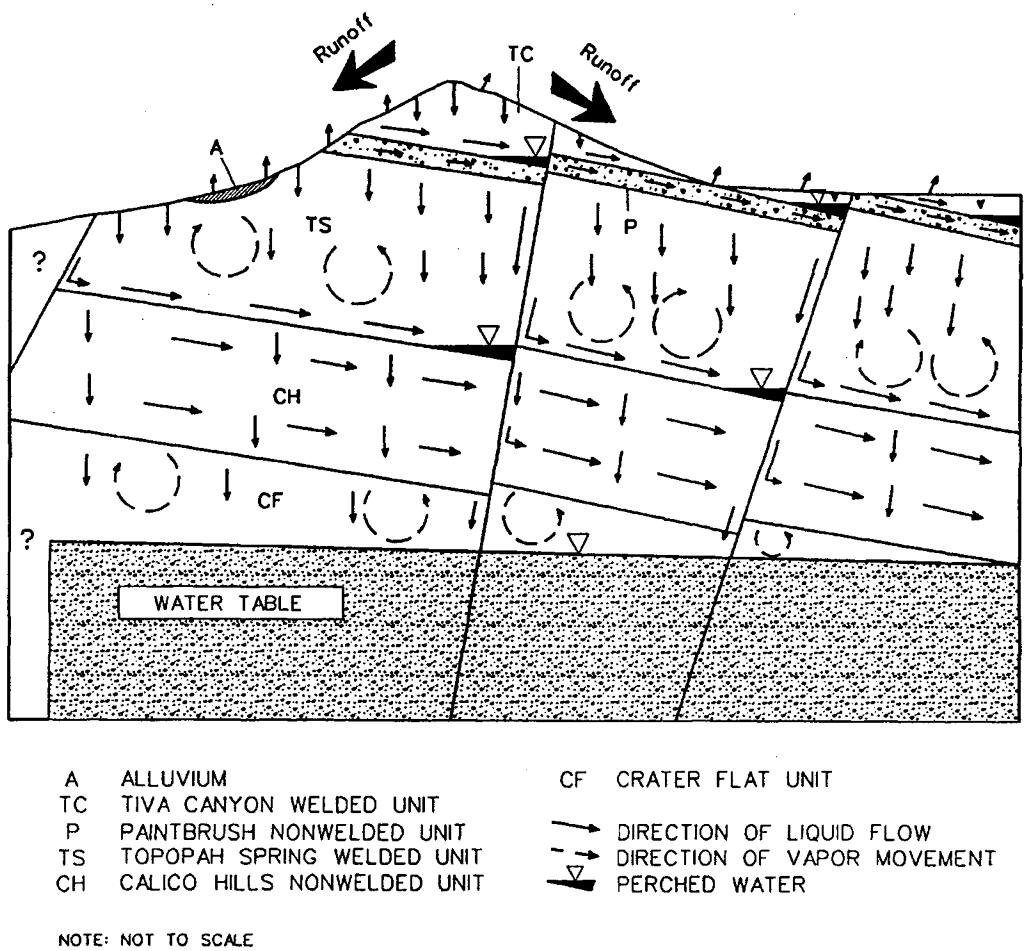


Figure 7-20. Current Conceptual Model of Ground Water Flow in the Unsaturated Zone at Yucca Mountain (LBL96)

A small proportion of the water percolating through the fractures slowly diffuses into the matrix of the Tiva Canyon welded unit. Downward flow in the matrix is very slow because of the small effective hydraulic conductivity of the matrix. During dry periods, some of the diffused water flows back into the fractures and probably reaches the land surface by vapor diffusion. The mass of water involved during this process is likely to be negligible compared to the percolating water.

The densely fractured Tiva Canyon unit, with small matrix porosity and permeability, overlies the very porous, sparsely fractured Paintbrush unit. A marked contrast in material properties exists at the contact between these two units; depending on the magnitude of the infiltration flux, this contrast could impart a significant lateral component of flow. Flow of water through fractures of the Tiva Canyon unit occurs rapidly until it reaches the contact. At this point, the velocity is significantly decreased because of the greater effective porosity and lesser hydraulic conductivity of the Paintbrush unit. As a result, lateral, unsaturated flow of water above this contact can occur. Perched water may occur above this unit if displacement along faults has created significant differences in permeability on opposite sides of the fault.

The saturated hydraulic conductivity of the Paintbrush nonwelded unit in the direction of dip is 10 to 100 times greater than saturated hydraulic conductivity in the direction normal to the bedding plane. The combination of dipping beds and differences in directional permeability creates a downdip component of flow. The magnitude of this component depends on the magnitude of the principal hydraulic conductivity ratio. The permeability contrast may be sufficient to decrease vertical percolation into the underlying Topopah Spring welded unit to almost zero. In this case, water would flow laterally downdip until structural features are encountered that create perching conditions or provide pathways for vertical flow.

As water moves downward through the PTn, the effect of high porosity and low fracture density progressively moves water from fractures into the matrix. Except for areas where fast paths may exist (such as faults), beyond a certain depth in the PTn, flow may be almost entirely in the matrix. Travel times through the matrix of the PTn are thought to be relatively long because the matrix of this unit appears to act as a “sponge” which dampens out episodic infiltration pulses.

Water flows from the matrix of the Paintbrush nonwelded unit into the fractures or matrix of the underlying Topopah Spring welded unit. Owing to the thickness of this unit, it is hypothesized by ROB96 that water moving through the fractures eventually diffuses into the matrix and moves very slowly downward. An exception is the second subunit of the TSw (ROB96). In contrast to this conceptualization, the unsaturated zone expert evaluation panel estimated that up to 95 percent of the flow in the Tsw could remain in the fractures (GEO97).

Flow enters the Calico Hills nonwelded unit either from the matrix of the Topopah Spring welded unit or through structural flowpaths. How much flow occurs in the fractures of the lower part of the Topopah Spring unit is unknown, and therefore their potential to contribute to flow into the Calico Hills unit is also uncertain.

The nature of flow at the contact between the Topopah Spring welded unit and the Calico Hills nonwelded unit depends on whether the vitric or zeolitic facies of the Calico Hills unit is present. The permeability and effective porosity of the vitric facies are much greater than those of the matrix of the Topopah Spring unit, which may result in a capillary barrier where those units are in contact. Conversely, the permeability of the zeolitic facies is about the same as for the matrix of the Topopah Spring unit, resulting in continuity of matrix flux across the contact.

Flux within the Calico Hills unit may occur with some lateral component of downdip flux, because of the existence of layers with contrasting hydraulic conductivity in the unit. A large scale anisotropy probably is caused by intercalation of tuffs with alternately large and small permeability and by compaction.

Water that flows downdip along the top of the Calico Hills unit slowly percolates into this unit and slowly diffuses downward. Fracture flow is known to occur near the uppermost layers of the Calico Hills unit, but diffusion into the matrix may remove the water from the fractures deeper in the unit and thereby limiting flow mostly to within the matrix, except along the structural flowpaths. It is possible, however, that fractures provide significant avenues for rapid flow through this unit. Beneath the southern part of the block, the Crater Flat unit occurs between the Calico Hills unit and the water table. Included are the welded part and underlying nonwelded part of the Bullfrog Member of the Crater Flat Tuff.

Fluxes along many structural flowpaths are probably larger than within the units they intersect. The Calico Hills unit is more ductile than the overlying Topopah Spring unit, which may give the Calico Hills unit fracture sealing properties. In addition, because of the lesser shear strength of this unit compared to that of the Topopah Spring, gouge formation along faults and shear zones is more common. These properties may result in a smaller fracture conductivity in the Calico Hills unit. In the case where the structural flowpaths are hydraulically continuous across the upper contact of the Calico Hills unit, water would be more likely to flow downward without a significant change in its path until it reaches the water table. In cases where the structural flow paths are discontinuous across the upper contact, flow may be diverted downdip along this boundary. Intermediate conditions between the two extreme cases are also possible. Recent numerical modeling (LBL96, ROB96) of flow through the unsaturated zone has provided important insights into the possible characteristics of flow in each subunit of the unsaturated zone. Some of these insights are discussed in the following paragraphs.

<u>Discussion of Unsaturated Zone Conceptual Flow Model and Modeling of the Unsaturated Zone</u>

Under current conceptualizations the net infiltration rate through the unsaturated zone beneath Yucca Mountain is one of the most critical parameters for determining the nature of flow in the unsaturated zone, yet it is one of the least well characterized. Numerous modeling studies, based on varying conceptual models, have been performed to simulate unsaturated flow beneath Yucca Mountain (e.g., DOE94a, DOE95b, LBL96, ROB96). Sensitivity analyses performed in these studies indicate that uncertainty in the amount of net infiltration accounts for as much as 90 percent of the variability in the results.

The magnitude of infiltration flux has a significant bearing on the potential for lateral unsaturated flow beneath Yucca Mountain. In the Paintbrush nonwelded unit, the overall hydraulic conductivity parallel to bedding is 10 to 100 times greater than that in the direction normal to the bedding plane. At higher flux rates, the potential vertical flow rate of some units is exceeded, thereby inducing a significant lateral component of flow to the infiltration flux. Some authors have examined the possibility of “focused recharge,” a phenomenon in which surface rainfall runoff is directed to areas where faults intersect the surface. Significant amounts of recharge may infiltrate into these zones, which may induce lateral unsaturated flow in the underlying units (LEH92). One obvious area where this may be occurring is the northern extension of Solitario Canyon fault, which bounds Yucca Mountain on the west. As previously described, lateral flow could direct water to structural flow paths, which may then redirect the flow vertically downward, providing a “fast path” and potentially reduced travel times to the saturated zone.

There is growing evidence to suggest episodic water flow at Yucca Mountain may take place along “fast paths” (LBL95, FAB96, LBL96). Data obtained from recent sampling conducted within the ESF tunnels drilled into Yucca Mountain provide compelling evidence that not only does flow occur along “fast paths,” but that such flow is capable of moving considerable distances over a relatively short time frame. The amount of water which may be infiltrating by fast paths is obviously of critical importance to predicting repository performance. Samples taken in the ESF tunnel show elevated concentrations of some radionuclides, principally chlorine-36, as well as lesser amounts of tritium and technetium-99 (FAB96). Chlorine-36 is a radioactive isotope produced in the atmosphere and carried underground with percolating ground water. High concentrations of this isotope were added to meteoric water during a period of global fallout from atmospheric testing of nuclear devices, primarily in the 1950's. This “bomb-pulse” signal can be used to test for the presence of fast transport paths (FAB96).

Testing for bomb-pulse radionuclides was conducted by collecting and analyzing rock samples from the ESF. Systematic samples were collected every 200 m, and feature-based samples were collected whenever a structural feature such as the intersection of the tunnel with a fault, was recognized. The results of the testing indicate that most of the samples had ^{36}Cl ratios ranging from 400e-15 to 1300e-15. The analysis in LANL96 indicates that although many samples showed ^{36}Cl ratios above present day atmospheric levels, it is believed that they represent Pleistocene water which entered the system when the ^{36}Cl ratios of infiltrating water were higher than they are today. Samples with ^{36}Cl ratios above 1500e-15 were interpreted as containing a component of bomb pulse water, indicating that at least a small proportion of the water at those locations is less than 50 years old. Locations at which multiple samples showed indications of bomb-pulse ^{36}Cl ratios appear to be associated with the Bow Ridge fault zone, the Drill Hole Wash fault zone, and the Sundance fault zone (ROB96). The most significant result of the ^{36}Cl testing is that some water travels to the repository horizon in less than 50 years. It is important to recognize, however, that these results do not indicate that all water travels this quickly in the unsaturated zone. The ^{36}Cl data do not indicate what fraction of the water now in the unsaturated zone has traveled by fast paths, nor do they by themselves indicate the magnitude of infiltration fluxes. Age dating, numerical modeling, and other lines of evidence suggest that travel times for most of the unsaturated zone are on the order of thousands to tens of thousands of years (LBL96).

Recent numerical modeling studies (LBL96, LANL96, ROB96) suggest two important requirements for rapid (less than 50 years) transport of ^{36}Cl to the ESF: (1) a continuous, high permeability pathway must exist to depth, and (2) a means of focusing infiltration and maintaining flux to the pathway must exist for a sufficient time. The eastward dip of the highly permeable PTn unit allowed strong lateral flow which was subsequently diverted downward at faults in these simulations. The strong lateral, down dip flow in the PTn was subsequently channeled into local permeability highs. In both the Paintbrush and Calico Hills units several vertical “fast paths” developed in response to these conditions. The recent modeling suggests that where the PTn is relatively thick, it was necessary to modify fracture properties to represent greater fracture densities and/or fracture apertures in order for bomb-pulse ^{36}Cl to migrate to the ESF in less than 50 years (ROB96).

