CHAPTER 7

CURRENT INFORMATION CONCERNING A POTENTIAL WASTE REPOSITORY AT YUCCA MOUNTAIN

7.1 PRINCIPAL FEATURES OF THE NATURAL ENVIRONMENT

This section describes the principal features of the natural environment at Yucca Mountain and the surrounding area. This information is based primarily on the site characterization work of the Department of Energy (DOE). Particular emphasis is given to those aspects of the geology, mineralogy, structure, hydrology, and climate of the site that are most likely to affect the performance of a high-level waste repository. The glossary of technical terms at the end of this BID should be helpful to the reader.

7.1.1 Geologic Features

A description of the important features of Yucca Mountain and the surrounding area provides a picture of the geologic setting that serves as the context for understanding the repository design. Important aspects of the geology around the site, such as the presence of faults, seismicity, and the nature and distribution of rock types, are discussed.

7.1.1.1 Location and Principal Physical Features of the Site (Adapted from DOE95a)

The Yucca Mountain site is located in Nye County, Nevada approximately 150 kilometers (km) northwest of Las Vegas, Nevada (Figure 7-1). The site is at the southwestern boundaries of the Nevada Test Site and the adjoining Nellis Air Force Base and about 50 km east of Death Valley National Monument. The Yucca Mountain Region includes the southern Great Basin in southern Nevada and an adjacent area in California (Figure 7-2). The Great Basin, which is in the northern portion of the Basin and Range physiographic province, is bounded geologically by the margins of the Colorado Plateau to the east and southeast, by the Sierra Nevada and Transverse Ranges to the west and south, and by the Snake River Plain and flood basalts of the Columbia Plateau to the north. Typical Great Basin topography consists of north-south mountain ranges separating narrow structural valleys with internal drainages. The Colorado River, flowing along the margin of the Colorado Plateau and topographically isolated from Yucca Mountain, provides the only external drainage. Yucca Mountain is situated in the southern section of the Great

Basin, in the Southwest Nevada Volcanic Field (SNVF). This area is bounded on the south by the Death Valley region and the Mojave Desert of California. Yucca Mountain is a narrow ridge which trends north-south and extends approximately 20 km from the southern margin of the Timber Mountain caldera complex. The area is mapped on the following U.S. Geological Survey 7.5-minute topographic quadrangles: Amargosa Valley, Big Dune, Busted Butte, Crater Flat, East of Brady Mountain, and Pinnacles Ridge (formerly Topopah Spring NW).

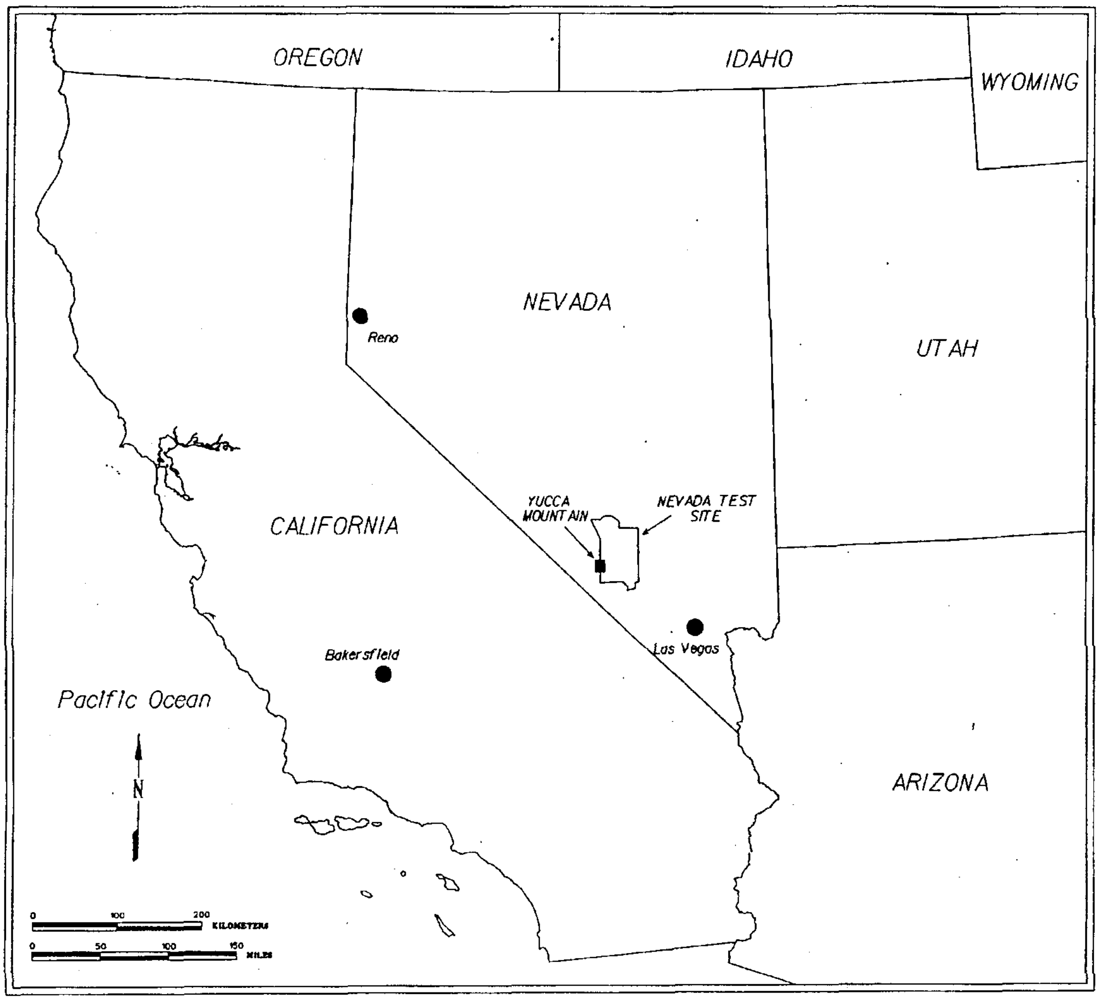

Figure 7-1. Location of Yucca Mountain (DOE94a)

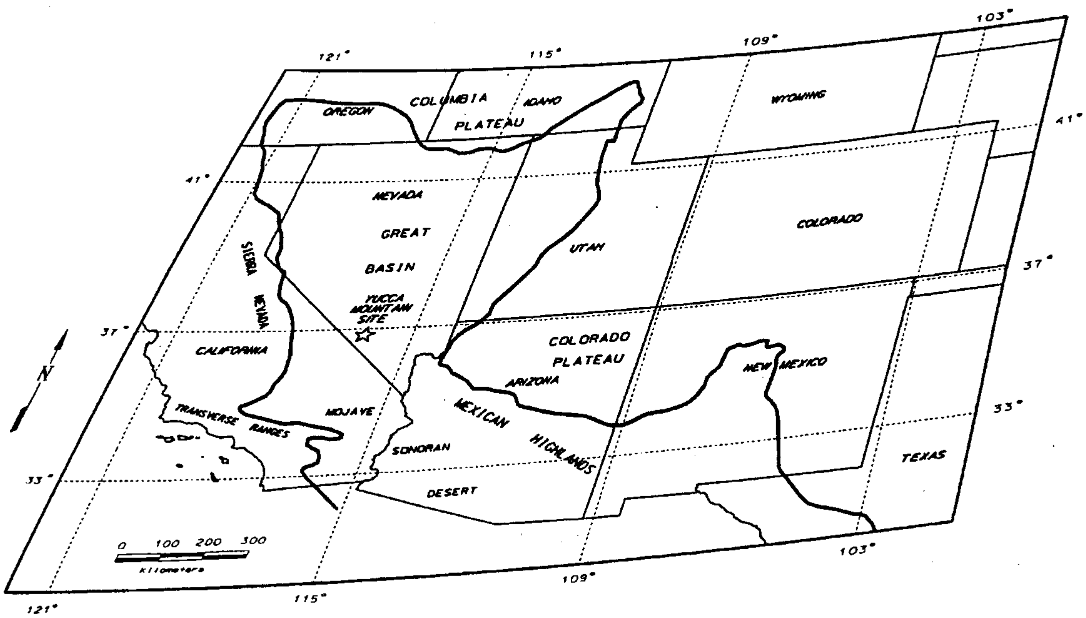

Figure 7-2. Boundaries and Larger Subdivisions of the Basin and Range Physiographic Province. Province boundary is indicated by heavy solid line (HUN74)

Yucca Mountain is an irregularly shaped upland, six to 10 km wide and about 40 km long. Uplands in the Yucca Mountain area are composed of ridge crests, valley bottoms, and intervening hill slopes (DOE88) with dominantly north-trending echelon ridges and valleys controlled by high-angled faults. The fault blocks, composed mostly of welded fine-grained volcanic rocks, are tilted eastward. As a result, the fault-bounded west-facing slopes are generally high, steep, and straight, whereas the east-facing slopes are more gentle and usually deeply dissected. Except where protected by a resistant rock layer capping the lip slopes, the ridge crests are mostly angular and eroded. Valleys range from shallow, straight, steeply sloping gullies and ravines to relatively steep, bifurcating, gently sloping valleys and canyons. Hill slopes are typically narrow and moderately steep near the crest, with progressively gentler slopes toward the valley floor. The crest elevation of Yucca Mountain ranges between 1,500 and 1,930 meters (m) above sea level. The summit is about 650 m above the floors of adjacent washes in Crater and Jackass Flats.

The main drainage system for the Yucca Mountain area, including the Timber Mountain area, the Calico Hills, and the mesas lying to the south of Timber Mountain, is in the Amargosa Valley. This drainage, east of Beatty, Nevada, carries runoff from the region south through the Tecopa basin into the southern part of Death Valley. The Amargosa Valley carries significant runoff only after extraordinarily heavy precipitation. There are no perennial streams or natural bodies of surface water on or adjacent to the Yucca Mountain. The major drainages, Solitario Canyon on the west, Forty Mile Wash on the east, and tributary drainages are primarily on the east flank of the mountain and flow only briefly immediately after rainstorms (Figure 7-3).

Bedrock exposures are common at higher elevations in the Yucca Mountain Region. Many of the hill slopes have a discontinuous veneer of blocky talus and wedges of colluvium cover the lower hill slopes. The rates of erosion in the Yucca Mountain area are lower than in similar arid areas in the southwestern U.S. and other parts of the world. Conditions contributing to these low erosion rates include existence of fine-grained volcanic rocks which are relatively erosion-resistant, insufficient runoff during interpluvial periods to remove hillslope colluvium, and topography that has not been significantly affected by Quaternary tectonic activity (WHI93). Regional erosion projections over 10,000 years are less than one meter of down cutting in canyons above the potential repository block, and less than 0.02 m of slope retreat (DOE95a).

7.1.1.2 Geologic History of the Region (Adapted from DOE95a)

The physiography and geomorphic features in the Yucca Mountain area influence the characteristics of the surface water system, and to some extent, the ground water system as well. The flow of water into, within, and around a repository at Yucca Mountain would directly affect its ability to contain the waste over time. The composition and chemical behavior of ground water at Yucca Mountain will be affected by the type, size, and abundances of primary and secondary mineral phases in the contacting rock formations. Furthermore, the geologic processes and events important to repository performance and design can only be understood within the broader context of the geologic history of the region. Current and future geologic processes and events are a direct product of the area’s geologic history; projecting their effect on repository performance requires an understanding of causes, frequencies, durations, and magnitudes over time. For example, projecting the potential frequency and magnitude of earthquakes is based on the historical record of past seismic activity. This information has been developed from records of past seismicity and geologic studies on the effects of faulting (displacement of strata across faults, topographic features, etc.) in the vicinity of the site.