The presence of perched water has implications for travel times, flow paths, and fluxes of water through the unsaturated zone. Analysis of water from several perched water zones documents a number of important findings, including perched water compositions that are out of equilibrium with pore water, showing little fracture/matrix interaction (DOE96d). This indicates that the perched water probably reached its present location without extensive travel through and interaction with the rock matrix, thus suggesting that this water had traveled relatively quickly through the unsaturated zone. Recently-measured tritium concentrations in perched water are at background levels, therefore suggesting that perched water is older than thermonuclear weapons testing. Also, preliminary data from isotope testing of perched water samples from boreholes UZ-14 and SD-7 indicates an apparent residence time of about 10,800 years, with corrected ages ranging from 5,000 to 10,800 years (LBL96). A detailed conceptual model of perched water is presented in LBL96.

Radionuclide Transport in the Unsaturated Zone

The travel time of radionuclides beneath Yucca Mountain is a function of both physical and chemical processes and interactions between fluid and rock. In terms of physical processes, radionuclides travel by gas phase and liquid phase advection, dispersion, and diffusion. Radionuclide travel times to the accessible environment are a function of the percolation flux distribution in the unsaturated zone and the advective flux distribution in the saturated zone, as well as the hydrostratigraphy along the ground water flow paths between the repository and the accessible environment. The percolation flux distribution within the Topopah Spring hydrostratigraphic unit (and other unsaturated zone units below it) is a function of the infiltration rate and the complex mechanism of ground water flow in the unsaturated zone. Chemical influences on radionuclide travel times include retardation processes involving liquid and gas phase diffusion, ion-exchange, adsorption on solids, surface complexation, colloidal suspension, chemical reactions, mineral alteration and dehydration reactions, radioactive decay, and precipitation/dissolution reactions.

In particular, the key conceptual uncertainty in the transport of radionuclides through the unsaturated zone at Yucca Mountain is the presence of fracture flow and transport which might, if fracture pathways are continuous and interconnected, lead to the formation of "fast paths" to the underlying saturated zone.

Uncertainties in chemical retardation mechanisms and the lack of rock/radionuclide interaction data also lead to considerable uncertainty in predicting future repository performance. For instance, in TSPA (DOE95b), modeling efforts have simulated fluid/rock interactions that can serve to chemically retard the transport of radionuclides with a simple equilibrium (infinite capacity) distribution coefficient (K_d) model. Generally, values for distribution coefficients are related to both the chemical nature of the individual hydrostratigraphic unit and to the properties of the radionuclide. Since distribution coefficients are used to model such a wide variety of phenomenological processes, they are modeled in TSPA-95 as stochastic parameters with a high degree of uncertainty. This process results in a broad range of predicted times it would take radionuclides to travel from the repository to the water table. Radionuclides that are little affected by chemical retardation (e.g., I, Tc) could reach the water table within the same time frame as the ground water. Alternatively, K_ds used in TSPA-95 for a number of radionuclides (i.e., Am, Ra, Cs, Sr) result in travel times to the water table that are 50,000 times greater than those for the ground water. Plutonium exhibits significant sorption on all types of Yucca Mountain tuffs, with sorption coefficients often in excess of 100 cubic centimeters per gram (cc/g) (ROB96). Detailed analysis of laboratory data for ^{237}Np showed that a nominal sorption coefficient of 2.5 cc/g could be used in the clinoptilolite-rich zeolitic rocks, with a value of 0 cc/g elsewhere. Measured K_d values for ^{79}Se are on the order of one cc/g. Sorption of uranium, similar to ^{237}Np, is significant only for zeolitic tuffs (ROB96).

Recent numerical modeling of the role of rapid transport through fractures was studied for ^{237}Np (ROB96). For peak dose criteria, the model indicates that the peak may be a result of rapid radionuclide transport through fractures. However, this does not mean that most of the radionuclides travel through fractures. According to this model, 10 percent of the source radionuclides typically travel rapidly in the fracture system, while 90 percent traveled much slower in the matrix material. (Other conceptualizations suggest that up to 95 percent of flow is in the fractures.) These results must be interpreted with the realization that the distribution of the simulated flux between the fractures and matrix is entirely the result of the parameters used to characterize the system. The Calico Hills, the primary unit through which radionuclides must travel to get to the water table, is poorly characterized; nothing is known of its fracture hydraulic properties.

Simulations of ^{36}Cl ratios and ^{14}C in the unsaturated zone indicate that infiltration rates between one and five mm/yr are more consistent with the field measurements than infiltration rates on the order of 0.1 mm/yr (ROB96). The environmental isotope simulations also helped provide a reasonable explanation for the bomb-pulse ^{36}Cl ratios measured in the ESF. This explanation involves disturbance of the PTn (e.g., faulting) which led to increased bulk fracture permeabilities and provided a local hydrologic environment conducive to rapid fracture flow of a small fraction of the total infiltrating flux. The flow in the fractures associated with these disturbances is rapid enough to transport solutes from the ground surface to the ESF in less than 50 years.

When flow and transport in fractures is simulated using a particle tracking method, a bimodal distribution of travel times is obtained — an early arrival through fractures, followed by a much delayed breakthrough of radionuclides that traveled through the matrix (ROB96). Although ROB96 predicts that the percentage of the total radionuclide inventory that travels rapidly to the water table is small, the radionuclide flux entering the saturated zone is at its greatest level during this period, and thus the peak dose is controlled by fracture transport. Migration of radionuclides through fractures is likely to be retarded by diffusion and in some cases adsorption. ROB96 noted that there is an inverse relationship between infiltration rate and arrival time of first breakthrough peak.

Due to sparse data and limited or nonexistent testing of the CHn, characterization of fracture hydrologic properties in this unit is based on speculation and application of theoretical relationships (ROB96). Model simulations indicate that the nature of fracture flow in the Calico Hills is critical to characterizing the performance of the site. Changes in estimated hydrologic property values estimated for these units have considerably altered the simulated flow and transport behavior through the unsaturated zone natural barrier.

7.1.2.2 Hydrologic Characteristics of Saturated Zone Units

In contrast to the unsaturated zone in which the flow of water is considered to be primarily vertical, ground water flow in the saturated zone at Yucca Mountain is principally in the horizontal direction. This consideration, coupled with the fact that it is the saturated zone in which most downgradient radionuclide transport from a repository would occur, requires the description of saturated zone hydrology to cover an area much greater than Yucca Mountain itself. Thus, while the discussion of unsaturated zone hydrology is conveniently limited to the Tertiary volcanic rocks beneath the proposed repository, this section broadens in scope to include not only the saturated volcanic rocks, but also the adjacent Paleozoic carbonates and the alluvial basin fill deposits. Because of the complex three-dimensional geometric relationships of these geologic materials, the BID breaks the description of saturated zone hydrology into two parts. Section 7.1.2.2 is restricted to a description of each of the three individual geologic materials (volcanic rocks, alluvium, and Paleozoic carbonates) and their hydrogeologic properties; Section 7.1.2.3 attempts to describe the geometric and hydrologic relationships of the various units to one another and to present an integrated picture of regional ground water flow.

Before beginning a detailed description of the hydrologic properties of the individual aquifer units, it will be helpful for the reader to keep in mind the following information while reading this section. As previously described, Yucca Mountain is composed of a thick sequence of Tertiary volcanic rocks. Beneath Yucca Mountain, the thickness of these rocks is more than 1,800 m (SPE89). The Tertiary volcanic sequence is underlain by complexly folded and faulted Paleozoic sedimentary rocks, including thick sections of carbonate rocks (SPE89). The Paleozoic rocks beneath the volcanic section are water-saturated and capable of transmitting ground water, probably over great distances. Bounding Yucca Mountain on three sides are downdropped basins filled with alluvial deposits eroded from the surrounding mountains. Water recharged in the higher altitude areas north of Yucca Mountain flows generally southward through the volcanic, carbonate, and alluvial aquifers toward discharge areas located in the southern Amargosa Desert and in Death Valley.

Volcanic Aquifer

At Yucca Mountain, where the volcanic rocks may or may not be fractured and where the hydrologic properties can change significantly in a single stratigraphic unit, stratigraphic units are useful only in a very general sense for defining hydrogeologic units. The volcanic rock section beneath Yucca Mountain has been divided informally into the four hydrogeologic units shown in Figure 7-21: (1) the upper volcanic rock aquifer, (2) the upper volcanic confining unit, (3) the lower volcanic aquifer, and (4) the lower volcanic rock confining unit. Note that the boundaries of these hydrogeologic units do not correspond necessarily to stratigraphic or thermal/mechanical units as defined by other studies. Ground water flows through all of these units to some degree (where saturated); these hydrogeologic unit designations serve primarily to distinguish between zones which transmit relatively large quantities of ground water ("aquifers") and zones which transmit lesser, but not necessarily insignificant, amounts of ground water ("confining units") (DOE95e; USG94a).

The largely nonwelded and intensely altered lower volcanic section, the Lithic Ridge Tuff and older tuffs, is a confining unit. The variably-welded Crater Flat Tuff constitutes an aquifer of moderate yield. The tuffaceous beds of Calico Hills are largely nonwelded and are zeolitized where saturated; however, this unit is significantly less altered than the lower volcanic section. Where saturated, it is generally a confining unit, but locally parts of the formation are permeable.

The Topopah Spring Member of the Paintbrush Tuff is predominantly densely welded and has abundant lithophysal horizons. It contains the zones of greatest primary and secondary permeability and constitutes the most productive aquifer in the tuff section, where it is saturated (FRI94). Units of the lower volcanic aquifer generally are completely or mostly in the saturated zone. Because it is deeper, increased lithostatic load probably accounts for part of the difference between the two aquifers, but the lower aquifer also tends to be less fractured than the upper volcanic aquifer. The lower volcanic aquifer is also more altered, which accounts for the decreased permeability (USG96a).

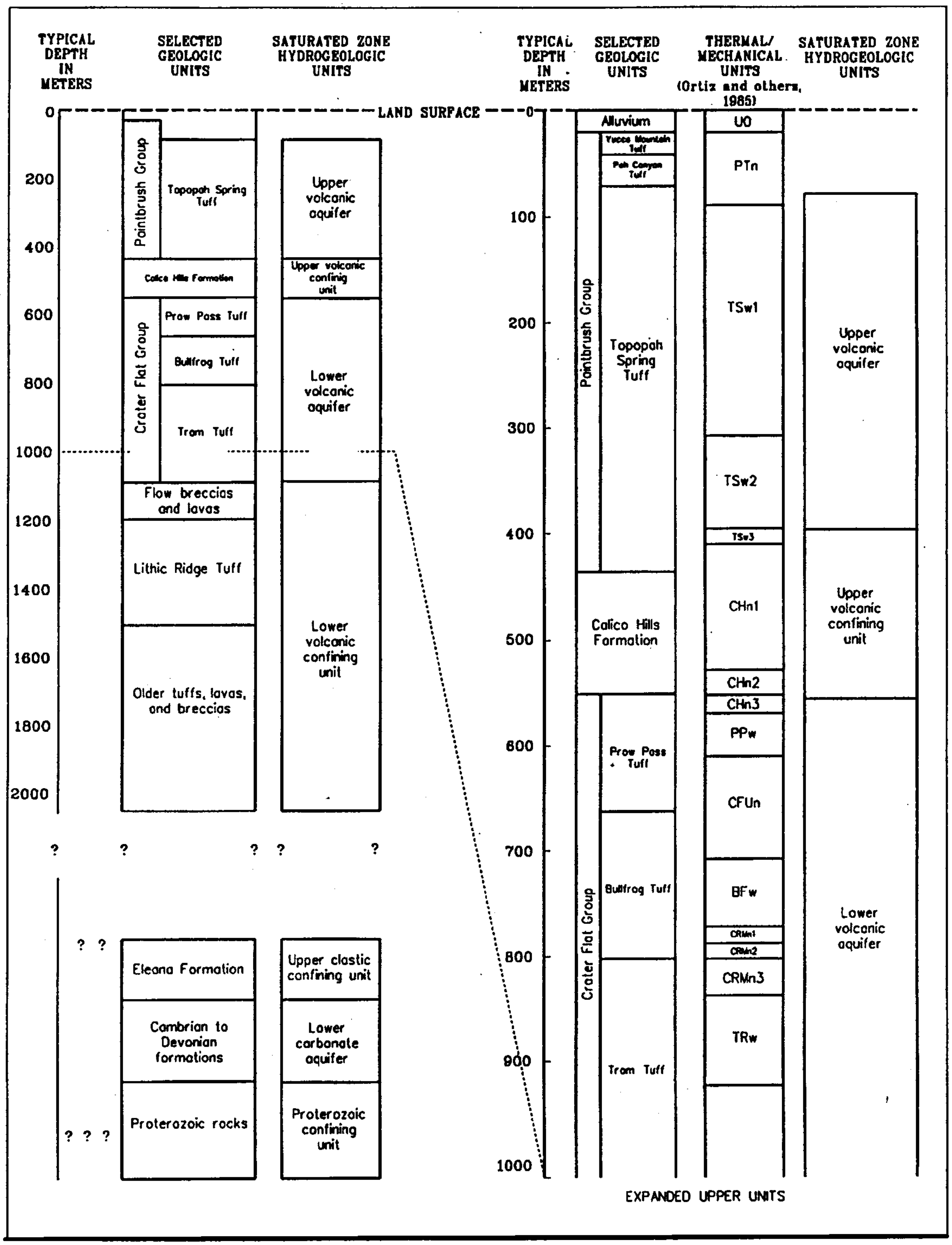


Figure 7-21. Saturated Zone Hydrostratigraphy of Volcanic Rocks (USG96a)

The physical properties within each formation vary considerably, largely due to variation in the degree of welding of the tuffs. The nonwelded tuffs are characterized by having a relatively large primary porosity, but low permeability. This low permeability results from small pore sizes and the presence in many nonwelded units of secondary alteration minerals (primarily zeolites and clays). The welded tuffs are typically very hard and densely welded. The welded tuffs are commonly more highly fractured than the nonwelded units. The fractures in the welded tuffs endow them with a significant bulk permeability. For this reason, many of the welded tuff units are capable of transmitting greater quantities of water than their nonwelded counterparts (USG84a).

The occurrence of the water table is not restricted to any one hydrogeologic unit. Directly beneath Yucca Mountain, the water table occurs primarily within the Calico Hills Formation and toward the southern end of Yucca Mountain in the underlying Crater Flat Tuff. To the east of Yucca Mountain, in the vicinity of Forty Mile Wash, the water table occurs in the Topopah Spring member of the Paintbrush Tuff. The occurrence of the water table in different hydrostratigraphic units is attributable to three factors: (1) the vertical displacement of hydrostratigraphic units by the numerous faults that dissect the area, (2) the eastward dip (five to 10 degrees) of the volcanic units, and (3) the variable elevation of the water table. See USG93a and USG84b for graphical depictions of the relationship of the water table to stratigraphic units and FRI94 for a map of the geology at the water table.

Aquifer Geometry

The thickness of the volcanic units is greatest to the north of Yucca Mountain toward the eruptive centers of the Timber Mountain Caldera Complex (USG85a; USG90a), diminishing gradually from the eruptive centers to zero thickness at the limits of the southwest Nevada volcanic field. The thickness of the volcanic deposits also varies considerably for two reasons. First, these units were deposited on a topographic surface of considerable relief. Second, erosion and postdepositional structural events have significantly modified their original distribution and thickness (USG85a, p. 8). In the vicinity of Yucca Mountain, the only direct measurement of the thickness of the volcanic sequence has been at Well UE-25p#1, where the thickness was measured to be 1,244 m. Seismic reflection studies have not yielded definitive data, owing to absorption of reflected energy by the thick volcanic cover (USG85a). Drill hole USW H-1, located immediately north of the proposed repository boundary, was drilled to a depth of 1,829 m entirely in volcanic rocks. Thus, the thickness of the volcanic sequence at the north end of Yucca Mountain may exceed 2,000 m.

The saturated thickness of the volcanic unit has been measured only at Well UE-25p#1. At this location, the water table is 752.6 m above mean sea level (MSL) and the bottom of the volcanic sequence was encountered at 129.1 m below MSL, giving a saturated thickness of the volcanic rocks of approximately 881.7 m (USG84c). Other information can be used to provide a crude approximation of the saturated thickness of the volcanic units. For example, the elevation of the water table beneath Yucca Mountain ranges from 1029 m above MSL at the northern part of Yucca Mountain to 729 m above MSL at the southern end of Yucca Mountain, a difference of 300 m (USG94a). Assuming that the bottom of the volcanic sequence beneath Yucca Mountain is 129 m below sea level everywhere (which it assuredly is not), the saturated thickness of the volcanic sequence would range from about 1,158 to 858 m.

The subsurface extent of the volcanic units south of Yucca Mountain is not reliably known because the volcanic rocks dip under and are covered by alluvial deposits of the Amargosa Desert. See Figure 7-15 for an illustration of the generalized extent of the volcanic rocks in southern Nevada and Figure 7-22 for a schematic cross-section showing the southward thinning of the volcanic units. Aeromagnetic maps suggest that the volcanic rocks pinch out at about the latitude of Lathrop Wells, and therefore, alluvial deposits constitute most or all of the cover in the Amargosa Desert (USG85a). Further evidence for the disappearance of the volcanic rocks is provided by two oil exploration wells drilled in the Amargosa Valley (DRI94). These two wells were drilled through alluvium into the underlying carbonate aquifer without encountering any volcanic rocks. USG85a, p. 12, notes that the "southward thinning of the volcanic rocks has been placed in question by recent north-south unreversed seismic refraction measurements. Preliminary profiles suggest that some highly magnetized volcanic rocks may indeed thin as proposed, but that an underlying rock sequence of less magnetized volcanic rocks may continue southward far beyond Lathrop Wells." USG91a notes the presence of rhyolitic volcanic units within the Amargosa Basin, although the genetic relationship of these units, if any, to the volcanic rocks that comprise Yucca Mountain is not clear.

Bare Mountain, located approximately nine kilometers to the west of Yucca Mountain across Crater Flat, consists of Paleozoic rocks. Tertiary volcanic rocks are known to lie beneath the area may be located at the eastern bounding fault of Bare Mountain. To the north and east of Yucca Mountain, the volcanic sequence continues for several to several tens of kilometers.

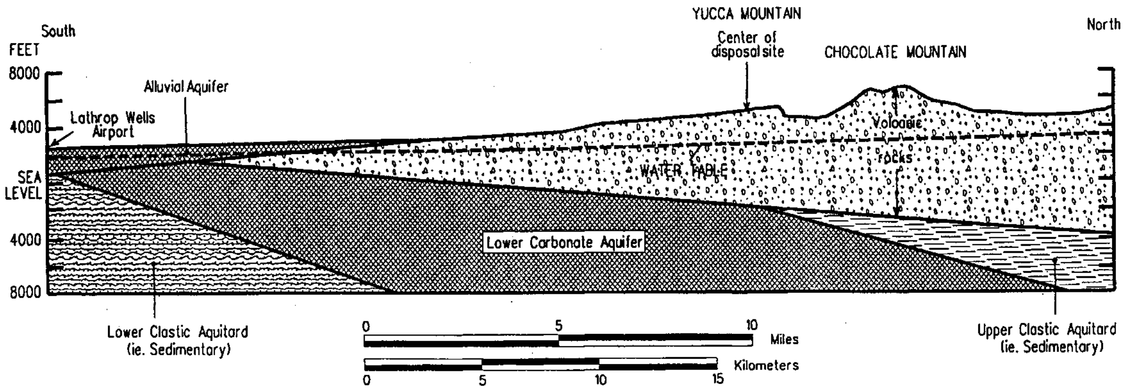


Figure 7-22. Schematic North/South Cross-Sectional Illustration of Thinning of Volcanic Units Beneath the Amargosa Desert (USG85a)

<u>Hydraulic Conductivity</u>

Rock properties largely control the characteristics of water occurrence and flow in the saturated zone. Rock properties, in turn, are dependent on eruptive history, cooling history, post-depositional mineralogic changes, and structural setting. Permeability of ash-flow tuffs is in part a function of the degree of fracturing, and thus, the degree of welding. Densely-welded tuffs fracture readily; airfall tuffs do not. Therefore, the distribution of permeability is affected by irregular distribution of different tuff lithologies and is a function of proximity to various eruptive centers. Permeability is also a function of proximity to faults and fracture zones (USG82a).

The most reliable method for determining aquifer hydraulic properties are pumping tests, especially those in which drawdowns are measured and analyzed in wells other than those being pumped. More than 150 individual aquifer tests have been conducted at and around Yucca Mountain since the 1980s. Most hydraulic data were from tests conducted in the lower volcanic aquifer and in the lower volcanic confining unit. Very few data were available for the upper confining aquifer and the upper volcanic confining unit. Almost all the tests were single-borehole tests in specific depth intervals and included constant-discharge, fluid-injection, pressure-injection, borehole flow meter, and radioactive tracer tests. Multiple-borehole tests have been conducted only at the C-well complex (USG96b, DOE96a). Most reported values of hydraulic conductivity available in the published literature were calculated from transmissivity values calculated from single-borehole pumping tests and should be regarded as "apparent hydraulic conductivity." Single-borehole tests do not record drawdown data from a large enough sample of the aquifer to be considered reliable. Drawdown data in the pumped well may be affected by a variety of factors such as fractures, well efficiency, borehole storage, gravity drainage, and borehole plumbing. USG96b reported that transmissivity and apparent hydraulic conductivity values determined using multiple-borehole hydraulic tests tend to be much higher—about two orders of magnitude—than values reported for single-borehole tests conducted at the same borehole.

Laboratory permeameter testing has been conducted on core samples taken during drilling of boreholes at Yucca Mountain. Welded units were reported to have matrix hydraulic conductivities with geometric means ranging from $2.0x10^{-6}$ to $3.0x10^{-6}$ m/day and bulk hydraulic conductivities of 0.09 to 10.1 m/day. The nonwelded units have variable hydraulic conductivities, with geometric means ranging from $2.6x10^{-5}$ to $3.0x10^{-2}$ m/day (USG84a).

USG91b reports that, for Well USW H-6, water production during pumping tests was coincident with fractured, partially, and partially- to moderately-welded tuff units. The reverse was not necessarily true; that is, not all fractured partially-welded tuff units produced water. USG91b also states that for Well USW H-6 "porosity and permeability of these rocks is generally inversely related. Porosity is greatest near the top and bottom of ash flow tuff units and is the least near the center. Permeability, as indicated by water production, is greatest near the center of units, where the degree of welding is greatest."

Hydraulic conductivity of the Topopah Spring Member, as determined from aquifer testing of a 120 meter interval of Well J-13, located about five miles east of the crest of Yucca Mountain, is about one m/d. Below the Topopah Spring Tuff Member, tuff units are confining beds. Hydraulic conductivities of units tested below the Topopah Spring Member at Well J-13 range from 0.0026 to 0.15 m/d (USG83).

Beneath Yucca Mountain, the Topopah Spring Member is above the water table. Wells installed in Yucca Mountain are open to the upper volcanic aquitard (Calico Hills Formation) and the lower volcanic aquifer (Crater Flat Tuff). Pumping tests conducted in these wells derived water primarily from the Bullfrog and Tram Members of the Crater Flat Tuff (USG91b). Hydraulic conductivities calculated from single-borehole pumping test data are shown in Table 7-5.

Table 7-5. Hydraulic Conductivities Calculated from Pumping Test Data

Well	K (m/day)	Source
UE-25b#1	0.46	USG84d
USW H-4	0.3 - 1.1	USG85c
USW H-6	0.85	USG91b
USW G-4	1.34	USG86

In addition to the cautions expressed above regarding the accuracy of single-borehole pumping test analyses, it is important to recognize that the values of hydraulic conductivity presented here are average values for the entire pumped interval in the well. Borehole flow surveys, in conjunction with acoustic televiewer logging, indicate that the volcanic rocks are highly inhomogeneous in the vertical direction and that the majority of water yielded from the wells derives from a few highly fractured water-bearing zones of limited thickness. The hydraulic conductivities shown above are likely to significantly underestimate the actual horizontal hydraulic conductivity of the water-bearing zones and to overestimate the hydraulic conductivity of the less transmissive zones. USG91b estimates hydraulic conductivities for specific intervals within the volcanic section. The authors calculated a hydraulic conductivity of about 9.1 m/d for a 15.2-meter section of the Bullfrog Member and 6.7 m/d for a 10.4-meter section of the Tram Member.

As previously stated, multiple-borehole tests have been conducted only at the C-well complex (USG96b, DOE96a). The pumping tests at this location involved pumping of selected horizons isolated by inflatable packers. In this way, transmissivity and hydraulic conductivities can be calculated for individual members of an aquifer or confining unit. The following description of transmissivity and hydraulic conductivity data is taken directly from DOE96a.