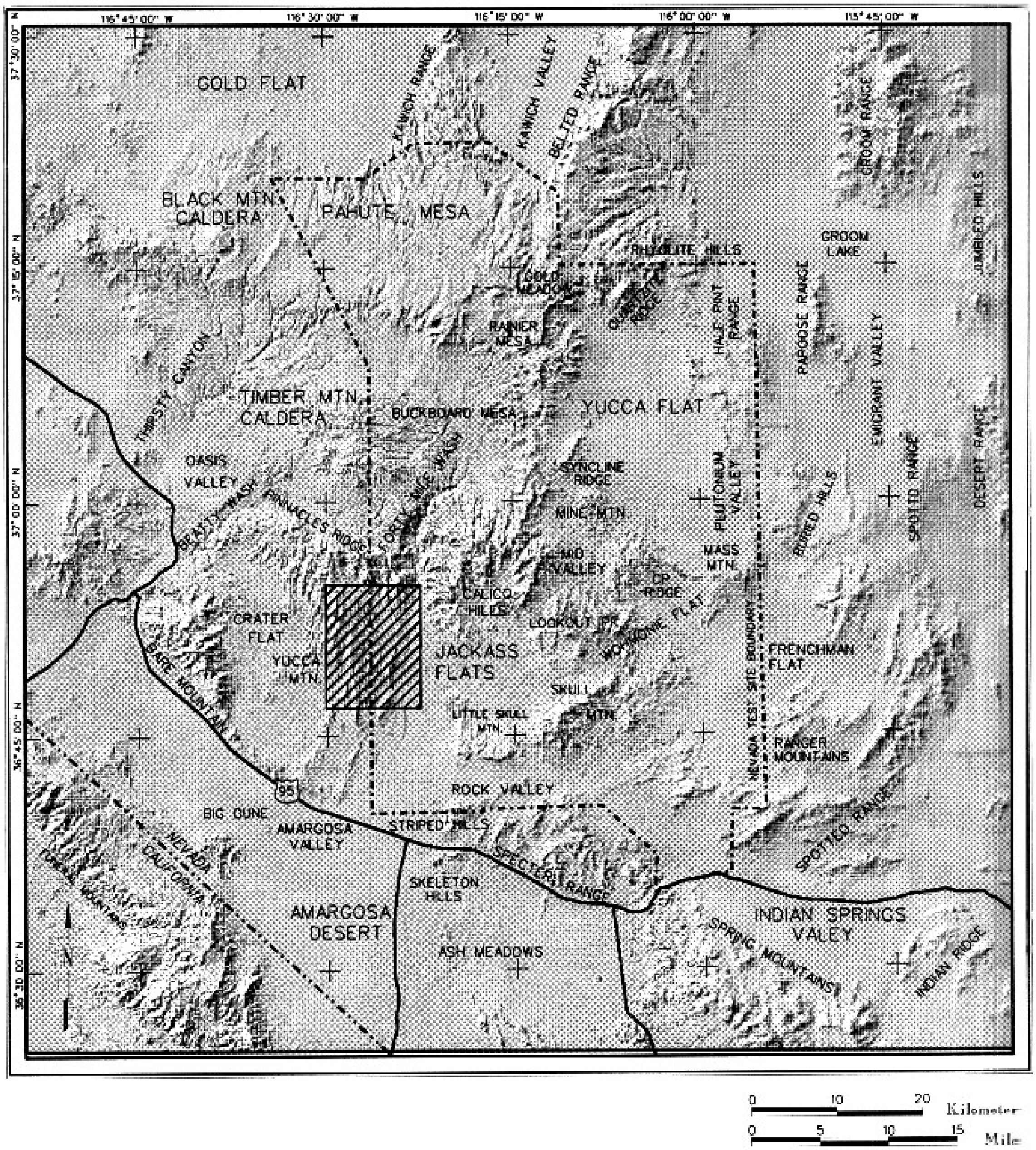

Figure 7-3. Physiographic Features in the Yucca Mountain Site Area (DOE88)

In general terms, the Yucca Mountain Region is characterized by a thick section of Precambrian and Paleozoic sedimentary rocks overlain by a sequence of Tertiary silicic volcanic rocks (see Figure 7-4). The older rocks have been folded and faulted by a compressional tectonic process and the entire stratigraphic section subsequently deformed by extensional basin-and-range tectonics. Uplifted ranges, such as Yucca Mountain, are separated by basins partially filled with alluvial deposits.

A basement complex of older Precambrian metamorphic and younger Precambrian igneous rocks is presumed to underlie the area. The basement rocks are overlain by a westward-thickening accumulation of shallow marine late Precambrian and early Cambrian marine sediments, quartzite, siltstone, shale, and carbonate rocks. These deposits are interpreted as a rifted continental margin miogeosyncline, shown in Figure 7-5, formed seaward of the highlands area. These rocks are locally fossiliferous. Deposition that continued through the Devonian Period is represented by carbonate and shale with interbedded quartzite and sandstone, thickening from up to 500 meters in western Utah to at least 6,100 meters in central Nevada.

In late Devonian and early Mississippian time, the Antler Orogeny, a mountain-building event, formed a north-northeast trending highland area adjacent to the Roberts Mountains Thrust. Large volumes of sediments eroded from the highlands into a foreland basin in the eastern half of the Great Basin, forming thick flysch[17] deposits adjacent to the highlands and shallow-water shelf carbonates to the east (Figure 7-6). Erosion of the highlands and deposition into the basin continued through the Permian Period, decreasing as the mountain-building waned. In Mesozoic and early Cenozoic time, these rocks were folded and displaced along thrust faults with extensive fracturing of the brittle rocks in the upper thrust plates. This faulting was accompanied by intrusion of granitic stocks, uplift, and erosion of the land surface (DUD90).

Middle and late Cenozoic crustal uplifting and extension in the region occurred over an area 1,500 km long and 500 to 1,000 km wide. The stretching, estimated at 10 to 50 percent of the original width and locally as great as 100 percent, resulted in northerly trending faults with sliding and tilting of large crustal blocks, forming the characteristic structure and topography of the Great Basin.

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[17] Flysch deposits are typified by the widespread sandstones, marls, shales, and clays exemplified by deposits occurring at the northern and southern borders of the Alps.

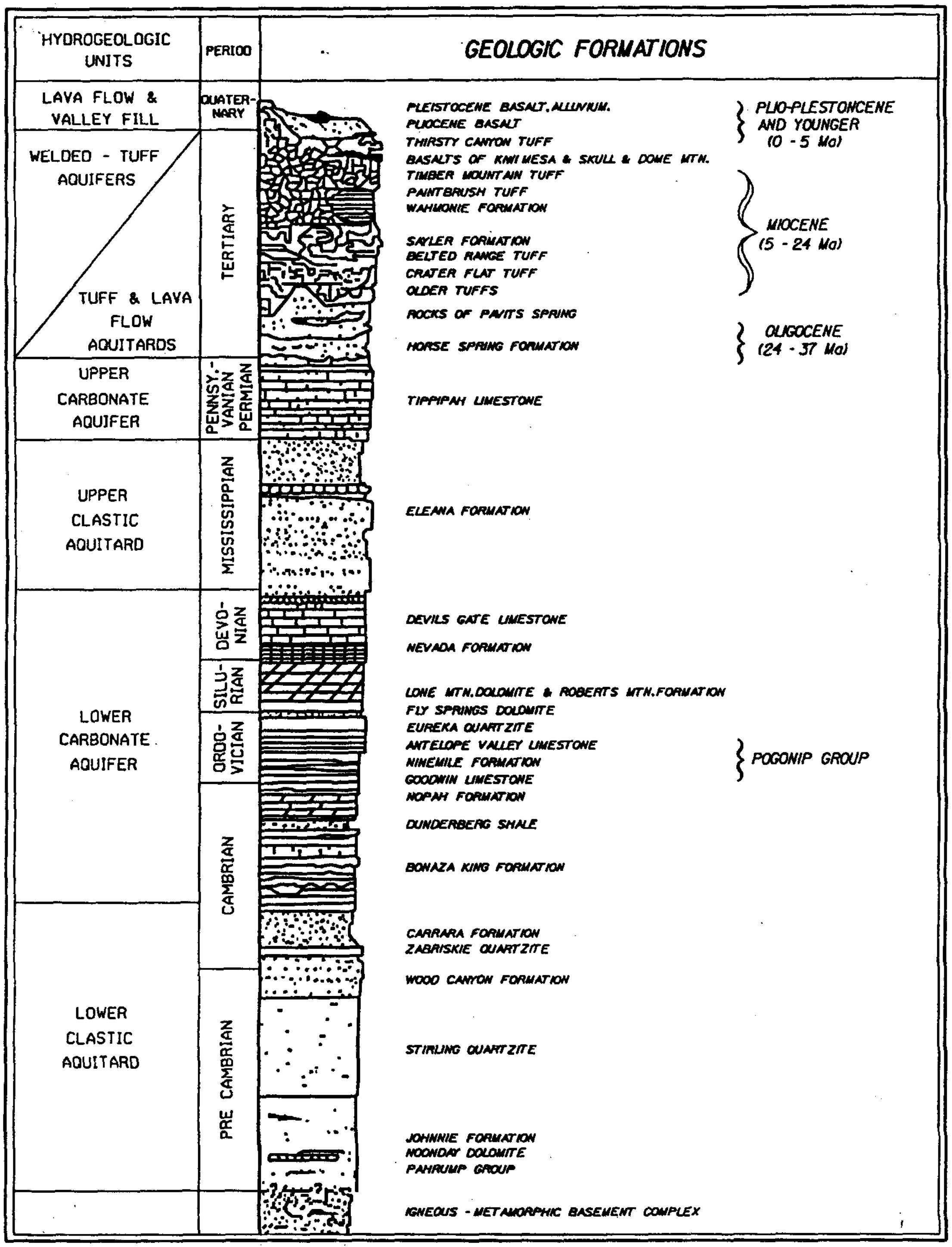

Figure 7-4. Generalized Regional Stratigraphic Column Showing Geologic Formations and Hydrological Units in the Nevada Test Site Area (Modified from DOE95a). The repository host rock at Yucca Mountain is in the Tertiary age Paint Brush Tuff.

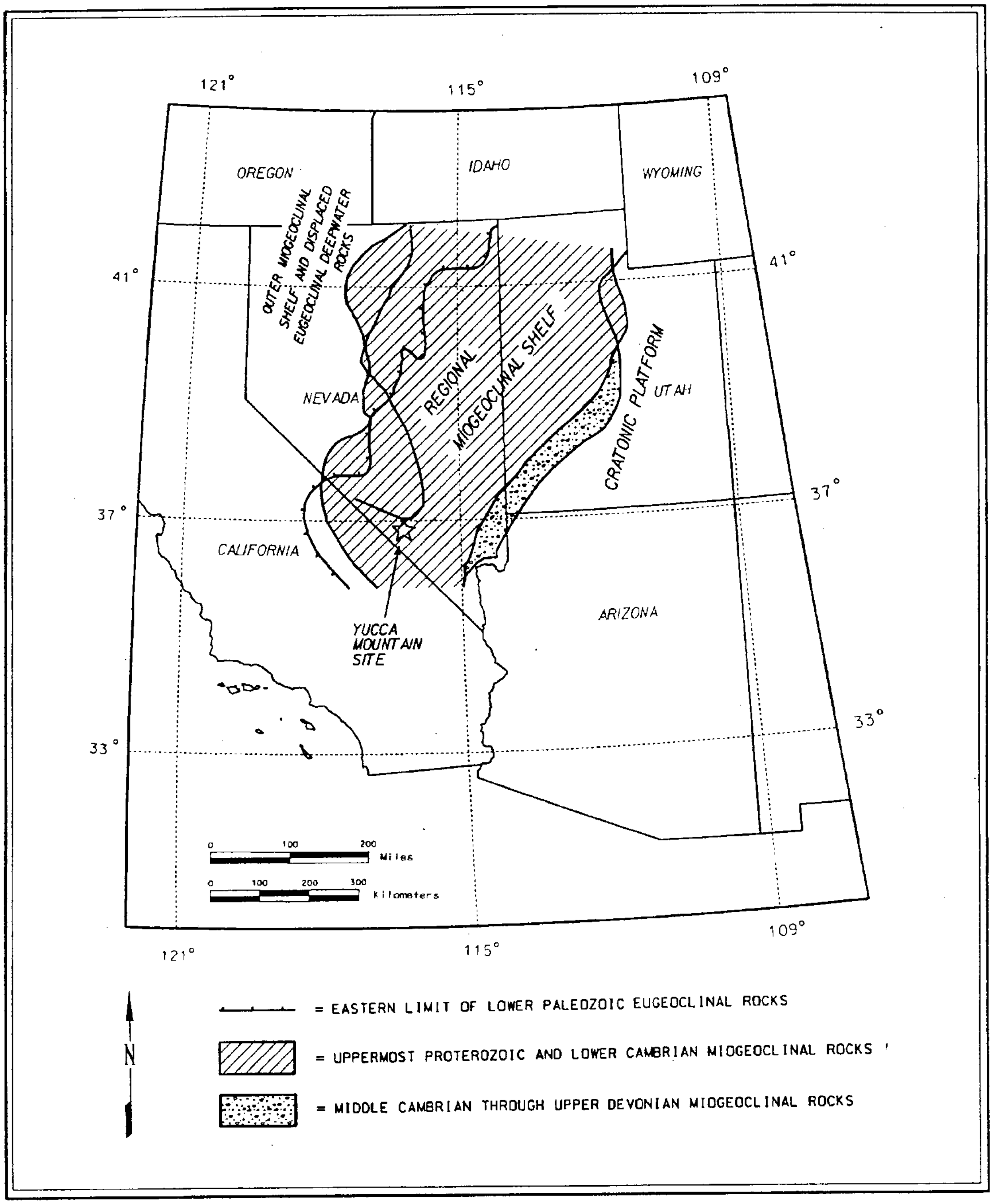

Figure 7-5. Late Precambrian Through Mid-Paleozoic Paleography of the Great Basin (Modified from DOE95a)