The results of four pumping tests conducted from June 1995 to May 1996 indicate that the transmissivity of the Calico Hills interval typically is 100-200 ft^2/d; the transmissivity of the Prow Pass interval typically is 400-700 ft^2/d; the transmissivity of the Upper Bullfrog interval typically is 400-1,000 ft^2/d; and the transmissivity of the Lower Bullfrog interval typically is 18,000-20,000 ft^2/d. The pumping tests conducted in 1996 indicate that transmissivity is about the same from UE-25 c#1 to UE-25 c#3 as it is from UE-25 c#2 to UE-25 c#1 (DOE96a). Horizontal hydraulic conductivities were calculated from computed transmissivities by dividing the transmissivity by the thickness of the transmissive rocks in the interval. Horizontal hydraulic conductivity typically is one to five ft/d in the Calico Hills interval and five to 10 ft/d in the Prow Pass interval. The horizontal hydraulic conductivity of the Upper Bullfrog interval typically is two to three ft/d from UE-25 c#1 to UE-25 c#3 and eight to 10 ft/d from UE-25 c#2 to UE-25 c#3. The horizontal hydraulic conductivity of the Lower Bullfrog interval typically is 70-90 ft/d from UE-25 c#1 to UE-25 c#3 and 150-210 ft/d from UE-25 c#2 to UE-25 c#3. Composite horizontal hydraulic conductivity from UE-25 c#2 to UE-25 c#3 consistently was found to be twice the composite value from UE-25 c#1 to UE-25 c#3. Ratios of vertical to horizontal hydraulic conductivity were determined to range downward from 0.08 to 0.0008 in the Calico Hills, Prow Pass, and Upper Bullfrog intervals. Note that the anisotropy in calculated hydraulic conductivities between UE-25 c#2/#3 and UE-25 c#1/#3 is opposite of that predicted on the basis of prevalent fracture orientations. The layout of the three boreholes to form a triangular pattern, with boreholes UE-25 c#1/#3 located along a line estimated to be the major semiaxis of the permeability tensor and UE-25 c#2/#3 along a line estimated to be the minor semiaxis of the permeability tensor (USG96a, p. 48). One possible explanation for this can be found in the relative distances of the wells from each other. Well #1 is twice the distance from #3 (pumped well) than is well #2; the apparent anisotropy may result from fracture/channeling effects associated with sampling the aquifer at different scales.

Porosity

In terms of bulk porosity, the volcanic sequence may be considered to consist of two different types of tuffs: welded and nonwelded (or bedded). The welding process generally reduces the matrix porosity. Therefore, the welded tuffs typically have a lower porosity than the non-welded tuffs (USG75, USG84a). The welded tuffs are also more highly fractured than their nonwelded counterparts. USG84a reports that welded units have a mean fracture density of eight to 40 fractures per cubic meter and mean matrix porosities of 12 to 23 percent. The nonwelded units have a mean fracture density of one to three fractures per cubic meter and mean matrix porosities of 31 to 46 percent. In both rock types, however, matrix porosity probably comprises the majority of bulk porosity because fracture porosities, even in the more highly fractured units, are reportedly quite small (USG85d). USG85d, using a theoretical model to calculate fracture porosity, reports a fracture porosity of tuffs penetrated by Well USW H-4 ranging from 0.01 to 0.1 percent. Matrix porosities probably decrease with depth due primarily to lithostatic loading and formation of secondary minerals (SPE89).

Effective Porosity

Effective porosity is that portion of the total porosity that contributes to saturated flow. Many of the volcanic rocks are characterized by relatively small pore sizes and lack of inter-connectedness of pores; thus, the effective porosity is normally significantly less than the total porosity. USG84a, p. 18, reports that preliminary laboratory studies of the vitric facies of the Calico Hills unit show that only about five percent of the pore space is large enough to contribute significantly to flow under saturated conditions. USG85d, p. 28, considers that fracture porosity is a reasonable estimate of effective porosity. USG83, p.13, reports that effective porosities in samples of welded tuff, vitrophyre, and zeolitized clayey pumiceous tuff range from 2.7 to 8.7 percent.

Storage Properties

Numerous pumping tests have been conducted in water wells completed in the volcanic rocks at Yucca Mountain and may be used to estimate storage properties. However, most calculations of storage coefficients for the volcanic rocks are based on single well pumping tests which generally do not produce reliable estimates of storage properties. The ground water storage characteristics of the fractured tuffs at Yucca Mountain are complex (USG85d). Estimates of storage properties of the volcanic rocks vary widely, depending partly upon the lithology and the degree of hydraulic confinement of the unit being tested. A particular hydrostratigraphic unit may be under unconfined conditions at one location and under confined conditions at another. USG91b calculates a storage coefficient of about 0.2. USG93a, p. 78, calculated storage coefficients for the more densely welded units that ranged from $1x10^{-5}$ to $6x10^{-5}$; for nonwelded to partially-welded ash flow tuff zones storage coefficients were estimated to range from $4x10^{-5}$ to $2x10^{-4}$. Composite storage coefficients calculated from the multiple-borehole C-well tests ranged from 0.001 to 0.004 (DOE96a).

The degree of confinement of the volcanic aquifers and confining units varies in ways that are consistent with the geology of the intervals and their distance below the top of the saturated zone (USG96b, DOE 96a). Beneath Yucca Mountain, the water table is either within or below the Calico Hills interval (upper volcanic confining unit); this interval typically responds to pumping as an anisotropic, unconfined aquifer. The underlying Prow Pass and Upper Bullfrog intervals (part of the lower volcanic aquifer) respond to pumping as either a leaky, unconfined or fissureblock aquifer. The Lower Bullfrog, isolated by intervals of nonfractured rock, typically responds to pumping as a nonleaky, confined aquifer.

<u>Recharge and Discharge</u>

Precipitation is the primary source of recharge to the volcanic aquifer (USG86; USG83). Snowmelt in the Timber Mountain area to the north of Yucca Mountain, as well as on Yucca Mountain itself, provides some of the precipitation-derived recharge. The occasional intense rainstorms experienced in the area also provide a source of recharge to ground water. However, because so much of the water that falls either evaporates immediately or is directed into steep channels along the flanks of the mountains to the permeable talus and alluvial deposits at the base of the mountain, the extent of this contribution is less certain.

Various methods have been employed to estimate the amount of precipitation that recharges the saturated zone beneath Yucca Mountain (NDC70; USG84e; USG82b). The most frequently employed approach is to divide the recharge area into a number of zones by altitude and to assume higher precipitation at the higher altitude zones. Some fraction of this precipitation, usually less than 10 percent, is then assumed to recharge the underlying saturated zone. Enhancements of this method allow for variable infiltration fractions to account for factors such as topography, rock type, and vegetation. In the volcanic system, recharge is more easily quantified than discharge, and discharge is usually calculated by assuming that outflows are equal to inflows. This assumption is necessary, but questionable. Some researchers have raised the possibility that the volcanic aquifer may still be equilibrating to a long term pulse of higher recharge during the wetter climate of the Pleistocene (about 10,000 years ago) (USG85f, USG96a). This possibility is not inconsistent with apparent ground water ages of 9,000 to 15,000 years calculated for the volcanic aquifer (USG93a; USG83). NDC70 estimated that the maximum recharge for Crater Flat and Jackass Flats is three percent of the precipitation rate, or about 4.5 mm/y. USG84a considers this the upper bound for the recharge rate that may be occurring in certain parts of the saturated zone beneath Yucca Mountain, estimating that recharge ranges from approximately 0.5 to 4.5 mm/year. Recent evidence, discussed previously, indicates that the percolation flux through the unsaturated zone probably ranges from one to 10 mm/yr, and averages approximately five mm/yr. Most of this percolation flux would be expected to recharge the saturated zone.

An upward hydraulic gradient from the underlying Paleozoic carbonate unit to the volcanic units (measured in Well UE-25p#1) indicates the potential for flow in the carbonate rocks to move into the overlying volcanic units. Additional evidence of upwelling flow from the carbonate aquifer includes zones of elevated ground water temperature and carbon isotopic relationships. Elevated temperature measurements from the upper saturated zone indicate the possibility of upwelling from the carbonate aquifer along the Solitario Canyon fault and in the area between the Bow Ridge and Paintbrush Canyon faults (USG96a, FRI94). Stuckless et al. (STU91) used the relationship of the $^{13}C/^{12}C$ ratio to the $\delta^{14}C$ of the ground water to argue for at least three sources of water under the mountain. They tentatively identified the three sources as: (1) lateral flow from the tuff aquifer to the north; (2) local recharge, probably introduced dominantly by flow in flash-flood watercourses on the eastern side of Yucca Mountain (Forty Mile Wash); and (3) water that upwells from the deep carbonate aquifer into the tuff aquifer. Savard (SAV94) has documented recharge to the volcanic aquifer from intermittent streamflow in Forty Mile Wash. In a saturated zone ground water model developed by the USGS, areal recharge had to be specified along Forty Mile Wash for the model to adequately simulate measured potentiometric levels in the vicinity of Yucca Mountain (USG84e).

Potential pathways by which ground water leaves the volcanic units include downgradient outflow, pumping, outflow to the carbonate aquifer, and flow into the unsaturated zone. Of the four pathways, flow into the unsaturated zone, where it occurs, is probably among the least significant (USG96a). There is no direct evidence that water from the volcanic units flows into the carbonate aquifer. Vertical hydraulic gradients, where measured, indicate the potential for flow is from the carbonate aquifer to the volcanic aquifer. The DOE states that the "current conceptual model for the regional ground water flow system considers that ground water in the volcanic rocks beneath Yucca Mountain moves generally southward and discharges in the subsurface into the valley fill alluvium as the volcanic section thins and ultimately pinches out south of Yucca Mountain" (DOE95f). Currently, water is pumped from the volcanic aquifer from two wells, J-12 and J-13, located in Jackass Flat near Forty Mile Wash. These wells supply water for part of the Nevada Test Site, as well as for all site characterization activities at Yucca Mountain, including human consumption.

Paleozoic Carbonate Aquifer

Thick sequences of carbonate rock form a complex regional aquifer system or systems that are largely undeveloped and not yet fully understood. Secondary permeability in this sequence has developed as a result of fracturing and enlargement of existing fractures by solution. The area underlain by carbonate rocks is characterized by relatively low volumes of runoff. Flow can be complex and may include substantial interaction with volcanic and basin fill aquifers (USG75).

Due to the extensive, thick cover of volcanic rocks and alluvium in the vicinity of Yucca Mountain, the local characteristics of the Paleozoic sequence are not well known. In eastern Nevada, the Paleozoic sequence of sedimentary rocks is commonly divided into four general hydrogeologic units: the lower clastic aquitard, the lower carbonate aquifer, the upper clastic aquitard, and the upper carbonate aquifer. Evidence from drill hole data and geologic mapping in surrounding mountain ranges indicates that only the lower carbonate aquifer may be present in the vicinity of Yucca Mountain and to the south.

Aquifer Geometry

Evidence suggests that the lower Carbonate aquifer underlies the entire area. Exposures of Paleozoic rocks at the perimeter of the study area include Bare Mountain to the west of Yucca Mountain, the Funeral Mountains south of the Amargosa Desert, and the Specter Range to the east and southeast. Further evidence comes from three drill holes which have penetrated the overlying units to reach saturated carbonate rocks — borehole UE-25p#1 on the eastern flank of Yucca Mountain, which penetrated through Tertiary volcanic rocks into the underlying carbonate sequence, and two oil wildcat wells drilled near Amargosa Valley. Additional information regarding these wells is provided in Table 7-6.

Examination of the altitudes of the top of the carbonate aquifer in Table 7-6 indicates that the buried surface of the buried carbonate aquifer is quite irregular. This variability is probably a combination of relief of the original erosional surface of the carbonate units coupled with structural offsets produced by faulting.

Saturated thickness of this aquifer is largely unknown; USG75 indicates that water circulates freely to depths of at least 1,500 feet beneath the top of the aquifer and up to 4,200 feet below land surface. The effective flow thickness of the aquifer depends, in part, upon the lithostatic pressure at depth, which in turn depends on the thickness of the column of rock overlying the carbonate aquifer.

Table 7-6. Borehole Location and Depth Data for Wells Drilled to the Lower Carbonate Aquifer in the Vicinity of and Downgradient of the Yucca Mountain Area

Well ID*	Latitude & Longitude	Surface Altitude (m)	Depth to Carbonate Aquifer (m)	Altitude (MSL) of Top of Carbonate Aquifer (m)
UE-25 p#1	36°49′38″/ 116°25′21″	1,114.9	1,244	-129.1
Federal-Federhoff 5-1	36°35′32″/ 116°22′54″	772.9	259	513.9
Federal-Federhoff 25-1	36°37′07″/ 116°24′26″	783.9	671	112.9

*Note: Information for well UE-25 p#1 obtained from USG84c. Information on oil exploration wells obtained from DRI94.

Hydraulic Conductivity

Interstitial permeability of the carbonate rocks is negligible; essentially all of the flow transmitted through these rocks is through fractures. Permeability measurements of the carbonate rocks are reported as transmissivity values, as opposed to hydraulic conductivity values, because the thickness of the carbonate unit through which water is flowing is not well known. Estimates of fracture transmissivity range from 1,000 to 900,000 gallons per day per foot (USG75). USG75 reports the results of six pumping tests in the lower carbonate aquifer. The average calculated transmissivity was 13,000 gallons per day per foot.

Porosity

USG75 reports that total porosity determinations were made for 16 samples of the lower carbonate rocks. Total porosities ranged from 0.4 to 12.4 percent with an average of 5.4 percent. Fracture porosity of the rock is estimated to range from 0 to 12 percent of rock volume.

Effective Porosity

Due to the extremely low matrix permeability of the carbonate rocks, effective porosity can be approximated as the effective porosity of the fractures. Many of the fractures in the carbonate units are partially filled with clay or other materials which reduce both fracture permeability and effective porosity. USG75 reports that effective porosity values determined for 25 samples of the lower carbonate rocks ranged from 0.0 to 9.0 percent, with an average of 2.3 percent.

Storage Properties

USG75 reported that, based on examination of rock cores, the effective fracture porosity of the lower carbonate aquifer is probably a fraction of one percent; accordingly, the storage coefficient under unconfined conditions is not likely to exceed 0.01. Because of the extremely low effective porosity of the carbonate rocks, the specific storage under confined conditions probably ranges between 10^{-5} and 10^{-6} per foot. Where the aquifer is several thousand feet thick the storage coefficient may be as large as 10^{-3}.

Recharge and Discharge

Direct areal recharge to the carbonate aquifer occurs where these rocks are exposed at the surface. The highest amounts of areal recharge are expected to occur in highland areas where precipitation levels are highest and where the highly fractured rocks are exposed at the surface. Recharge to the carbonate units may also derive from downward infiltration through overlying volcanic or alluvial deposits. The relationship of flow potential in the carbonate aquifer to that in the overlying units is not well known. No downward gradients have been measured between the carbonate aquifer and overlying units in the study area. This would seem to indicate that the recharge areas for the carbonate aquifer are located relatively far away from Yucca Mountain. North of the proposed repository area is an area of relatively high hydraulic gradient, measured in the saturated volcanic rocks. One proposed explanation for this high hydraulic gradient is an inferred east-west striking graben which provides a conduit for ground water flowing in the volcanic aquifer to drain into the underlying carbonate aquifer (FRI94). If this is the case, then the carbonate aquifer is being recharged by flow from the overlying volcanic units at this location.

The only measurements of potential in the carbonate aquifer made near Yucca Mountain indicate vertically upward hydraulic gradients over wide areas of the carbonate unit. Over at least part of the study area (in borehole UE-25 p#1) and beyond (specifically in the Amargosa Desert east of the Gravity and Specter Range Faults), upward hydraulic gradients have been measured between the carbonate aquifer and overlying units. These upward hydraulic gradients indicate the potential for upward flow, but do not demonstrate that such flow is occurring in these areas.

Discharge from the carbonate aquifer would occur in those areas where such flow actually occurs. FRI94 describes anomalously high ground water temperatures measured beneath Yucca Mountain in the saturated volcanic aquifer which indicates upward flow (discharge) from the carbonate aquifer into the overlying volcanic units may be occurring in the vicinity of the Solitario Canyon Fault.

One major discharge location for flow in the regional carbonate aquifer is at Ash Meadows, located southeast of Yucca Mountain. It is not clear, however, whether discharge at Ash Meadows includes any ground water that has flowed beneath Yucca Mountain (this point is discussed in more detail in Section 7.1.2.3). Additionally, Death Valley, located about 60 kilometers south-southwest of Yucca Mountain, is regarded by many researchers as the base level or terminus for the entire regional system and, as such, accommodates discharge from the carbonate aquifer (USG88a). There are also numerous small, relatively low flow springs located throughout eastern Nevada, though to a lesser extent in the study area, which represent discharge points from the carbonate aquifer(s) (USG75).

Alluvial Aquifer

Valleys, topographic basins, and other topographic and structural lows are filled with variable thicknesses of unconsolidated, often poorly-sorted sand and gravel deposits. Lacustrine and eolian deposits are found locally. Basin-fill deposits are generally 2,000 to 5,000 feet thick, but in some basins exceed 10,000 feet in thickness. Basin-fill ground water reservoirs are restricted in areal extent, generally being bounded on all sides by mountain ranges. Beneath the central parts of the deeper valleys, the water table is encountered in the alluvium. At and near the valley margins, the alluvium is relatively thin and the water table occurs in the underlying consolidated rocks.

In the Yucca Mountain area, several basin-fill aquifers or potential aquifers exist. These are: Crater Flats, west of Yucca Mountain; Jackass Flats, east of Yucca Mountain; and Amargosa Valley, located south of Yucca Mountain. The Amargosa Valley aquifer is substantially larger and more significant as an aquifer than the Crater Flats and Jackass Flats basins (USG91a). Farther to the south, across the Funeral Mountains, lies the Death Valley alluvial aquifer.

Aquifer Geometry

The intermontane alluvial basins tend to be elongated in a north-south direction and are of roughly the same dimensions as the mountain ranges that separate them (FIE86). The alluvial fill thickens toward the center of the basins. The Crater Flats and Jackass Flats alluvial basins are bounded on their northern sides by mountainous areas at approximately the latitude of the north end of Yucca Mountain. Crater Flat is bounded at its southern end by a small, southeast trending ridge of rock outcrops. Topographic map patterns and satellite photographs (DOE95g) suggest that the Crater Flat Basin may be closed. The Jackass Flats basin does not have a well-defined southern terminus; it appears to have an outlet at its southwestern end which merges into the larger, northwest trending Amargosa Desert Basin. The Amargosa Basin is bounded on its northwest end by the Bullfrog Hills and on its southwestern boundary by the Paleozoic carbonate sequences of the Funeral Mountains. Both the Crater Flats and Jackass Flats alluvial basins are bounded below by their contact with Tertiary volcanic rocks (USG88b; USG83). South of Yucca Mountain, the volcanic sequence thins and probably pinches out (USG85a). If so, alluvial deposits may rest directly on top of Paleozoic carbonate units in the southern part of the basin. As previously described, two oil exploration wells drilled in the Amargosa Desert, near the town of Amargosa Valley, went through sedimentary (mostly alluvial) deposits into the carbonate aquifer. The thickness of the alluvial deposits at these wells was 259 m and 671 m, respectively (See Table 7-6). The exact nature of the sediments through which these wells were drilled is not clear, as drilling logs were not examined. DRI94 refers to the sediments both as “alluvium” and as “Neogene.” Czarnecki and Wilson (HST91, p. 22) refer to deep (600 m) boreholes in the south-central Amargosa Desert which terminated in “Tertiary basin-fill sediments” underlying the Quaternary alluvial fill, thus opening the possibility that the Quaternary alluvial basin-fill sediments do not directly overlie the Paleozoic carbonate sequence, but are instead separated from it by an unknown thickness of undifferentiated Tertiary sediments.

Thicknesses of the deposits in the three alluvial basins in the study area are not well known due to the scarcity of drill holes that penetrate the entire alluvial sequence. Two drill holes in Crater Flat (USW VH-1 and USW VH-2) penetrate through the alluvial cover into volcanic rocks. Thickness of the alluvium in drill hole USW VH-2 is approximately 305 m, with a depth to water of 164 m. In Jackass Flats, Well J-13 penetrated approximately 137 m of alluvium prior to entering Tertiary volcanic rocks; the alluvium was not saturated at this location (USG83). Most of the wells drilled in the Amargosa Valley are water wells for irrigation and water supply. Since most of these wells encountered sufficient water in the alluvium, drilling was not carried through to the underlying units; thus, direct evidence for the thickness of the Amargosa Basin alluvial deposits is lacking. Indirect evidence (geophysical methods) indicates that the thickness of the alluvial cover in the southern Amargosa Desert may be as much as 1,585 m (USG89).

Saturated thickness and depth to water varies considerably among basins and within a given basin. In basins where significant discharge areas exist (typically manifested as dry lakes or playas), depth to water may be only a fraction of a meter to a few meters. Other alluvial basins may have no saturated zone at all. In the Amargosa Basin, south of Yucca Mountain, the water table in some irrigation wells is about 56 m deep. Considering that the basin may be over 1500 m deep, the thickness of the saturated zone in the Amargosa Basin could be over 1500 m. A study conducted in the Amargosa Basin area (USG89) concluded that at least 85 percent of the alluvial thickness in the Amargosa Basin is saturated.

Hydraulic Conductivity

USG75 reports the results of several single well pumping tests in alluvial aquifers at the Nevada Test Site. These wells are located outside of the area studied for the Yucca Mountain Project, but the formations tested are broadly similar, and the results are generally applicable to alluvial deposits within the immediate area of concern. These authors found the hydraulic conductivity of the alluvial deposits to range from 0.020 to 2.84 m/d. Due to the discontinuous nature of individual lenses or units within alluvial fill, hydraulic conductivity is expected to show wide variations in magnitude.

Porosity

The sediments which comprise the alluvial fills are typically coarse grained and poorly sorted, most of them having been deposited by flash flood conditions over many thousands of years. Although sediments such as these characteristically have relatively large total porosities, measured porosities tend to be highly variable due to their poorly sorted nature. USG75 reports that the total interstitial porosity of 42 samples of valley fill range from 16 to 42 percent and averaged 31 percent. Caliche, where present, would reduce porosity, perhaps significantly. USG75, p. 37, reports that caliche is a common cementing material at all depths in a shaft sunk in alluvium in the northwestern part of Yucca Flat to a depth of 550 feet.

Effective Porosity

Poorly sorted sediments often have values of effective porosity that are substantially less than their total porosity. Given the grain size and poorly sorted nature of the alluvium, effective porosity values may range from a few percent to perhaps as much as 25 to 30 percent.

Storage Properties

NDC63 estimated specific yield for the alluvial deposits in the Amargosa Basin using grain size distribution methods. The estimated average specific yield for this basin is 17.34 percent; actual values ranged from not less than 10 percent to not greater than 20 percent (NDC63).

Recharge and Discharge

There are several potential sources of recharge for the alluvial aquifers in the vicinity of Yucca Mountain. One source is direct recharge from precipitation falling on the alluvial areas. Recharge is also derived to some extent from infiltration of intermittent surface waters of the Amargosa River and washes draining off the mountains (SAV94). A third source of recharge to alluvial aquifers is infiltration or leakage from underlying bedrock aquifers. Human activity may also provide a source of recharge to the aquifers, chiefly by return infiltration of irrigation and percolation of sewage or wastewater. The primary method of estimating recharge in the alluvial aquifers is to calculate discharge from the aquifer, most of which occurs as evapo-transpiration at playas, and to assume inflows are equal to outflows. NDC63 and USG85e provide details of calculation methods and estimates of recharge for the Amargosa Basin; values are discussed in Sections 7.1.2.3 and 7.1.2.4.

The nature and relative importance of potential recharge sources to the Amargosa Desert alluvial aquifer is a matter of some debate. Perhaps the major source of recharge to the alluvial aquifer is lateral flow into the alluvial deposits from the thinning volcanic aquifer to the north (USG86). This is contradicted by USG85f, which uses ground water geochemical data to argue that "ground water in the west-central Amargosa Desert ....was recharged primarily by overland flow of snowmelt in or near the present-day stream channels, rather than by subsurface flow from highland recharge areas to the north," and that "much of the recharge in the area occurred during Late Wisconsin time" (USG85f, p F1). This conclusion fails to account for the eventual fate of water in the volcanic units to the north and is probably too restrictive.

The upward hydraulic gradients measured in the lower carbonate aquifer support the idea that much of the outflow from the volcanic aquifer moves into the alluvial aquifer. Although this outflow presumably occurs somewhere between Yucca Mountain and Amargosa Valley, the potentiometric surface, at the scale at which it is currently mapped, provides little indication as to how or where this transition occurs. A recent study, using streamflow data and a modified version of the HYMET model for the Amargosa River, suggests that the alluvial aquifer may also be receiving recharge via upward flow from the carbonate aquifer (INY96).

USG91a shows water level altitude maps for 1950's (predevelopment) conditions in the Amargosa Desert. Comparison of this map with more recent (1987) water level altitude maps indicates that aquifer development may have had a significant impact on water levels and flow directions. Pumping of the alluvial aquifer may have induced upward flow from the underlying lower carbonate aquifer into the alluvial system. The extent to which areal recharge occurs via infiltration of present-day precipitation falling directly onto the alluvial valleys is thought to be minimal. This is because of the infrequent rainstorms and the shallow depths to which rainfall soaks into the desert soil during such events. After a rainstorm, much of this water rapidly evaporates back into the atmosphere (USG85f).

Several potential modes for natural discharge from alluvial basins exist, including interbasin flow to other alluvial basins; leakage to the underlying units, either volcanic or carbonate; and evapotranspiration (NDC63). Discharge from the alluvial aquifers also occurs in the form of ground water withdrawals by pumping. In the Amargosa Valley alluvial basin, ground water is pumped for domestic and irrigation purposes (USG91a). Quantitative estimates of recharge and discharge from the Amargosa alluvial basin are discussed in more detail in Section 7.1.2.4.