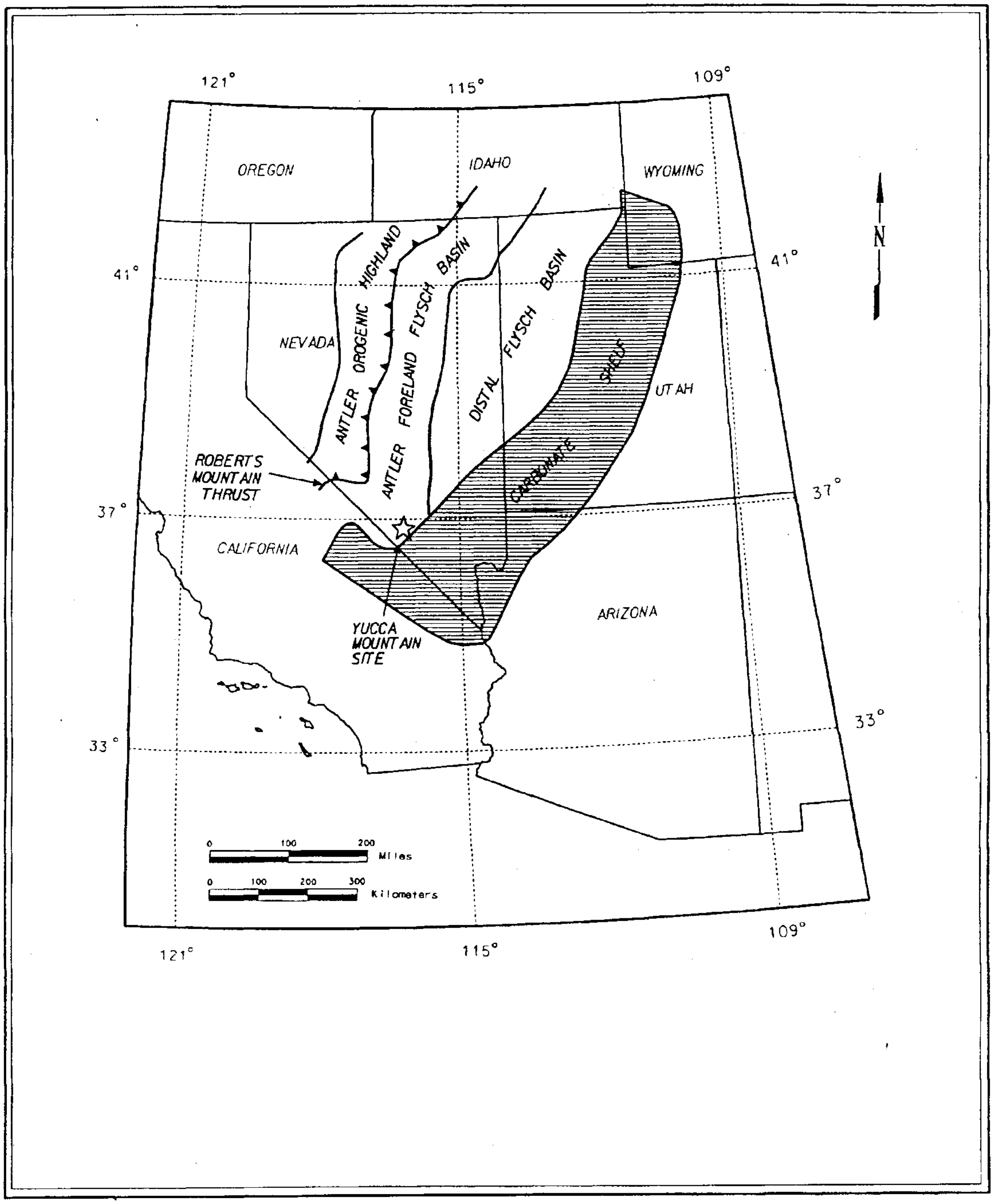

Figure 7-6. Late Devonian and Mississippian Paleogeography of the Great Basin (Modified from DOE95a)

Accompanying these crustal adjustments, volcanic eruptions in the vicinity of Yucca Mountain formed a series of calderas and deposited numerous thick beds of pyroclastics, tuff, and lava, aggregating up to three km in thickness near Yucca Mountain. The major episodes of silicic volcanism ceased about 7.5 million years ago (mega annum; Ma); however, relatively few basaltic eruptive centers formed in the basins adjacent to Yucca Mountain perhaps as recently as 4,000 years ago, with most of the local basaltic eruptive centers being formed over 75,000 years ago.

7.1.1.3 Stratigraphy of the Yucca Mountain Area (Adapted from DOE95a)

An understanding of the stratigraphy of the rocks at Yucca Mountain and the surrounding area is important to: (1) designing and constructing the repository, (2) assessing the potential of the natural barrier to retard the movement of radionuclides from the repository, and (3) describing the expected behavior of ground water movement through these rocks. For example, the physical properties of the rocks at the repository horizon determine the effects of heat generated by the radioactive waste on the near-field environment in the postclosure time period. They can also determine the speed at which radionuclides can be transported through the repository.

The stratigraphy of the southern Great Basin is highly varied, with formations ranging in age from Precambrian to Holocene, that is, from over 500 million years old to 10,000 years old. These rocks, briefly described in Table 7-1, are divided into eight general groups based on age, lithology, and history.

At Yucca Mountain, the stratigraphy is dominated by mid-Tertiary rocks of volcanic origin that erupted from the southwestern Nevada volcanic field. The stratigraphic sequence can be divided into four general categories based on similarities in lithology, age, and history of deposition or emplacement: (1) pre-Cenozoic rocks, (2) mid-Tertiary pyroclastic rocks, (3) younger basalt, and (4) late Tertiary to late Quaternary surficial deposits (Figure 7-7). These categories are discussed in the following sections.

Table 7-1. Stratigraphy of the Southern Great Basin

Older Precambrian Crystalline Rocks	These include extensive exposures of older Precambrian schist and gneiss and younger Precambrian igneous rocks in eastern Clark and southeastern Lincoln Counties. Outcrops of Precambrian granite, pegmatite, amphibolite, and gneiss exist in southern Lincoln County. Schist, gneiss, and gneissic quartz monzonite, possibly as young as late Proterozoic, are exposed in the Bullfrog Hills and Trapman Hills of southern Nye County.
Precambrian and Lower Cambrian Rocks	Late Precambrian and early Cambrian strata include a westward-thickening prism of quartzite, siltstone, shale, and carbonate interpreted as a rifted continental margin miogeosyncline. This prism has been divided into two depositional systems in Nevada: an eastern quartzite and siltstone system and a western siltstone, carbonate, and quartzite province.
Middle Cambrian through Devonian	Middle Cambrian through Devonian rocks exposed in the southern Great Basin consist of carbonates and shales, with interbedded quartzite and sandstone with thicknesses from up to 500 m in western Utah to at least 6,100 m in central Nevada. Strata of middle Cambrian through Devonian age comprise the Lower Carbonate Aquifer.
Mississippian through Permian Sedimentary Rocks	Thick flysch* deposits result from erosion of the north-northeast trending highland formed during the Antler Orogeny in late Devonian and early Mississippian time. This sedimentation continued through Permian time, declining as the orogeny waned.
Mesozoic Rocks	Mesozoic sedimentary rocks, locally present only in Clark County, consist of continental and marine sandstone, siltstone, and limestone of the Triassic and Jurassic Aztec Sandstone, Chinle Formation, and Moenkopi Formation. Approximately 30 separate Mesozoic to Tertiary granitic plutons are exposed in Esmeralda County, west of Yucca Mountain. These range in size from less than one km^2 to the 1,000 km^2 Inyo Batholith.
Tertiary Sedimentary Rocks	Tertiary sedimentary rocks, such as the Esmeralda and Horse Spring Formations, crop out throughout the southern Great Basin. These consist of poorly to moderately consolidated alluvial deposits and fresh water limestones in variable thicknesses of up to 1,000 m. They are commonly found interbedded with volcanic deposits.
Tertiary and Quaternary Igneous Rocks	The most prevalent Tertiary igneous rocks of the southern Great Basin are pyroclastic deposits of rhyolitic to trachytic composition. Eruptions from four calderas at Yucca Mountain between approximately seven and 16 Ma produced a complex mixture of pyroclastic flow and fall deposits, epiclastic deposits, and subsidiary lavas approximately 3050 m in thickness at Yucca Mountain. This was followed by scattered, small-volume basaltic or bimodal basaltic-andesitic lava and scoria eruptions.
Tertiary and Quaternary Surficial Deposits	Late Tertiary to Quaternary surficial deposits occur throughout the region as unconsolidated alluvial fan, pediment, and basin fill deposits of highly variable thickness and character.

* Deposits largely of sandy and calcareous shales.

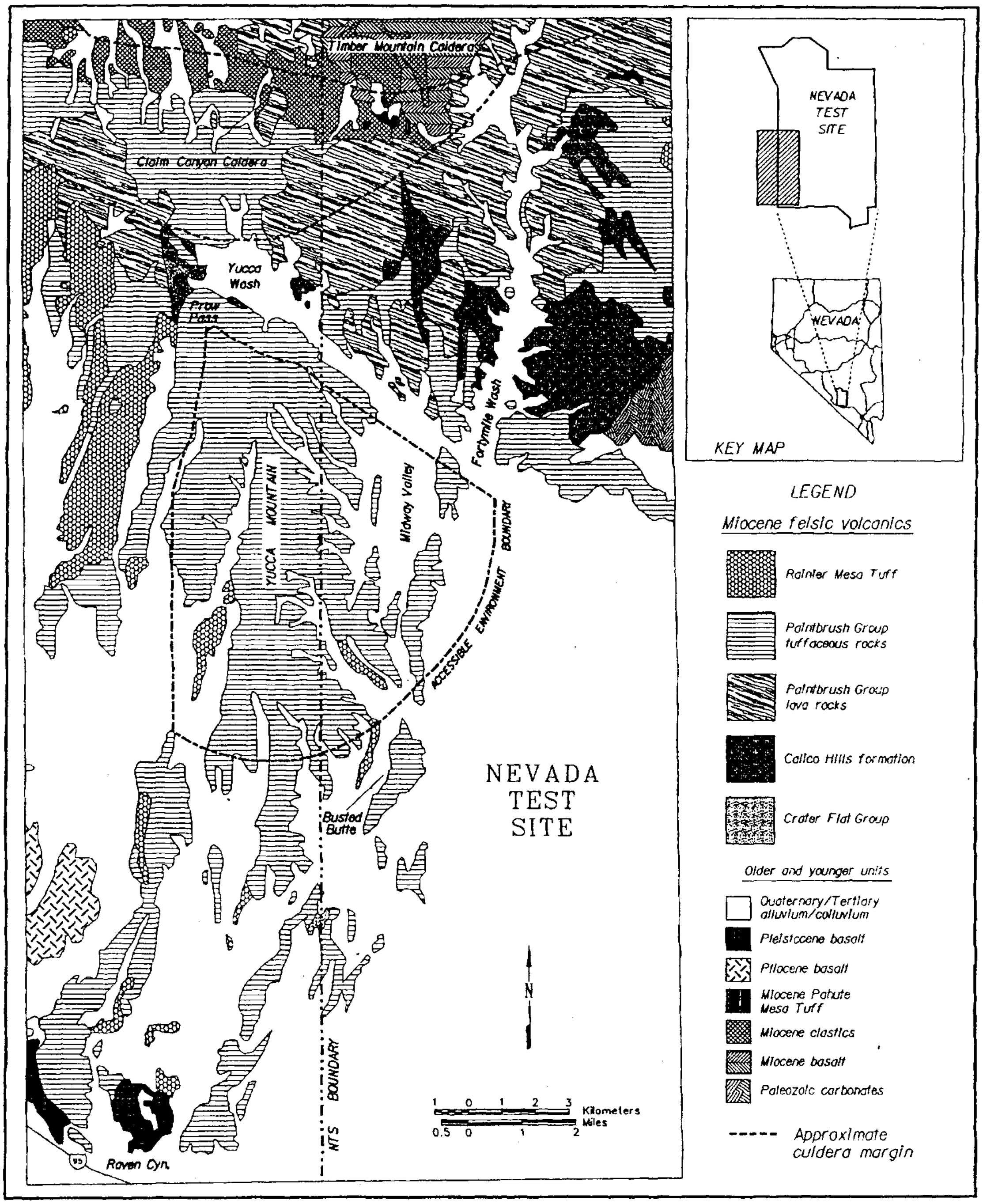

Figure 7-7. Simplified Geologic Map Showing the Distribution of Major Lithostratigraphic Units in the Yucca Mountain Area (Modified from DOE95a).

Pre-Cenozoic Rocks

Pre-Cenozoic rocks, believed to consist primarily of Paleozoic sedimentary strata, underlie the volcanic rocks at Yucca Mountain. Little detailed information is available as to their thickness, lithology, and contact with overlying stratigraphic units. Exposures of highly deformed Paleozoic rocks occur at scattered localities in the vicinity of Yucca Mountain, including the Calico Hills to the east, Bare Mountain to the west, and Striped Hill to the south. Carbonate rocks have been detected at a depth of 1,244-1,807 m in a borehole two km east of Yucca Mountain (DOE95a).

In the Calico Hills, exposures of carbonate rocks occur in the upper plate of a gently dipping thrust fault over a black shale sequence containing minor amounts of siltstone, sandstone, conglomerate, and limestone. These strata are locally highly folded, making correlation with stratigraphic units elsewhere in the region uncertain.

At Bare Mountain, there is a varied sequence of pre-Cenozoic sedimentary and meta-sedimentary rocks, totaling about 6,650 m in thickness and ranging from Precambrian to Mississippian in age. Fourteen Paleozoic and two Proterozoic formations are represented. Dolomite and limestone dominate, with minor stratigraphic units of clastic rocks (quartzite, sandstone, and siltstone).

Paleozoic rocks found at a depth of 1,244 to 1,807 m in a borehole two km east of Yucca Mountain are almost entirely dolomites and have been identified as related to the Lone Mountain Dolomite and the Roberts Mountains Formation. Seismic reflection data are inconclusive as to the thickness and extent of pre-Cenozoic rocks underlying Yucca Mountain, but the thickness is believed to be substantial.

Mid-Tertiary Pyroclastic Rocks

These rocks, resting unconformably on older pre-Cenozoic rocks, compose the portion of Yucca Mountain most important to the design and performance of the repository because they are the host rocks for the repository and define the pathways for ground water flow into and out of the repository. Volcanic rocks ranging in age from about 11.4 to 15.2 Ma form the bulk of the volcanic sequence, including the host rock of the potential repository, known as the Topopah Spring tuff (Figure 7-8). The volcanic sequence consists of welded and nonwelded silicic pyroclastic flow, fallout tephra deposits, and volcanic breccias erupted from nearby calderas in the southwestern Nevada volcanic field. Non-welded tuffs typically have large primary porosity.

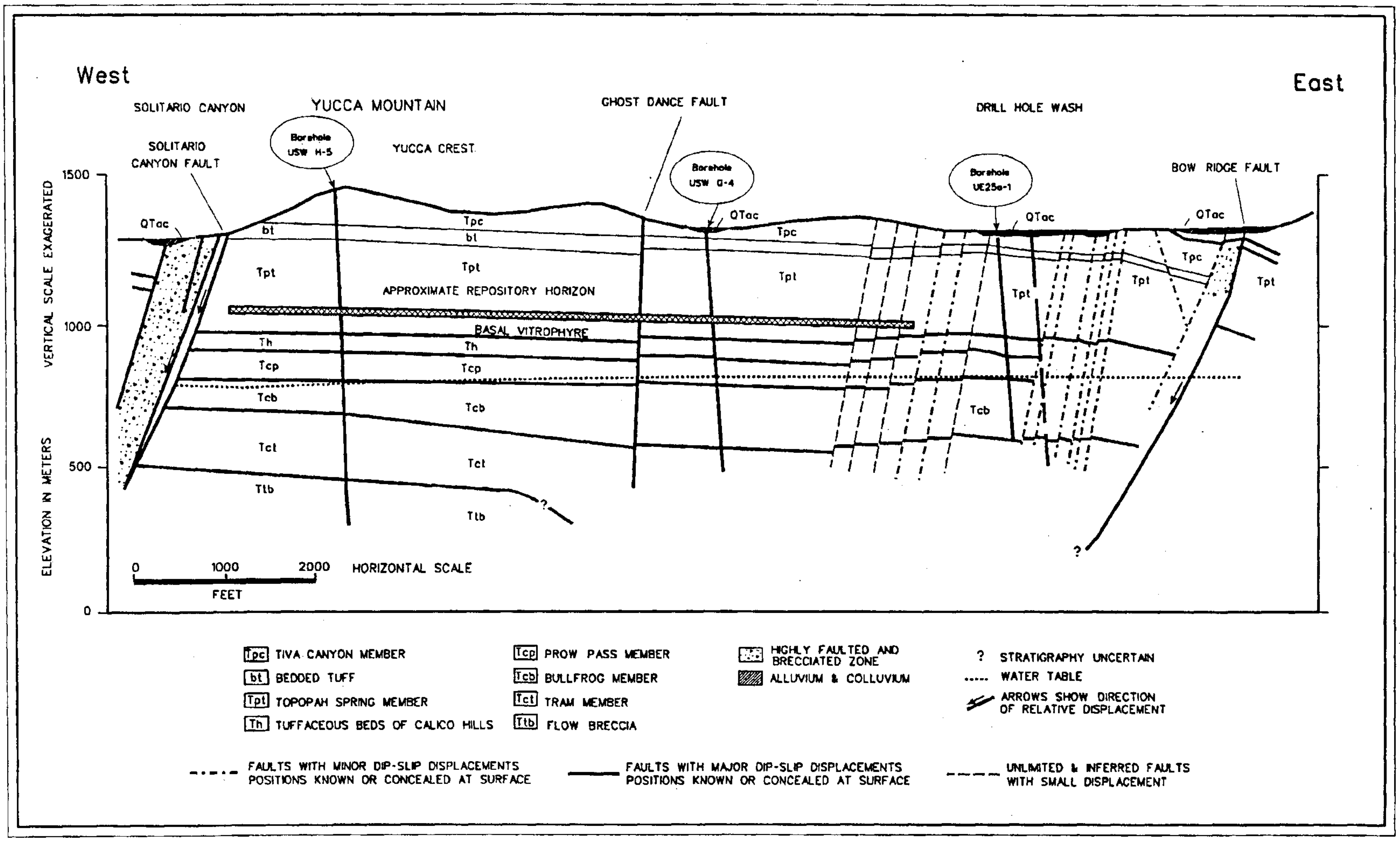

Figure 7-8. East-West Geologic Cross Section for the Yucca Mountain Site

This figure shows the relative positions of various rock units at the site, including the unit proposed for the potential repository (Topopah Spring Member of the Paintbrush Tuffs) and the fault zones that are closest to the site (USG88a)

However, the large porosity is poorly interconnected resulting in low permeability. The harder, welded tuffs are commonly more highly fractured and, consequently, have significant bulk permeability. The principal stratigraphic units are listed in Table 7-2, in order of increasing age (adapted from DOE94a).

Table 7-2. Principal Stratigraphic Units

Unit	Age (Ma)
Younger Post-caldera Basalts	0.27-3.8[a]
Older Post-caldera Basalts	8.5-10.5[a]
Shoshone Rhyolite Lava	9
Timber Mountain Group	
Ammonia Tanks Tuff	11.45
Rainier Mesa Tuff	11.6
Post-Tiva/pre-Ranier Rhyolites	12.5
Paintbrush Group	
Tiva Canyon Tuff	12.7
Yucca Mountain Tuff	-
Pah Canyon Tuff	-
Topopah Spring Tuff	12.8
Calico Hills Formation	12.9
Crater Flat Group	
Prow Pass Tuff	13.1
Bullfrog Tuff	13.25
Tram Tuff	13.45
Dacite Lava and Flow Breccia	
Lithic Ridge Tuff	14.0
Older Tuffs - Pre-Lithic Ridge	14-16

(a) Based on information from DOE95a to be discussed subsequently in Section 7.1.1.7. The age of the older post-caldera basalts ranges from 10.4 to 6.3 Ma; for the younger post-caldera basalts, the age ranges from 4.9 to 0.004 Ma.

Many of these formations, particularly those in the Prow Pass Tuff, Calico Hills Formation, and the Paintbrush Group, are further subdivided into members or units. The formations are summarized below, from oldest to youngest, with an emphasis on thickness, general composition and minerals important to radionuclide retardation along potential ground water transport pathways.

a. Pre-Lithic Ridge Volcanics. The oldest known volcanic rocks in the area were deposited approximately 15 million years ago and are represented in site boreholes by 45 to 350 m of bedded tuffaceous deposits, pyroclastic flow deposits, and quartz-latitic to rhyolitic lavas and flow breccia. Correlation of these rocks with other rocks in the area is difficult because of their heterogeneous character and varying degrees of alteration.

b. Lithic Ridge Tuff. This thick, massive pyroclastic flow deposit overlying the older tuffs appears to represent several eruptive surges and ranges in thickness from 185 m north of the site to 304 m at the south end of the site. This unit is nonwelded to moderately welded and has been extensively altered to smectites and zeolites.

c. Dacitic Lava and Flow Breccia. Dacitic lava and flow breccia overlie the Lithic Ridge Tuff in deep boreholes at the northern and western parts of Yucca Mountain but are absent elsewhere. Observed thicknesses in boreholes range from 22 m to 249 m. Much of the unit has been moderately to intensely altered to smectite clays and zeolites.

d. Crater Flat Group. This group, overlying dacitic lavas and flow breccias in the northern part of Yucca Mountain and the Lithic Ridge Tuff in the southern part, includes three rhyolitic, ash-flow-tuff sheets—the Tram, Bullfrog, and Prow Pass Tuffs, in ascending order. The Crater Flat Group is distinguished from other pyroclastic units at Yucca Mountain by the relative abundance of quartz and biotite phenocrysts.

- **Tram Tuff**. The Tram Tuff appears to comprise at least 28 separate magmatic pulses and includes two subunits distinguished on the basis of the relative abundance of lithic fragments. The lower subunit is rich in these fragments throughout, while the upper unit is poor in lithic clasts. The upper subunit, 126 to 171 m thick, is partially welded and has a microcrystalline ground mass.

  There are six to 22 m of ash-fall and reworked tuff, primarily comprising zeolitic pumice clasts, between the Tram and the overlying Bullfrog Tuff.

- **Bullfrog Tuff**. The Bullfrog Tuff is 68 to 187 m thick, consisting mostly of pyroclastic flow deposits with thin-bedded tuffaceous deposits. North of borehole USW G-4 (see Figure 7-8), this tuff consists of a moderately to densely welded core enclosed by nonwelded to partially welded zones. To the south, the tuff is composed of two welded zones separated by a one-meter-thick bed of welded fallout tephra.