Potentiometric and hydrochemical data indicate that the Alkali Flat (also known as the Franklin Lake Playa), located in the southern end of the Amargosa Desert, is a major discharge area for the alluvial aquifer system. Estimated discharge at Alkali Flat is about 10,000 acre-feet per year (DOI63). Discharge at the playa occurs primarily through evapotranspiration, the principal component of which is bare-soil evaporation (USG90b). Some ground water may flow beneath the mountain at the south end of the playa and continue southward (USG96a). Regional water table maps of the alluvial aquifer (see USG91a) also suggest that a portion of the flow in the alluvial aquifer may be moving southwest through the abutting carbonate rocks of the Funeral Mountains, and discharging into Death Valley. The extent to which this occurs is unknown.

7.1.2.3 Regional Ground Water Flow and Hydrology

The nature of regional ground water flow in the Yucca Mountain area is governed by the complex three-dimensional nature of the geological and structural units through which it flows. As previously described, the geological setting in this area involves a basement of Paleozoic 1 sedimentary rocks which have been complexly folded and faulted. The Paleozoic sequence is overlain in many areas by a thick section of volcanic rocks and/or alluvial basin fill deposits. The Paleozoic and volcanic sequences have been disrupted by faults which have juxtaposed various units against one another and created the basin and range structure. The resulting geological and stratigraphic complexity creates a correspondingly complex regional ground-water flow system.

Key to understanding regional ground water flow in this area is the concept that the large-scale flow system may comprise up to three coexisting ground water flow subsystems: local, intermediate, and regional. These subsystems exist one on top of the other, as well as side by side. This concept is illustrated in Figure 7-23. The coexistence of such subsystems means that deep regional flow can pass beneath shallow local areas of high permeability and that the presence of hydraulic barriers or variations in permeability can cause appreciable discharge upgradient from the hydraulic terminus of the system. Major flow systems in the Great Basin are defined by the dominant flow system, whether it be local, intermediate or regional. Where consolidated rocks are permeable enough to afford significant identifiable hydraulic continuity on a regional scale, the local and intermediate types of systems are considered to be subsystems with major regional flow systems. Boundaries between systems are only generally defined; some may represent physical barriers to flow, such as masses of intrusive rocks, while others represent ground water divides or divisions where an area of parallel flow ultimately diverges downgradient.

Regional Ground Water Flow Systems in the Yucca Mountain Area

The Great Basin is considered to consist of 39 “major flow systems” (USG93b). The study area is located within the Death Valley Ground Water Flow System (DVGWS) which covers an area of 15,800 square miles (40,100 km^2) in Nevada and California (Figure 7-24). The boundaries of the DVGWS are not precisely known; traditional lateral boundaries are topographic divides that

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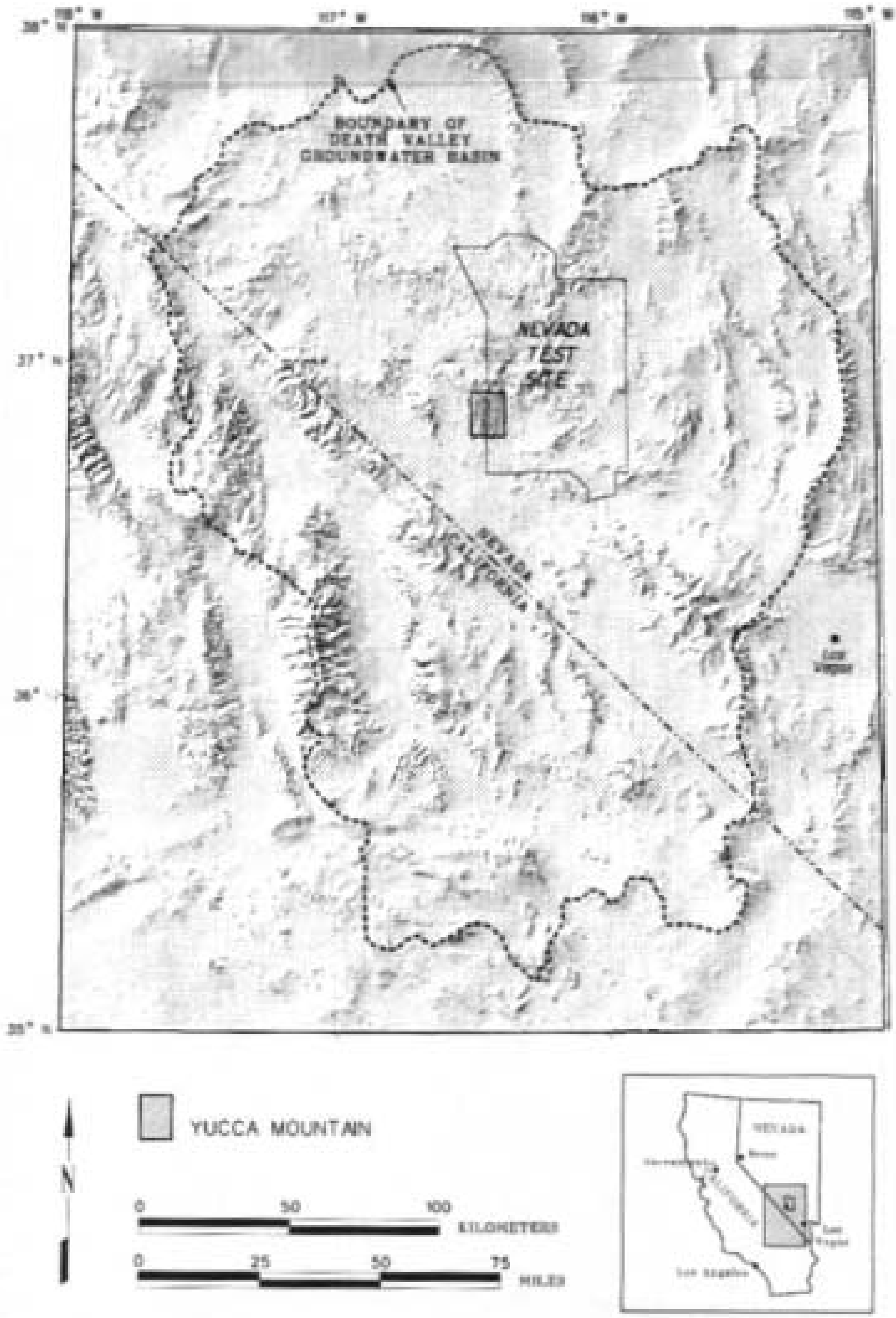

Flood plain, hydrologic regimen of this area dominated by the river. Water table fluctuates in response to charges in river stage and diversions. Area commonly covered by phreatophytes (shown by random dot pattern).

Approximate point of maximum stream flow.

Figure 7-23. Schematic Illustration of Ground Water Flow System in the Great Basin (USG76a)

Figure 7-24. Death Valley Ground Water Flow System (USG96a) may be physical barriers to ground water flow or may coincide with ground water mounds formed by local recharge. Rarely, however, are these boundaries true hydraulic barriers.

The DVGWS is further subdivided into a small number of hydrogeological subareas or basins. Yucca Mountain is located within the Alkali Flats-Furnace Creek Ranch subbasin (Figure 7–25). Definition of the hydrologic boundaries of the basins is greatly hindered by the complexity of the geologic structure, the limited potentiometric data, and most critically, the interbasin movement of ground water through the thick and aerially extensive lower carbonate aquifer (USG75). The basin covers an area of about 2,800 mi^2 and was named after the two major discharge areas near its southern end (USG82c). The principal aquifers in the northern part of the subbasin are volcanic aquifers; valley-fill and carbonate rock aquifers dominate in the southern part. The subbasin receives water from recharge within its boundaries and probably also receives water as underflow from adjoining subbasins. Ground water leaves the subbasin as evapotranspiration at discharge areas or as interbasin outflow (USG96a). Alkali Flat is an area where ground water discharge occurs almost entirely through evapotranspiration. The other major discharge is thought to be from springs near Furnace Creek Ranch, near the headquarters of the Death Valley National Monument. A 1984 study (USG84g) estimated discharge from the subbasin at about 15,600 acre-ft/yr; of this total, about 10,000 acre-ft/yr discharges at Alkali Flat and the remainder discharges from springs and as evaporation near Furnace Creek Ranch in Death Valley. More recent work (HST91) developed a conceptual model that excluded the Furnace Creek Ranch discharge area from the shallow flow system that includes Yucca Mountain. HST91 reported that a ground water divide could exist in the Greenwater and Funeral Ranges between the southern Amargosa Desert and Death Valley. Such a divide, if it exists, could limit discharge from the shallow flow system in the Amargosa Desert to the Furnace Creek Ranch area, although it would not necessarily affect the deeper flow system that may also contribute discharge to the Furnace Creek Ranch area.

Adjoining the Alkali Flats-Furnace Creek Ranch subbasin to the east is the Ash Meadows subbasin. These subareas are separated by an irregular north-south line which runs east of Yucca Mountain. In general, ground water flow in these basins is considered to originate from recharge in the upland areas of the basin and to move in a southerly direction toward discharge points in alluvial basins located in the southern parts of the basins. The southern portion of the boundary between the Alkali Flat-Furnace Creek Ranch subbasin and the Ash Meadows sub-basin is located along a line of springs (Ash Meadows) which coincides with the trace of a buried fault.

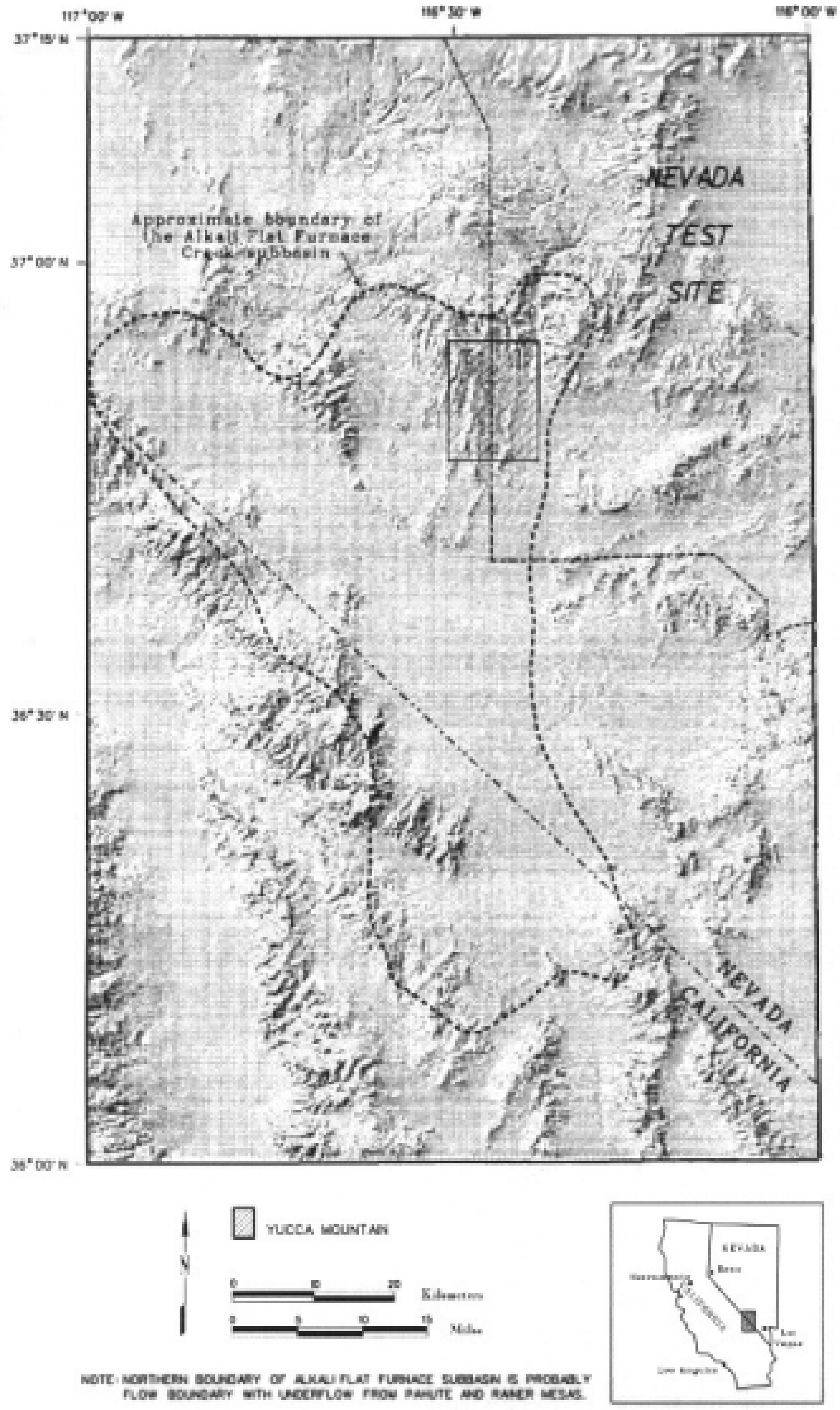

Figure 7-25. Alkali Flat-Furnace Creek Ranch Ground Water Subbasin (USG96a)

This fault causes water to rise to the surface by juxtaposition of permeable and impermeable units of the Paleozoic rocks. Subsurface outflow into the Alkali Flat-Furnace Creek Ranch subbasin is probable, especially in the vicinity of the buried fault. Geochemical and potentiometric data suggest leakage of water from the carbonate aquifer into the alluvial aquifer east of the fault line (USG85f). The degree of connectedness of the two subbasins may be more significant than localized leakage across the bounding fault. USG96a suggests that "deep hydraulic connection through the carbonate aquifer may connect the Ash Meadows area on the east side of the Amargosa Desert to the Furnace Creek Ranch area of Death Valley. This possible connection is consistent with the observation that the hydrochemistry of water from springs that discharge at Furnace Creek Ranch is similar to the hydrochemistry of water discharging at some springs in the Ash Meadows area. This similarity in hydrochemistry allows the possibility of westward ground water flow through deep aquifers beneath the Amargosa Desert, whereas flow through the shallower aquifers seems to be predominately southward" (USG96a).