- **Prow Pass Tuff**. The Prow Pass Tuff is a sequence of variably welded pyroclastic deposits that erupted from an unidentified source between 13.0 and 13.2 Ma. The formation, 90 to 165 m thick across the repository area, consists of four pyroclastic units overlying a variable sequence of bedded tuffs. These units, designated Unit 1 through 4 by decreasing age, are characterized by orthopyroxene pseudomorphs and the abundance of siltstone and mudstone lithic clasts. Unit contacts are defined by fallout tephra horizons and abrupt changes in sizes and amounts of pumice and lithic clasts.

A bedded tuff unit at the base of the Prow Pass Tuff consists of unwelded, altered tuffaceous deposits with a total thickness ranging from less than one meter to 11 m in boreholes.

Unit 1, a pumiceous pyroclastic flow deposit with an aggregate thickness of 25 to 70 m in cored boreholes, consists of three subunits separated on the basis of their lithic clast content.

Unit 2 consists of nonwelded to partially welded lithic-rich pyroclastic flow deposits with an aggregate thickness of three meters to 34 m in cored sections. The unit has not been subdivided since distinguishing characteristics are lacking; however, locally preserved ash horizons and abrupt changes in the amount and size of pumice and lithic clasts suggest at least three flow deposits.

Unit 3 consists of 40 m to nearly 80 m of multiple welded pyroclastic flow deposits, either separated by thin fallout tephra horizons or defined by abrupt changes in the amount and size of pumice and lithic clasts. Two of three flow deposits have been identified in most core holes but have not been correlated.

Unit 4 is distinguished by comparatively abundant pseudomorphic pyroxene in pumice clasts and rock matrix and by a comparatively low ratio of flesic to mafic phenocryst minerals. This unit includes three irregularly distributed subunits. The aggregate thickness in cored sections ranges from about 4 m to as much as 20.5 m.

e. Calico Hills Formation. The Calico Hills Formation, a series of rhyolite tuffs and lavas, includes five pyroclastic units overlying a bedded tuff unit and a local basal sandstone unit in the Yucca Mountain area. The formation thins southward across the site area, declining from about 290 m in the north to 43 m in the south. Basal beds of the Calico Hills Formation include two units. One unit consists of a nine- to 39-meter-thick bedded tuff unit containing coarse-grained fallout, primary and reworked pyroclastic-flow deposits, and fallout-tephra deposits. The other unit consists of a 0- to 5.5-meter-thick volcaniclastic sandstone unit with abundant lithic clasts and swarms of altered (to clay minerals) pumice clasts, interbedded with rare pyroclastic-flow deposits.

The pyroclastic units are composed of one or more pyroclastic-flow deposits separated by pumice- and lithic-fallout tephra deposits included with the unit lying above. Five units, designated Units 1 through 5 by decreasing age, can be distinguished on the basis of textural characteristics (percentages of various clastic material). In the northern part of Yucca Mountain (below the proposed repository horizon) the formation is high in zeolites, which compose 60 to 80 percent of the rock. In the southern portion of Yucca Mountain, the rock remains vitric.

Unit 1 is a nonwelded, lithic rich, pyroclastic-flow deposit ranging from 0 to 58 m thick in cored sections. Pumice clasts constitute 10 to 15 percent of the unit and lithic clasts increase from three to seven percent at the top to 15 to 20 percent at the base; phenocrysts compose seven to 12 percent of the rock.

Unit 2, 0 to 54 m thick, is a nonwelded, pumiceous, pyroclastic-flow deposit composed of 20 to 40 percent pumice clasts and up to five percent lithic clasts. Fallout deposits at the base are ash-rich, have a porcelaneous appearance, and are less than one meter thick.

Unit 3 is a nonwelded lithic-rich pyroclastic flow deposit 22 m to 100 m thick in cored sections. The unit is generally composed of 10 to 40 percent pumice clasts and five to 10 percent lithic clasts.

Unit 4 is a 0 to 57 m thick nonwelded, pumiceous pyroclastic flow deposit, with pumice clasts and lithic clasts constituting 10 to 30 percent and one to five percent, respectively. Thinly bedded ash-fall deposits, reworked pyroclastic-flow tuffs, and tuffaceous sandstone form a thin basal subunit.

Unit 5 is a nonwelded to partially-welded pyroclastic-flow deposit ranging from 0 to 20 m thick in cored sections. The unit is characterized by a bimodal distribution of pumice clast sizes—larger, slightly flattened clasts of 20 to 60 mm and smaller equidimensional clasts of two to 12 mm. The unit is composed of 20 to 30 percent pumice clasts and two to five percent lithic clasts.

f. Paintbrush Group. This group—one of the most widespread and voluminous caldera-related assemblages in the southwestern Nevada volcanic field—consists of primary pyroclastic flow and fallout tephra deposits, lava flows, and secondary volcaniclastic deposits from eolian and fluvial processes.

Eruptive centers for the Topopah Spring and Pah Canyon Tuffs are uncertain, but the Claim Canyon caldera (see Figure 7-7) is identified as the source of the Tiva Canyon and perhaps the Yucca Mountain Tuffs.

- The **Topopah Spring Tuff** (Figure 7-8) is the host rock for the proposed Yucca Mountain repository. The tuff has a maximum thickness of about 350 m in the vicinity of Yucca Mountain. The unit is divided into two members—an upper crystal-rich member and a lower crystal-poor member—each of which is subdivided based on variations in crystal content, phenocryst assemblage, pumice composition, distribution of welding and crystallization zones, depositional features, and fracture characteristics.

  The upper, crystal-rich member is characterized by greater than 10 percent phenocrysts, with a basal transition zone where the percentage increases from five to 10 percent. The member is divided into vitric, nonlithophysal, and local lithophysal zones.

The lower, crystal-poor member is characterized by less than three percent phenocrysts and is divided into devitrified rocks of the upper lithophysal, middle nonlithophysal, and lower lithophysal zones and a vitric zone. Below the vitric zone (the vitrophyre), concentrations of clay and zeolites increase significantly from alteration of the volcanic glass.

- The **Pah Canyon Tuff**, a simple cooling unit composed of multiple flow units, reaches its maximum thickness of 70 m in the northern part of Yucca Mountain and thins southward. This tuff varies from nonwelded to moderately-welded. Throughout much of the area, vitric pumice clasts are preserved in a sintered or lithified nondeformed matrix.

- The **Yucca Mountain Tuff**, a simple cooling unit in the Yucca Mountain area, varies in thickness from 0 to 30 m. Generally nonwelded, the unit is nonlithophysal throughout Yucca Mountain but contains lithophysae where densely welded in northern Crater Flat.

- The **Tiva Canyon Tuff** (Figure 7-8) is a large-volume, regionally extensive, compositionally-zoned (from rhyolite to quartz latite) tuff sequence that forms most of the exposed surface rocks exposed at Yucca Mountain. The tuff ranges in thickness from 100 to 150 m. Separation into crystal-rich and crystal-poor members and into zones within these members is based on similar criteria and characteristics discussed above for the Topopah Spring Tuff.

g. <u>Post-Tiva Canyon, pre-Rainier Mesa Tuffs</u>. A sequence of pyroclastic flow and fallout tephra deposits occurs between the Tiva Canyon Tuff and the Rainier Mesa Tuff in the vicinity of Yucca Mountain. The sequence ranges from 0 to 61 m thick and is intermediate in composition between Tiva Canyon and Rainier Mesa Tuffs.

h. <u>Timber Mountain Group</u>. This group includes all of the quartz-bearing pyroclastic flow and fallout tephra deposits that erupted from the Timber Mountain caldera complex about 11.5 Ma (see Figure 7-7). The complex consists of two overlapping, resurgent calderas—one formed by eruption of the Rainier Mesa Tuff and a younger, nested one formed by eruption of the Ammonia Tanks Tuff.

- The **Rainier Mesa Tuff** is one of the most widespread pyroclastic units of the Yucca Mountain area. It is a compositionally-zoned unit consisting of high-silica rhyolite tuff overlain by a considerably thinner quartz latite tuff restricted to the vicinity of the Timber Mountain caldera. Exposed thicknesses along the west side of the caldera are as great as 500 m. The formation is absent across much of Yucca Mountain, but appears in down-thrown blocks of large faults in valleys on either side. The tuff is nonwelded at the base, grading upward into partially- to moderately- welded devitrified tuff.

- The **Ammonia Tanks Tuff** consists of welded to nonwelded rhyolite tuff with a highly variable thickness of up to 215 m. It is absent across Yucca Mountain, but is exposed in the southern part of Crater Flat.

Hydrostratigraphy

The formal geologic stratigraphy for those rocks near the repository horizon has been reorganized into four major hydrostratigraphic units for ground water modeling and performance assessment. The groupings are based primarily on the degree of welding of the tuffs. These units and their relationship to formal geologic stratigraphy are as follows (descriptions taken from DOE95b):

- Tiva Canyon welded (TCw) unit: Consists of the moderately- to densely-welded zones of the Tiva Canyon geologic member. This unit is characterized by low matrix porosity (~10 percent), low matrix saturated hydraulic conductivity (~10^{-11}m/s), and high fracture density (10-20 fractures/m^3).

- Paintbrush nonwelded (PTn) unit: Consists of the lower partially-welded to nonwelded zones of the Tiva Canyon geologic member, partially-welded to nonwelded Yucca Mountain and Pah Canyon members, the porous interlayers of bedded tuffs, and the upper partially-welded to nonwelded part of the Topopah Spring member. This unit is characterized by high matrix porosity (~40 percent), high matrix saturated hydraulic conductivity (~10^{-7} m/s), and low fracture density (~1 fracture/m^3).

- Topopah Springs welded (TSw) unit: Consists of the welded zones of the Topopah Spring member. This unit is characterized by low matrix porosity (~10 percent), low matrix saturated hydraulic conductivity (~10^{-7} m/s), and high fracture density (8-40 fractures/m^3). The basal vitrophyre of the Topopah Spring member (TSv) is generally identified as a subunit because of its lower porosity as compared to the TSw unit.

- Calico Hills nonwelded (CHn) unit: consisting of the moderately-welded to nonwelded zones of the Topopah Spring member underlying the basal vitrophyre, the partially-welded to nonwelded tuffs of the Calico Hills formation, and other partially-welded to nonwelded tuffs located below the Calico Hills formation (i.e., the Prow Pass, Bullfrog and Tram members of the Crater Flat Unit). Portions of the lower Topopah Spring member are vitrified and zeolitic alteration appears in both the lower part of the Topopah Spring member and in the tuffaceous beds of the Calico Hills. This leads to a further division of this unit into vitric (CHnv) and zeolitic (CHnz) subunits. The fracture density (2-3 fractures/m^3) is similar in both zones, and the porosity in the vitric tuffs (~30 percent) is marginally higher than that of the zeolitic tuffs. However, matrix saturated hydraulic conductivity of the CHnv subunit (~10^{-9} m/s) is roughly two orders of magnitude higher than that of the CHnz subunit.

In some discussions of Yucca Mountain stratigraphy, the stratigraphic column is divided into thermal/mechanical units, rather than the more formal geologic formations or the hydrostratigraphic units (see, for example, Figure 6-7 in DOE94a). The boundaries between the thermal/mechanical units tend to be defined by the interface between welded and non-welded lithologies and the units are very similar to the hydrostratigraphic groupings.

Younger Basalt

The youngest volcanic rocks in the Yucca Mountain area are the basalts at Lathrop Wells, where multiple eruptions occurred over a period of about 120,000 years with the latest event occurring less than 10,000 years ago.

Surficial Deposits

Surficial deposits in the area reflect the effects of erosive processes and affect the surficial recharge of water to the underlying rocks. Numerous Quaternary/Tertiary surficial deposits have been defined in the Yucca Mountain area. These include alluvial, colluvial, and eolian deposits. The alluvial deposits range in age from late Tertiary (probably late Miocene) to late Holocene and generally consist of sandy gravel (granules to boulders), often with interbedded sands. These deposits occur along the washes, drainage channels, and valley slopes. The colluvial deposits are primarily of Quaternary age and generally consist of a thin mantle of angular gravels on slopes and highlands.