Ground Water Flow Directions and Potentiometric Surfaces

Within the DVGWFS, recharge from precipitation probably occurs at Timber Mountain, Pahute Mesa, Ranier Mesa, Shoshone Mountain, and the Spring Mountains. In the vicinity of Yucca Mountain, infiltration of runoff in Forty Mile Canyon and Forty Mile Wash probably contributes to recharge. On a regional and subregional scale, ground water is generally considered to flow from these recharge areas to discharge areas located at the southern end of the flow system (USG75). Much of the ground water which travels beneath Yucca Mountain probably discharges at Alkali Flat (Franklin Lake) in the southern Amargosa Desert and/or in the springs on the eastern side of Death Valley. Death Valley is the ultimate ground water discharge area and is a closed basin; no water leaves it as surface or subsurface flow (USG96a). Numerous workers have constructed potentiometric surface maps for this area, including USG75, USG82c, USG84f, USG91a, and USG94a. Availability and quality of potentiometric data for the subbasin are highly variable. Wells are irregularly distributed throughout the subbasin; the greatest density of wells is on Yucca Mountain itself and in the Amargosa Valley. Data are almost entirely lacking in the mountainous recharge areas north of Yucca Mountain. In the immediate vicinity of Yucca Mountain itself, numerous wells have been drilled to the saturated zone and the potentiometric surface is well-characterized. The potentiometric surface in Amargosa Valley and in the vicinity of Alkali Flat is also relatively well defined by numerous irrigation and monitoring wells. There are almost no potentiometric data available in the Greenwater and Funeral Ranges, which bound the Amargosa Desert on its southwestern side. Figure 7-26 shows the regional potentiometric surface for the DVGWFS. The following sections discuss in detail the nature of the potentiometric surfaces in each of the three main aquifer types.

Volcanic Aquifer

The lateral extent of the volcanic rocks that make up Yucca Mountain is not well defined, primarily because the volcanic units are buried beneath alluvial deposits in the topographically low areas. South of Yucca Mountain, the volcanic section is believed to thin and pinch out somewhere in the vicinity of Lathrop Wells (USG85a, DOE94b). Where the volcanic unit is not present, alluvial deposits presumably directly overlie Paleozoic sedimentary rocks. Where the volcanic units thin south of Yucca Mountain, ground water flowing in the volcanic aquifer discharges horizontally into the adjoining alluvial deposits and continues to flow in a southerly direction beneath the Amargosa Desert.

At the scale of Yucca Mountain, there are significant variations from the regional flow pattern, resulting in local ground water flow with a strong easterly component. The potentiometric surface beneath Yucca Mountain has been relatively well-characterized. Potentiometric surface maps are presented in USG95a, USG94a, and USG84f, among others. The potentiometric surface can be divided into three regions: (1) a small-gradient area (0.0001) to the southeast of Yucca Mountain, (2) an area of moderate-gradient (of about 0.015) on the western side of Yucca Mountain, where the water level altitude ranges from 775 to 780 m and appears to be impeded by the Solitario Canyon Fault and a splay of that fault, and (3) a large-gradient area (0.15 or more) to the north-northeast of Yucca Mountain, where water level altitudes range from 738 to 1,035 m (USG94a). Numerous theories have been proposed to explain the presence of the three domains and especially the cause of the large gradient area, where water levels decline by more than 900 feet over a distance of slightly greater than one mile. The position of the large gradient area does not correlate well with any observed geologic feature in the upper 1,500 feet of the mountain (FRI91). The area where the gradient has been defined is about 1.7 miles north of the design repository. If the gradient is caused by a barrier to ground water flow, it could be of particular importance to the design and performance of the repository; an increase in the permeability of such a barrier could cause a substantial rise in water table altitude in the area of the proposed repository. A rise in the water table would decrease the thickness of the unsaturated zone beneath the repository and decrease ground water travel time from the repository to the accessible environment (SIN89).

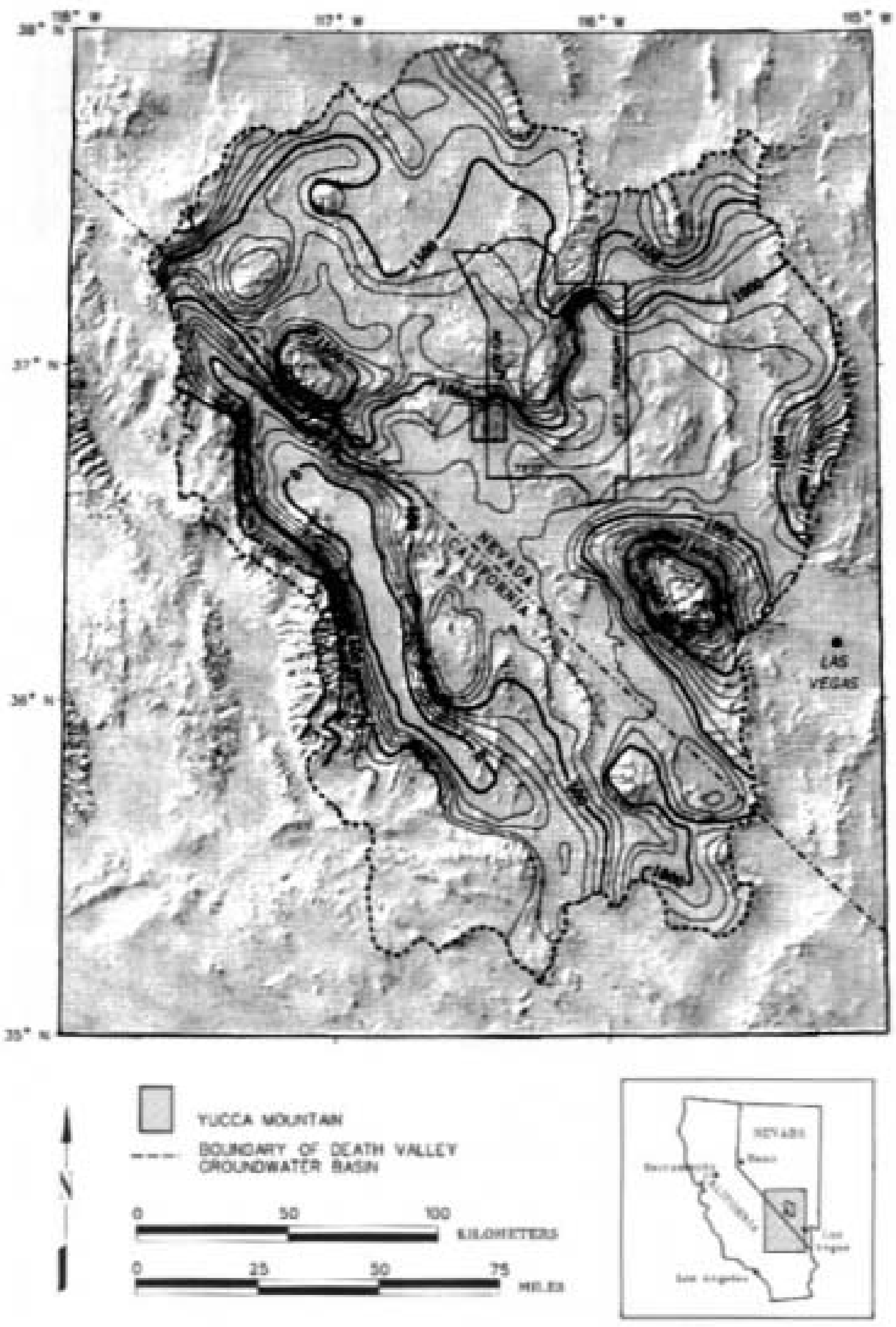

Figure 7-26. Potentiometric Surface in the Death Valley Ground Water Flow System (USG96a)

Possible causes of the large gradient other than the flow barrier include, but are not limited to: a fault or fault zone; an intrusive dike; a change in lithologic facies or a pinch-out; a change in fracture orientation, density, aperture, or fracture fillings; perched water zones; or some combination of the above phenomena. Fridrich et al. (FRI94) have proposed two models for the large gradient zone, integrating geologic, geophysical and geochemical evidence to support their analysis. These and other authors interpret a northeast trending gravity low and drill hole data to indicate the presence of a buried northeast striking graben (a downdropped block of rock bounded on both sides by faults) immediately south of the water table decline. The large gradient zone is coincident with the northern bounding fault of the proposed graben. The presence of the northern bounding graben fault, which is not exposed at the surface and is not known to have been encountered in any drill holes in Yucca Mountain, is central to both models proposed.

Briefly, the first conceptual model proposes that the buried fault zone provides a permeable pathway through the volcanic section into the underlying deep carbonate aquifer. The second model has the buried fault acting as the northern boundary for a much thicker and more transmissive volcanic section south of the buried fault. These authors also suggest that rapid draining of water in the large gradient zone may cause the low gradient area to the south and southeast. In this model, the small gradient zone may result partly from a reduced ground water flux in the volcanic rocks due to the capture of flow by the underlying deep carbonate aquifer.

Carbonate Aquifer

The lower carbonate aquifer has a maximum thickness of about 8,000 m. Because the carbonate aquifer in the study area is overlain by thick deposits of volcanic rocks or alluvium, flow directions and gradients are not well-defined. Regional ground water flow through the lower Paleozoic aquifer is considered to be generally southward. Small-scale potentiometric surface maps are presented in USG75. The lower carbonate aquifer is present below Yucca Mountain at a depth of about 1,000 m and extends southward below the Amargosa Desert into Death Valley. There are a very limited number of holes that penetrate the lower carbonate aquifer beneath the valley fill. Much of the physical knowledge of the system is based upon studies of the outcrop areas, most of which are in the mountain ranges. The best interpretation of available geological data indicates that the lower carbonate aquifer is continuous from beneath Yucca Mountain to Death Valley and is a potential pathway for radionuclide transport in what appears to be the ultimate discharge point for the aquifer in Death Valley.

The extent of hydraulic communication between the volcanic and underlying Paleozoic sequence is not well characterized. In the only well (UE-25p#1) at Yucca Mountain which penetrated into the Paleozoic sequence, an upward hydraulic gradient (from Paleozoic to the Tertiary) was measured. Analysis of earth-tide response of water levels in this well have been interpreted to indicate that the carbonate aquifer is well-confined by an overlying low-permeability confining layer and has a relatively high transmissivity (INY96). Additional evidence, including isotopic composition and temperatures of ground water beneath Yucca Mountain, supports the concept that ground water may be flowing from the Paleozoic aquifer into the volcanic aquifer (USG88c; STU91).

Alluvial Aquifer

Significant amounts of ground water occur in the alluvial aquifer beneath the Amargosa Desert. In the Amargosa Valley area, irrigation activity derives all of its water from wells completed in the alluvial aquifer, some of which yield water at rates of several hundred gallons per minute. Static water levels are less than 55 m below the surface in some locations. Figure 7-27, taken from USG91a, shows a map of the water table in the Amargosa Desert. USG91a also provides a map of depth to water in the Amargosa Desert. Ground water flow in the alluvial aquifer is generally perpendicular to the potentiometric contours. The potentiometric contours shown in Figure 7-27 indicate that the predominant flow direction is to the south. The ground water flow direction is also roughly parallel to the surface drainage direction. At the southern end of the Amargosa Desert, low permeability playa and lake bed deposits create locally-confined conditions. The potentiometric surface at Alkali Flat is in some locations above the ground surface (USG90b).