Two deposits of eolian sand ramp are defined, both formed of massive to poorly-bedded sand with five to 50 percent fine angular gravel. One deposit (late and middle Pleistocene) forms partially-dissected aprons between gullies on lower hill slopes. The other deposit (Holocene and late Pleistocene) forms undissected and poorly-exposed sand ramps along Forty Mile Wash.

Summary

The most important rocks affecting the design and performance of the proposed Yucca Mountain repository are the sequence of Miocene volcanic rocks that overlie, underlie, and are the host rocks for the repository. These silicic rocks consist of ash-flow and air-fall tuffs produced by eruptions from the Timber Mountain-Oasis Valley caldera complex. Most of the exposed surface rock over the repository is the 100-150 m thick Tiva Canyon Tuff. Below this, is the Yucca Mountain Tuff, which is largely nonwelded and up to 30 m thick. The Claim Canyon caldera segment lying to the east of the proposed repository site is a possible source for rocks in these units. The repository horizon is in the Topopah Spring Tuff which has a maximum thickness of 350 m in the vicinity of Yucca Mountain. These units are all part of the Paintbrush Group.

Next, in descending sequence, is the Calico Hills Formation consisting of rhyolite tuffs and lavas which, in turn, is underlain by the Prow Pass Tuff in the Crater Flat Group. The Prow Pass Tuff is 90 to 165 m thick under the potential repository location. The surface of the water table lies near the base of this unit. Lower lying units, generally in the saturated zone, include the 68 to 187 m thick Bullfrog Tuff and the Tram Tuff. These two tuffs are separated by six to 22 m of ash-fall and reworked tuff comprised mainly of zeolitic pumice clasts.

7.1.1.4 Major Fault Features of the Yucca Mountain Area (Adapted from DOE95a)

The faults present in the site area are important for several reasons. To avoid adverse effects of fault movement, areas of active fault movement should be avoided when deciding on the location of surface waste handling facilities for the repository, as well as when designing the underground waste emplacements locations. The fractured rocks in fault zones can also act as preferential pathways for ground water movement and radionuclide migration. Their location and hydrologic properties are important for developing an understanding of the flow system and performing quantitative calculations of ground water movement essential to assessing the repository's performance.

Faulting and the Structural Setting Around Yucca Mountain

The location of faults, and the extent of recent movement along these faults, is important to the location and design of surface facilities and the layout of the underground repository at the Yucca Mountain site. Seismic conditions in the area show at least some degree of correlation with the faults observed. Seismic activity could affect surface facilities of the repository. In addition, the fractured rock zones typical of fault zones often serve as preferential pathways for the movement of ground water. Rapid flow of ground water along fractures in the site area has been observed and DOE's current layout of the repository has been designed to avoid emplacing wastes in areas where the host rock is prominently fractured (e.g., the Ghost Dance Fault zone).

Yucca Mountain consists of a series of north-trending, eastwardly tilted structural blocks that were segmented by west-dipping, high-angle normal faults during a period of major extensional deformation. The site is situated near the southern end of the northwest trending Walker Lane Belt, a zone of northwest-directed shear about 700 km long and 100 to 300 km wide. This Belt absorbs part of the transform motion of the regional plates and the strain from the extension of the Great Basin. It parallels the San Andreas fault and the Sierra Nevada Mountains and is truncated on the south by the east-west Garlock fault (Figure 7-9).

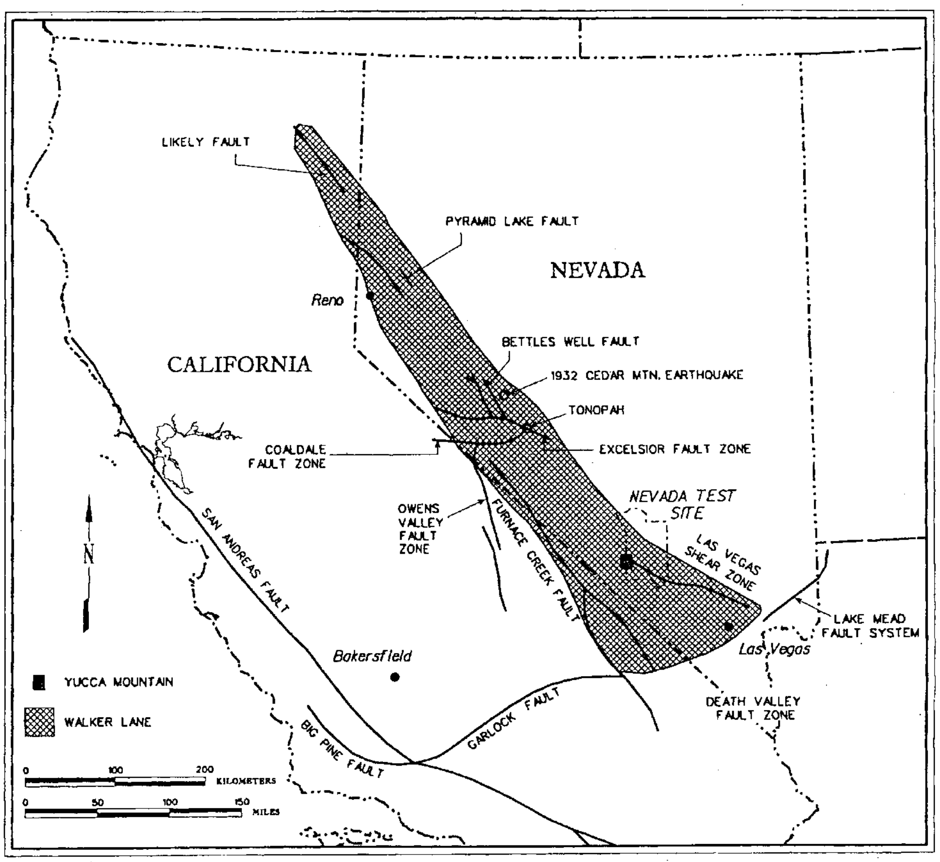

Figure 7-9. The Walker Lane Belt and Major Associated Faults (DOE88)

Cenozoic deformation probably took place on preexisting structures and is characterized by strike-slip faulting, regional folding, and large-scale extension (see, for example, STE90). The current type of deformation in the Walker Lane Belt probably began about five million years ago as an overlap between the right-lateral shear caused by the North American and Pacific plates and the gravity-driven extension of the regional uplift in the Great Basin. In the modern stress field, northwest-striking faults move with left-lateral strike-slip or oblique-slip along the fault planes.

In the Walker Lane Belt, right angle-shear totaling 4.27 to 7.35 millimeters per year (mm/yr) is distributed along three major faults: the Owens Valley, Panamint Valley-Hunter Mountain, and Death Valley-Furnace Creek faults. This, along with lesser amounts of slip on other fault systems to the east, correlates well with the approximate 10 mm/yr of slip estimated from field measurements.

The major north-trending faults transecting or close to Yucca Mountain are, from west to east, the Crater Flat, Windy Wash, Fatigue Wash, Solitario Canyon, Stagecoach Road, Ghost Dance, Bow Ridge, Midway Valley, and Paintbrush Canyon faults (Figure 7-10). Bedrock has been displaced downward and to the west along these faults, which show predominantly dip slip, with varying amounts of left-oblique slip, along the faults. Estimates of bedrock displacement over the past 12 million years range from less than 100 m to as much as 600 m, with the displacement increasing southward along each fault. The faults are projected up to 25 kilometers, but surface exposures can usually be traced only one kilometer or less. Dips of the fault planes are generally 70 to 75 degrees.

Several northwest-trending faults have been identified along valleys, the most prominent being the Yucca Wash, Sever Wash, Pagany Wash, and Drill Hole Wash faults. A northwest-trending shear zone, the Sundance Fault, crosses the potential repository site (Figure 7-11). These faults are thought to be strike-slip faults, with nearly horizontal slickenside lineations and vertical displacements generally less than five to 10 m.

Quaternary Faulting in the Yucca Mountain Area

Of particular concern for the Yucca Mountain site are faults considered to be Type I faults, as classified by the U.S. Nuclear Regulatory Commission (NRC). Type I faults or fault zones are those subject to displacement and are sufficiently long or located such that they may affect repository design and/or performance. Evidence of movement during the Quaternary Period (the past 1.6 million years) is the primary criterion for identification of these faults.

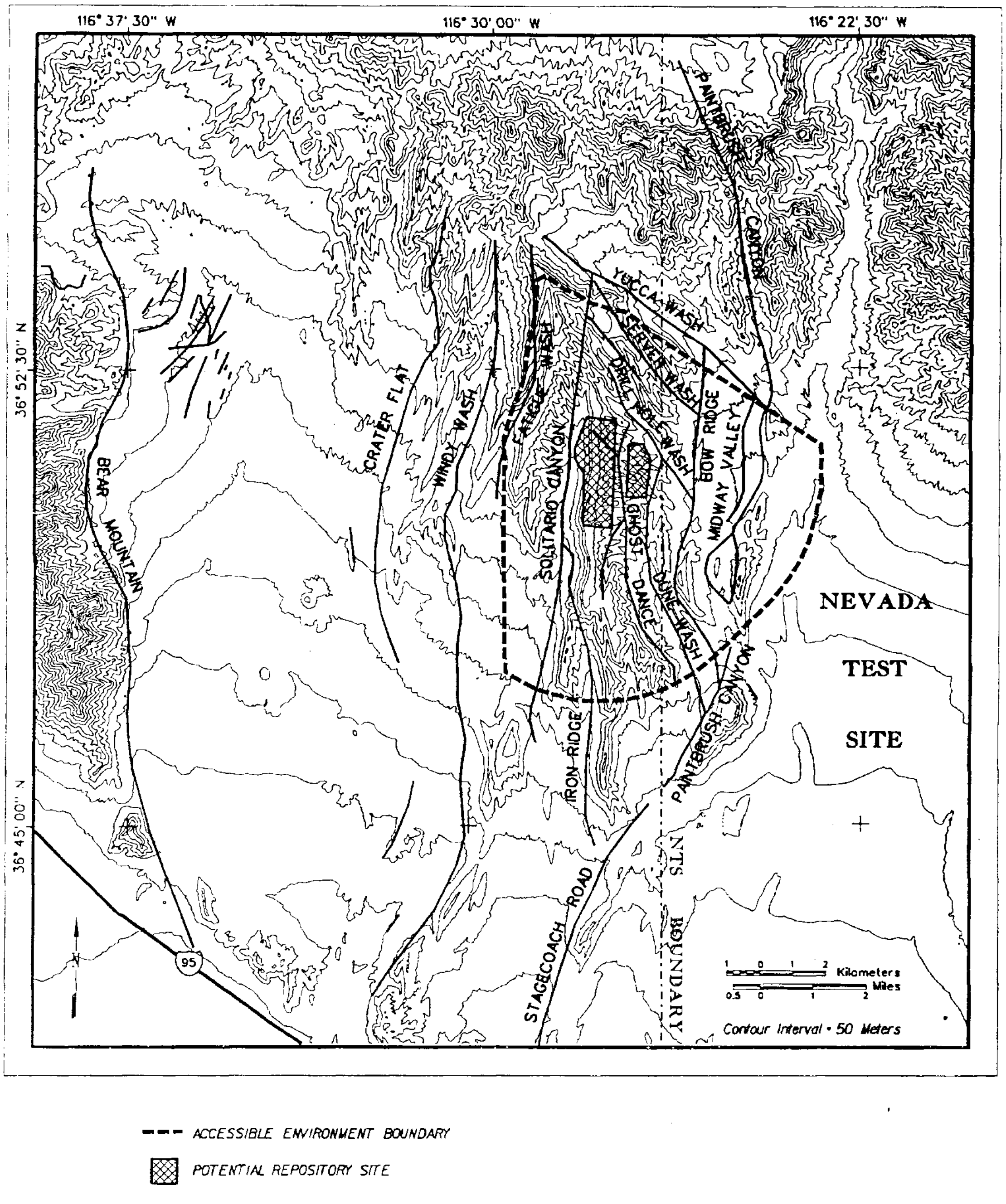

Figure 7-10. Major North-Trending Faults in the Vicinity of Yucca Mountain (DOE95k)