The potentiometric surface shown in Figure 7-27 is drawn from 1987 data. Comparison of this map with water level altitude maps for 1950’s (predevelopment) conditions (USG91a) in the Amargosa Desert indicates that irrigation pumping has had a significant impact on water levels and local flow directions. Pumping of the alluvial aquifer may also have induced upward flow from the underlying lower carbonate aquifer into the alluvial system.

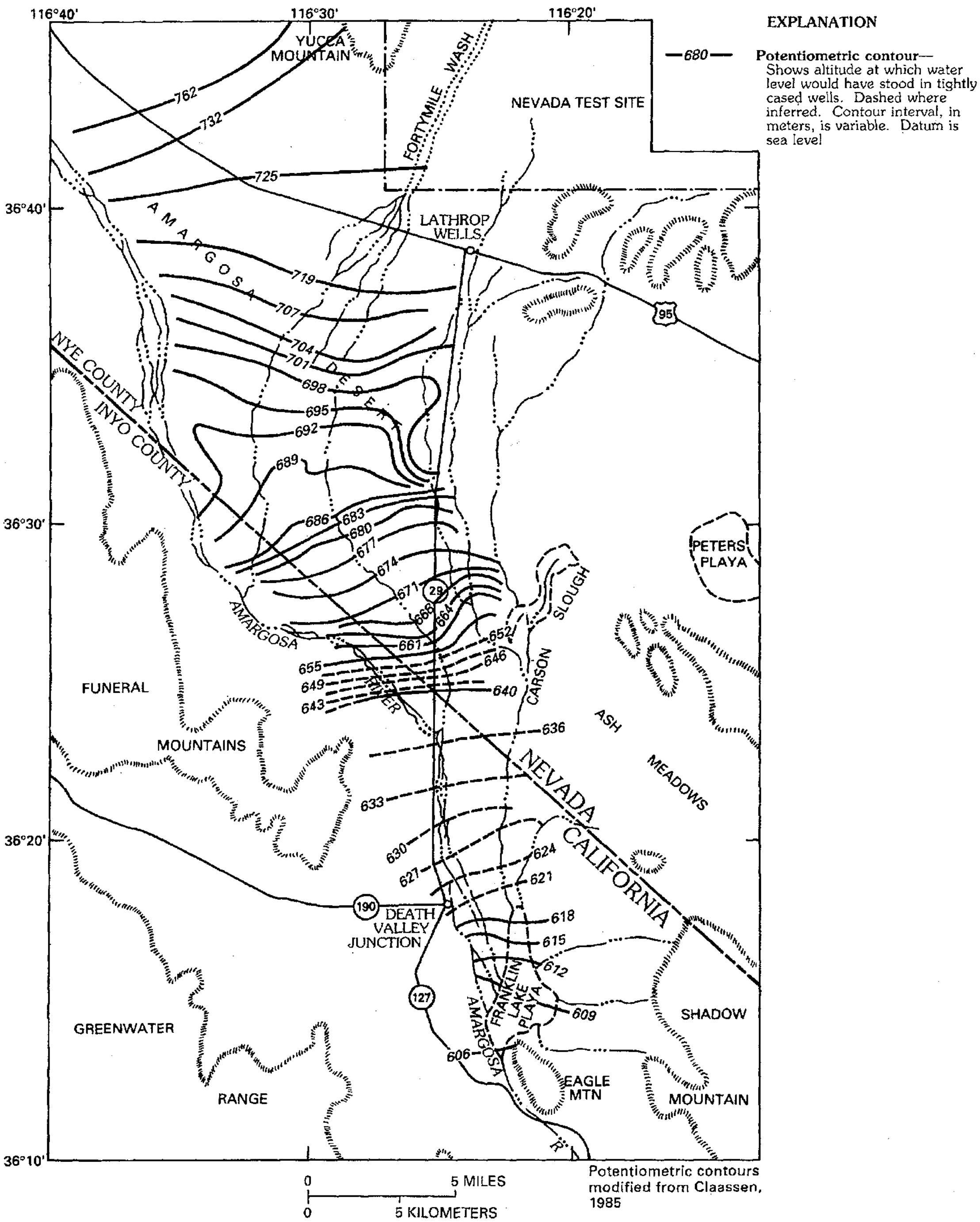

Figure 7-27. Potentiometric Surface in the Amargosa Desert. Ground water flow is generally south, perpendicular to contour lines (USG90b)

Ground Water Travel Times and Radionuclide Transport

The transport of radionuclides in the saturated zone away from a repository depends on a wide variety of factors including, but not limited to, ground water and host rock geochemistry; advective ground water velocities; radionuclide concentrations and retardation properties; flux rates of radionuclides from the unsaturated zone; the presence of sorbing materials such as zeolites and clays; rock fracture density; fracture-matrix interaction; future climate changes; and anthropogenic influences. Knowledge of the transport properties in the site-scale and regional flow systems would allow researchers to more completely address four of the most important questions surrounding repository performance and regional ground water flow issues in the area around Yucca Mountain:

1. What path would radionuclides from the repository follow?
2. How fast and how far would radionuclides travel in the saturated zone?
3. Where would radionuclides become accessible to the biosphere?
4. What will the concentrations of radionuclides be when they become accessible to the biosphere?

The answer to all of these questions is uncertain. The ability to know or predict the answers to these questions depends on performing sufficient scientific investigations over the study area in order to reduce the associated uncertainties to acceptable levels. Some level of uncertainty will always remain, as it is not possible to completely characterize any underground system.

Recent testing activities conducted at the C-well complex have been designed to provide more information regarding contaminant transport properties in the saturated zone (DOE96a, DOE96b). Tracer testing at the C-wells complex has included the injection of both conservative (non-sorbed/non-decaying) and nonconservative tracers (sorbed). All tracer tests were performed by establishing a quasi-steady convergent flow field and hydraulic gradient by pumping from borehole UE-25 c#3 for several days prior to the injection of tracer compounds. Test results are collected by analyzing samples taken at regular intervals from the pumped well and preparing "breakthrough curves" which plot the concentration of the tracer in the pumped well versus time. After the first detection of tracer compound, breakthrough curves typically show an initial rapid rise in tracer concentration, which then peaks and tails off gradually.

The first tracer test performed at the C-wells used sodium iodide, a conservative solute. Because it is negatively charged, sodium iodide does not sorb to zeolites and clays, and has an average matrix retardation coefficient of 0.93. The retardation coefficient should be less than one because of a process known as anion expulsion, wherein anions are repelled by negatively charged grain surfaces and arrive at the recovery well prior to neutrally-charged tracers. Test conditions were negatively impacted by decreasing pump discharge and the resulting nonsteady hydraulic gradient and flow rates. Tracer recovery data were analyzed to determine effective porosity and longitudinal dispersivity using an analytical solution. The analytical method employed has a high uncertainty and calculated parameters do not represent a unique solution to the breakthrough curve data. Test data were analyzed using several different sets of assumptions including a single-porosity solution, a weakly dual-porosity solution, and a moderately dual porosity solution.

In a single-porosity solution, calculated fracture porosity was 0.036 and longitudinal dispersivity was 17.00 ft. In a weakly dual-porosity solution, calculated matrix porosity was 0.032, fracture porosity was 0.0068, and longitudinal dispersivity was 20.75 feet. In a moderately dual-porosity solution, good matches were obtained using a matrix porosity of 0.0778, a fracture porosity of 0.0237 and a longitudinal dispersivity of 13.64 feet. It is important to recognize that parameters used in analyzing tracer recovery data have a high degree of uncertainty and that because the ground water flow field at the C-wells is anisotropic, the transport field is most likely anisotropic as well.

Subsequent to performing the conservative tracer test, two additional pilot tracer tests were performed. Both tests were conducted in the 100 meter thick isolated interval within the Bullfrog member of Crater Flat Tuff. This interval has the largest hydraulic conductivity of any interval at the C-holes. The objectives of these tests were to determine: (1) which injection well (c#1 or c#2) would result in a higher peak concentration of a conservative tracer, and thus be a better injection well for a reactive tracer test, and (2) what minimum mass of lithium bromide would have to be injected to conduct a successful reactive tracer test. Both pilot tests were successful in that they clearly identified that Well c#2 is the preferred injection hole for a reactive tracer test and that at least 80 kilograms (kg) of lithium bromide would be needed to ensure a successful test. The analysis of these tracer tests and any subsequent tests for transport parameters is not currently available.

The current state of knowledge suggests that ground water beneath the proposed repository moves laterally downgradient until the volcanic aquifer pinches out, at which point it discharges laterally into the alluvial aquifer. Radionuclides dissolved in ground water would potentially follow a similar path. Much of the ground water that enters the alluvial aquifer currently moves southward to the primary discharge location at Alkali Flat. Other actual or potential points of discharge for the system include water wells in the Amargosa Desert and springs in the Furnace Creek Ranch area of Death Valley.

Ground water travel times to any of these locations are not well known. Estimates of ground-water travel times can be developed by simple calculations or by more sophisticated numerical modeling. In either case, travel times calculations are based on hydraulic gradient, hydraulic conductivity, and effective porosity of the formation through which the water is flowing. Of these three parameters, hydraulic gradients are probably the best known and most easily measured. A range of ground water travel times in the Tertiary volcanic aquifer has been developed in support of DOE's Total System Performance Assessment conducted in 1993. TSPA93 predicted a range in advective velocities between 5.5 and 12.5 m/yr. These velocities represent average velocities in the Tertiary volcanic aquifer between the footprint of the potential repository and a 5 km "accessible environment" located to the south and east of the potential repository (DOE95f). Performance assessment parameters and results are more fully described in Sections 7.3 and 7.4.

A more recent study on radionuclide transport in the saturated zone (DOE96c) concluded that an advective travel time of five m/yr is in the middle of the range of reasonable estimates. At this velocity, unretarded radionuclides would take approximately 1,000 years to travel five km from the repository and 5,000 years to travel 25 km from the repository. This study also documents the results of preliminary, highly simplified radionuclide transport modeling work performed using advective velocities of five m/yr. The nature of downgradient breakthrough curves and resulting peak dose calculations were highly dependent on assumed values of dispersivity. The study also found that the breakthrough curves, travel times, and peak dose results were strongly dependent on the retardation properties of individual radionuclides, the presence of sorbing materials such as zeolites, and the possibility of fracture transport bypassing sorptive horizons within the volcanic aquifer.

No reliable estimates of advective velocity in the alluvial aquifers have been made downgradient of the potential repository.

An important unresolved issue is the extent of interaction between the volcanic aquifer and the underlying carbonate aquifer. The possibility that radionuclides might enter the regional lower carbonate aquifer, with its higher permeability, raises concerns that radionuclides could be transported as far as Death Valley. Current evidence, such as hydraulic head measurements in UE-25 p#1, isotopic data, and saturated zone temperature anomalies suggests that the lower carbonate aquifer has a higher hydraulic head than the overlying units. This upward gradient indicates that it is unlikely that radionuclide contaminants will be transported into the carbonate aquifer in the vicinity of Yucca Mountain. Velocities through the lower carbonate aquifer range from an estimated 0.02 to 200 feet per day, depending upon geographic position within the flow system (USG75). It should be noted that the figures given above are for an area of carbonate rocks outside, and much larger, than the study area. No data are available regarding actual ground water flow velocities in the study area. Carbonate rocks with solution-widened fractures, cavities, and caves typically exhibit an extremely large variation in ground water velocities. Ground water age dating (WIN76) using carbon-14 methods in the springs of Ash Meadows suggested ages of ground water in the majority of the springs ranging from 19,000 to 28,000 years. INY96 describe more recent studies which indicate that water may move through the lower carbonate aquifer in times less than 1000 to 2000 years.

7.1.2.4 Ground Water Resources and Utilization

Many of the studies performed in the Yucca Mountain characterization process have thus far focused narrowly on the immediate area in and around the proposed repository. Few studies to date have attempted to present a regional picture of ground water resources for the areas downgradient from Yucca Mountain. This section presents a summary description of water resources in the area downgradient (generally south) of Yucca Mountain.

Water Quality

<u>Volcanic Aquifer</u>

The chemistry of water flowing through the volcanic aquifers exhibits complex dependency upon rock composition, residence time in the aquifer, and position along a flow line (USG75). Ground water chemistry in a volcanic rock is controlled by primary glass, pumice fragments, and the diagenetic minerals (NAN89). Water samples from wells drilled in Yucca Mountain indicate that the water is predominantly a sodium bicarbonate water containing small concentrations of silica, calcium, magnesium, and sulfate (USG83). Sodium levels are generally elevated in these rock types due to the presence of volcanic glass, which is not stable in the presence of water and contains appreciable sodium. Two water wells, J-12 and J-13, currently supply water for site characterization activities at Yucca Mountain and have been pumped extensively for decades with no signs of deteriorating water quality (USG83; USG94b). (Additional sources of

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