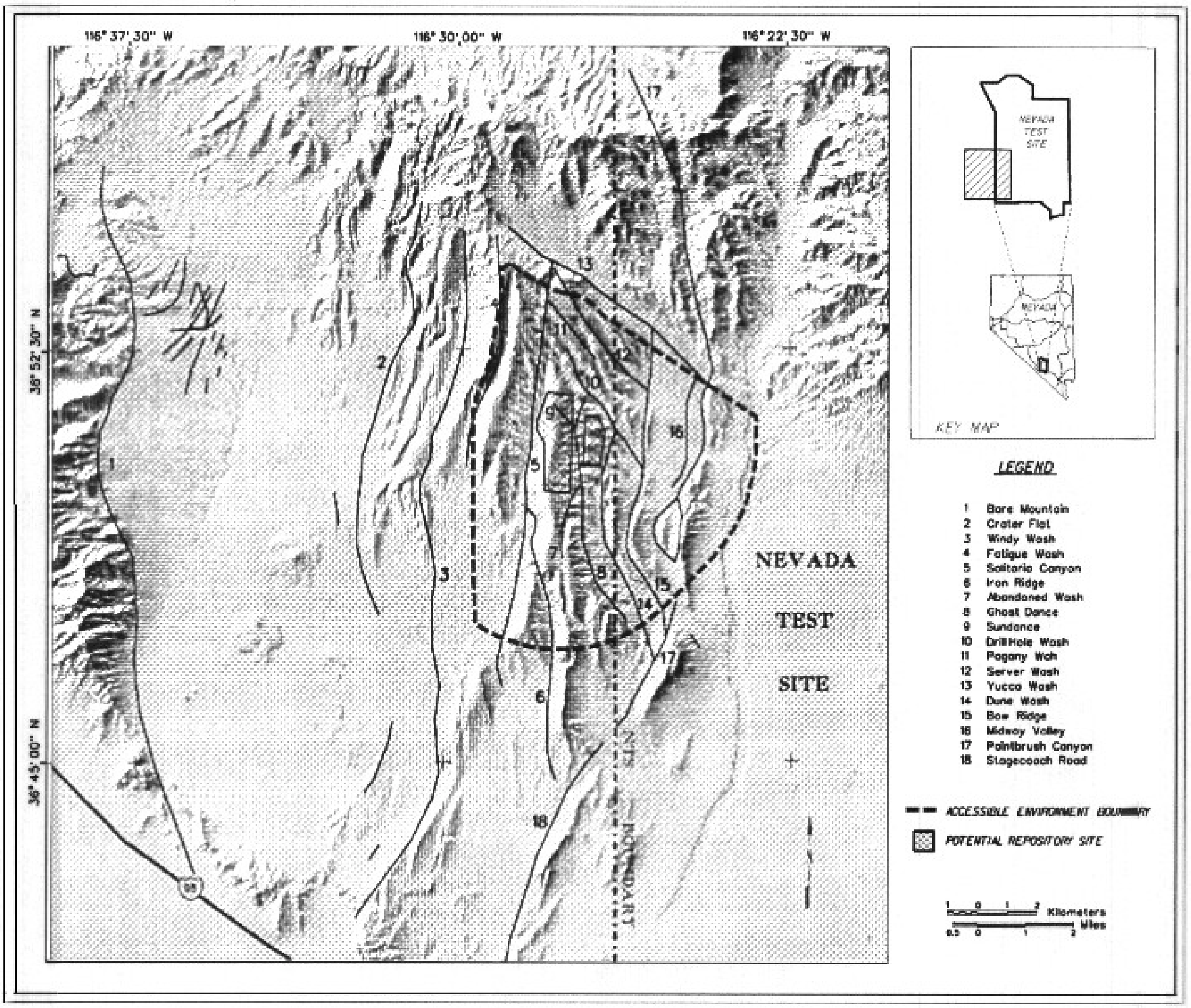

Figure 7-11. Index Map of Faults at and near Yucca Mountain (Modified from DOE95k)

Studies to identify and characterize faults that may be of concern to the Yucca Mountain facility have focused on evaluating the potential Type I faults within 100 km of the site, as well as a few major faults at greater distances. Some 82 known or suspected Quaternary faults and fault rupture combinations have been identified within 100 km of the Yucca Mountain site (Figure 7-12). DOE reports that 38 of these are capable of generating a peak acceleration of 0.1 g (the force of gravity) or greater at the ground surface of the proposed repository site; these are classified as relevant earthquake sources.[18] An updated compilation of faults has been prepared by the U.S. Geological Survey (USGS) which identifies 67 faults with demonstrable or questionable evidence of Quaternary movement and the capability of accelerations of at least 0.1 g at an 84 percent confidence limit (WHI96). Significant known or suspected Quaternary faults located within 20 km of the Yucca Mountain site are briefly described in Table 7-3.[19] The more distant major fault zones include: the Garlock Fault (125 kilometers south), the Owens Valley Fault (140 kilometers west), the Stewart-Monte Cristo Valley Fault (200 kilometers northwest), and the Dixie Valley Fault (see page 3.1-8 *et seq*, DOE95a).

Several of the north-trending faults show evidence of activity during Quaternary time; the total displacements on the most active of these is estimated to be less than 50 meters over the past 1.6 million years. Since the late Quaternary Period (<128,000 years), displacements have been as much as six m but are more commonly in the one to 2.5 m range. Recurrence intervals on the faults showing movement in the Quaternary Period fall in the range of tens of thousands of years, commonly between 30-80 thousand years with slip rates typically in the range of 0.01-0.02 mm/yr. The northwest-trending faults do not appear to have been active.

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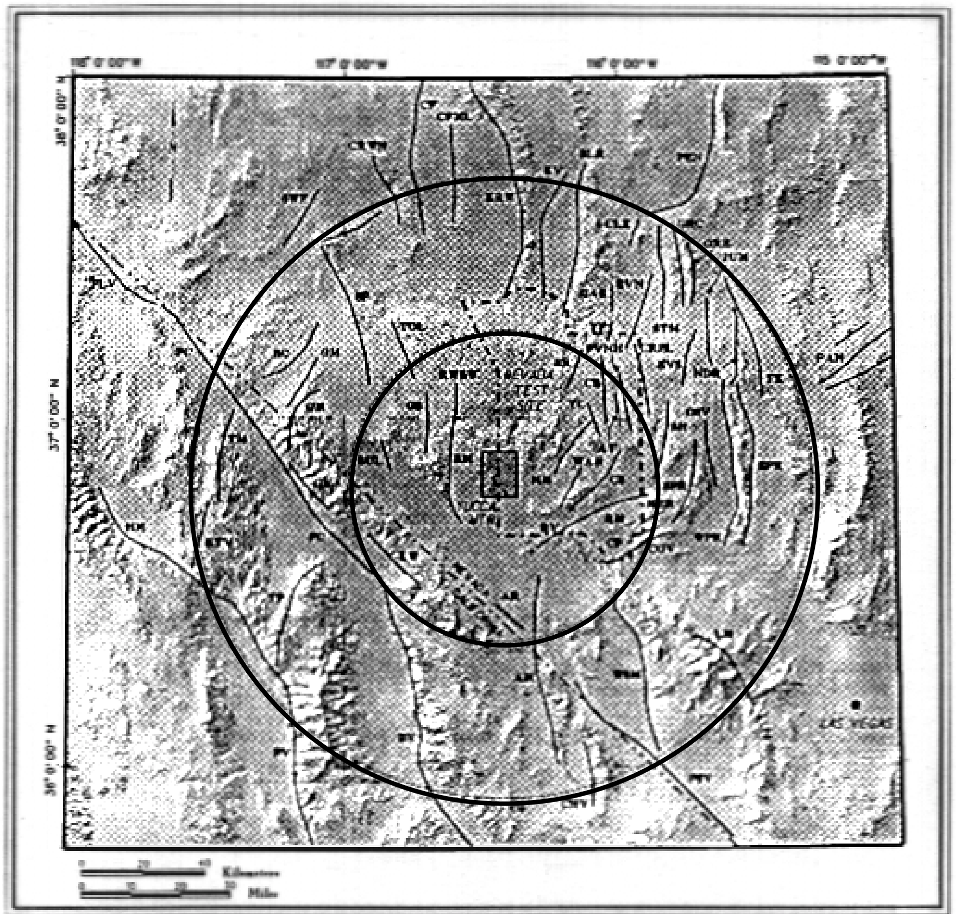
[18] The NRC-supported program of the Center for Nuclear Waste Regulatory Analyses has identified 52 Type I faults within a 100-km radius of Yucca Mountain (NRC97a).

[19] NRC-supported studies have identified 24 Type I faults within a 10-km radius of Yucca Mountain capable of generating peak accelerations of greater than 0.3 g (NRC97a).



AM - Ash Meadow
AR - Amargosa River
AT - Area Three
BC - Bonnie Claire
BH - Buried Hills
BLR - Belted Range
BM - Bare Mountain
BUL - Bullfrog Hills
CB - Carpetbag
CF - Cactus Flat
CFML - Cactus Flat-Mellan
CGV - Crossgrain Valley
CHV - Chicago Valley
CLK - Chalk Mountain
CP - Checkpoint Pass
CRPL - Cockeyed Ridge-Papoose Lake
CRWH - Cactus Range-Wellington Hills
CS - Cane Spring
DV - Death Valley
EPR - East Pintwater Range
ER - Eleana Range
EVN - Emigrant Valley North
EVS - Emigrant Valley South
FC - Furnace Creek
FLV - Fish Lake Valley
GM - Grapevine Mountains
GRC - Groom Range Central
GRE - Groom Range East
GV - Grapevine
HM - Hunter Mountain
ISV - Indian Springs Valley
JUM - Jumbled Hills
KRW - Kawich Range West
KV - Kawich Valley
KW - Keane Wonder
LM - La Madre
MER - Mercury Ridge
MM - Mine Mountain
NDR - North Desert Range
OAK - Oak Spring Butte
OSV - Oasis Valley
PAH - Pahranagat
PEN - Penoyer
PM - Pahute Mesa
PSV - Pahrump-Stewart Valley
PV - Panamint Valley
PVNH - Plutonium Valley-North -Halfpint Range
RM - Ranger Mountains
RTV - Racetrack Valley
RV - Rock Valley
RWBW - Rocket Wash-Beatty Wash
SF - Sarcobatus Flat
SOU - South Ridge
SPR - Spotted Range
STM - Stumble
SWF - Stonewall Flat
SWM - Stonewall Mountain
TK - Tikaboo Valley
TM - Tin Mountain
TOL - Tolecha Peak
TP - Towne Pass
WAH - Wahmonie
WPR - West Pintwater Range
WSM - West Springs Mountain
YF - Yucca Flat
YL - Yucca Lake

Figure 7-12. Index Map of Known or Suspected Quaternary Faults in the Yucca Mountain Region (Modified from DOE95a). Circles are 50 and 100 km radii from Yucca Mountain (YM). Faults are identified as follows:

Table 7-3. Known or Suspected Quaternary Faults within 20 km of the Proposed Repository Site

Fault Name	Trend	Apparent Length	Dip	Distance from Site	Latest Activity
Bare Mountain	N	20 km	E50-70	15 km W	Most recent surface rupture 16 to 21 thousand years ago (ka); one to 1.5 m displacement; recurrence interval 100 ka; slip rate 0.01 mm/yr
Crater Flat	NE	14-20 km	W70	5 km W	Quaternary deposits (17 to 30 ka) displaced less than one m
Windy Wash	N-NE	25 km	W63	3 km W	At least four events in past 300 ka; recurrence interval 75 ka; Pleistocene displacement approximately one m
Fatigue Wash	N	17 km	W73	2 km W	Five late Quaternary events; cumulative displacement 2.2 m
Solitario Canyon	N	20 km	W72	at W boundary	Multiple mid- to late-Quaternary events; 1.7 to 2.5 m displacement of Quaternary deposits
Stagecoach Road	N-NE	10 km	W73	SE corner of area	Three to seven events during late Quaternary; displacement one to 2.3 m; recurrence interval five to 70 ka; slip rate 0.01 to 0.06 mm/yr
Ghost Dance	N	3.5km	W80-90	center of area	No offset or fracturing of late Pleistocene or Holocene noted except for a single fracture in one trench. Fracture zone varies up to 213 m across.
Dune Wash	N-NW	8 km	W	at E side	No evidence of Quaternary activity found
Bow Ridge	N	10-19km	W65-75	2 km E	Most recent event 48±20 ka; cumulative displacement 0.3 to 0.7 m; likely recurrence interval 60 to 100 ka; slip rate 0.002 to 0.01 mm/yr
Midway Valley	N	1-4 km	W	3 km E	No recognizable ruptures of Quaternary deposits
Paintbrush Canyon	N	25-32 km	W41-71	E side of Yucca Mtn.	Six to eight events evident; Midway Valley excavation: most recent event at 38±6 ka; cumulative displacement 1.7 to 2.7 m; recurrence interval 20 to 80 ka, slip rate 0.007 to 0.02 mm/yr; Busted Butte exposure: Quaternary displacement 4.8 to 7.8 m; recurrence interval 40 to 125 ka; slip rate 0.006 to 0.01 mm/yr

The three major faults in the immediate region of Yucca Mountain are the Ghost Dance fault, which passes through Yucca Mountain and the proposed repository; the Bow Ridge fault, just to the east of Yucca Mountain; and the Solitario Canyon fault, just to the west of Yucca Mountain. According to DOE's interpretation of available data, the Solitario Canyon fault has shown no significant movement over the last 40,000 to 110,000 years. No movement has occurred during the last 10,000 years. The most recent surface-rupturing motion on the Bow Ridge fault is estimated to have occurred 48,000 ±20,000 years ago, with a recurrence interval most likely in the range of 60,000 to 100,000 years. There has been no offset or fracture on the Ghost Dance fault for the past 20,000 years.

7.1.1.5 Tectonics and Seismicity (Adapted from DOE95a)

The fault systems and the seismic history of the Yucca Mountain area must be considered in the larger context of regional tectonics. By so doing, predictions of future seismic hazards and their potential effects on the repository, as well as the performance of natural barriers, can be made with reasonable certainty, within the limits of the available data. This section discusses what is currently known about the tectonic setting of the region encompassing the repository site. Data concerning the seismicity of the area and historic earthquake activity are also presented.

Regional Plate Tectonic Setting

The plate tectonic setting of the southwestern United States is dominated by the interaction of the North American and Pacific Plates. In the Yucca Mountain Region, particularly west of Yucca Mountain, this interaction is complicated by the overlap of right-lateral plate boundary stress from these plate movements and extensional stress from the Basin and Range tectonics.

Based on geologic and geodetic measurements, the Pacific plate appears to be moving northwest at approximately 50 mm/yr relative to the North Atlantic plate. The stresses generated from this movement are distributed to structural features on the North American Plate and contribute to the tectonic processes (extension or compression of the crust, folding and faulting, etc.) in the region. About 35 mm/yr of the motion from the Pacific Plate is absorbed by the San Andreas fault system; another 5 mm/yr may be absorbed by coastal strike-slip faults parallel to and west of the San Andreas fault. The eastern edge of the Sierra Nevada microplate (composed of the Sierra Nevada Mountains and the Great Valley of California) appears to move northwest at approximately 10 mm/yr. This latter movement, between the eastern edge of the Sierra Nevada Mountains and the western edge of the Colorado Plateau, is most likely to contribute to the seismicity and tectonic processes around the Yucca Mountain site (Figure 7-13). Uncertainties in

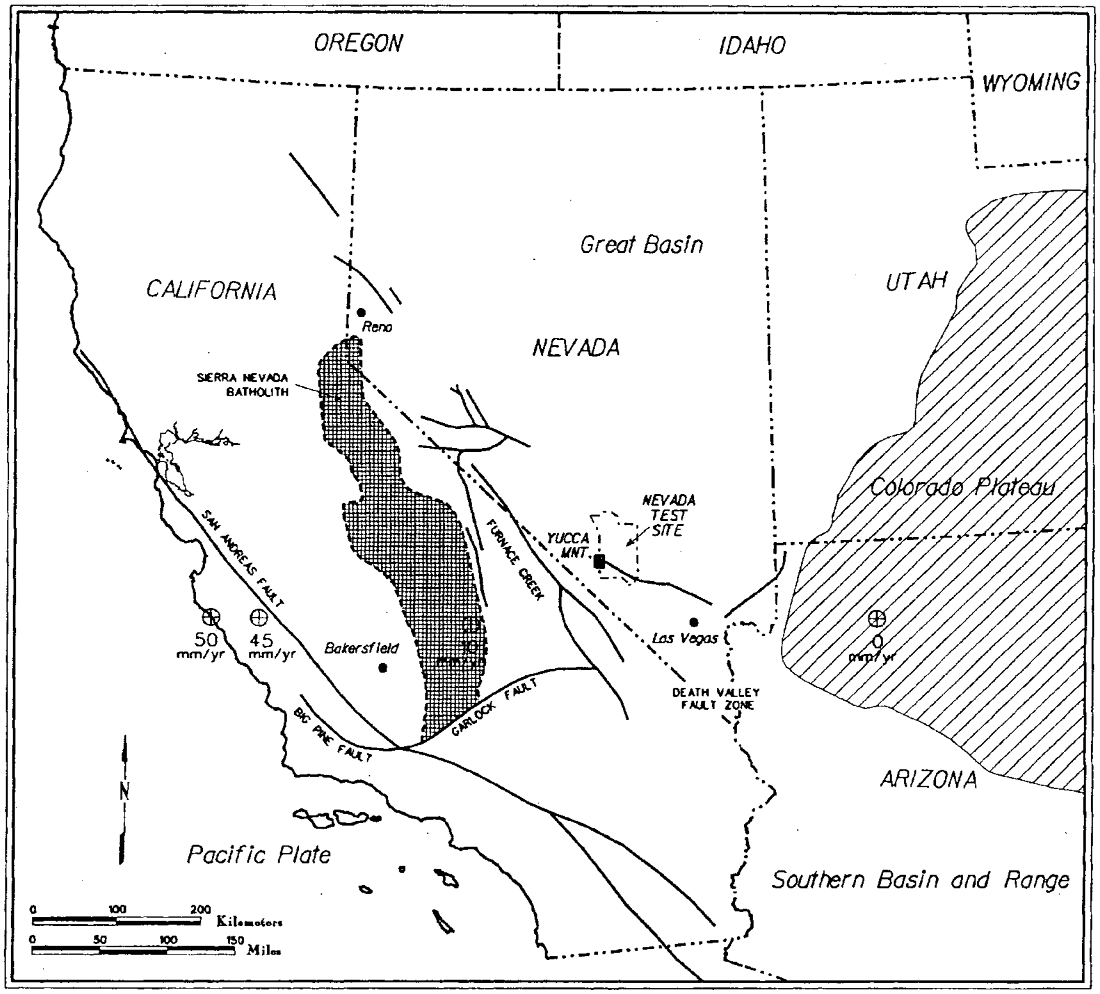


Figure 7-13. Sketch Map of the Western United States Showing Some Major Structural Features. Symbols (⊕) at the latitude of Las Vegas give approximate motions toward the NW in mm/yr relative to a "stable North America." This interpretation suggests that 10 mm/yr of NW movement occurs between the Colorado Plateau and the crest of the Sierra Nevada Range, 35 mm/yr occurs on the San Andreas Fault, and five mm/yr occurs west of the San Andreas Fault. This is consistent with the paleoseismic data and historic observations of strike slip faulting in this region. (Modified from DOE95a)

the understanding of the regional tectonic processes include: the amount of compression normal to the San Andreas fault induced by Pacific plate motion (N36°W ±2°), the rate of relative motion between plates, and the amount of motion taken up within the Sierra Nevada microplate.

The timing and mechanisms for producing the crustal extension which characterizes the structural and physiographic features of the Great Basin are a subject of debate. Several mechanisms have been proposed for the extensional tectonic processes that produced the major land forms of the Great Basin. Relatively high-angle, planar, normal faults cutting brittle crust can accommodate up to 10 or 15 percent of the crustal extension. Normal faults at a high angle at the surface and curving to lower angles at depth (listric faults) may accommodate much greater extension. Modeling of very low angle detachment faults suggests extensive crustal thinning that may accommodate extension of the crust by 200 percent or more.

The typical Basin and Range structures were developed by about 11 Ma. They are tilted fault block ranges with relatively large displacement, high-angle normal faults exposed at the surface bounding one or both sides of each range. Scott (SCO90) suggests that rates of fault movement were highest between 13 - 11.5 Ma and thereafter decreasing over time.

This crustal extension varied across the region in time and space. One thought is that rapid Miocene extension migrated westward from Yucca Mountain after about 11.5 Ma and may also have been nonuniform from north to south. Pliocene and later extension, accompanying a postulated region-wide uplift starting about five million years ago, is more evenly distributed and is taken up by movement on high-angle normal faults at depth which are coincident with the Miocene faults expressed at the surface. This belief is consistent with the evidence of the existence of faulting to depths of 15 km or more indicated by the pattern of hypocenters for the current seismicity in the region.

Structural Features and Seismicity

The relationship between specific structural features, particularly faults, and seismicity in the Basin and Range Province is not entirely clear. The Central Nevada Seismic Belt (CNSB), for example, is clearly associated with major faults or fault systems showing historic surface rupture. However, other zones of seismic activity and areas of diffuse activity show no evidence of historic surface faulting. One example is the east-west seismic belt, which includes the Nevada Test Site.

The apparently poor correlation between earthquakes and faults may be attributable, at least in part, to several factors: (1) the short historical record relative to the long recurrence intervals for earthquakes, (2) the difficulty of accurately locating epicenters in this remote area, and (3) the unknown geometry of faults at depth. Study of the paleoseismic record for the Quaternary Period suggests that, in the Yucca Mountain Region, recurrence intervals for surface rupture are on the order of thousands to tens of thousands of years.

Seismology of the Yucca Mountain Area

In the region around the site, there are several zones in which seismicity is concentrated: the Sierra Nevada-Great Basin Boundary Zone (SNGBZ), the CNSB, the Southern Nevada Transverse Zone (SNTZ), the Garlock Fault, and the Mojave Block. All of the zones, except the Mojave Block, are wholly or partially in the Walker Lane Belt, a major tectonic element of southwestern Nevada. In addition, there is a broad distribution of seismic activity that is not associated with any known major tectonic feature throughout much of the Great Basin.

The **Walker Lane Belt** tectonic element (Figure 7-9) consists of nine structural blocks acting more or less independently. The belt is defined by a style of faulting within and bounding the blocks which ranges from northwest-trending right-lateral slip (the Pyramid Lake, Walker Lane, and Inyo-Mono blocks) to northeast-trending left-lateral slip (the Carson, Spotted Range-Mine Mountain, and Lake Mead blocks) to east-west trending left-lateral slip (Excelsior-Coaldale block). Cumulative lateral offset on individual major faults ranges from a few kilometers up to 100 kilometers and faults rarely extend to adjacent blocks.

The Walker Lane Belt probably developed in the Mesozoic Period and is still active. Most of the faults show evidence of Cenozoic movement and numerous zones exhibit Quaternary and Holocene offset (STE90). Although the recurrence interval for the late Quaternary faulting is generally thousands to tens of thousands of years, recurrence may be on the order of decades in some sections of the seismic zone, e.g., the CNSB.

Of the four seismic zones identified in the Walker Lane Belt, the SNTZ is nearest to the Yucca Mountain site and is the most significant to repository performance. Although the other zones exhibit recent seismic activity, they are further removed from the Yucca Mountain site and are less likely to affect the repository.

The **Southern Nevada Transverse Zone**, which includes Yucca Mountain, is an arcuate belt of seismicity about 150 kilometers wide, extending from the southern region of the Intermountain

Seismic Belt (in southwestern Utah) to the Mammoth Lakes area in California. Historic earthquakes in this zone have been of moderate magnitude with no documented surface rupture. Earthquake events include the 1902 Pine Valley, Utah (M_L 6.3)[20], the 1966 Caliente-Clover Mountain, Nevada (M_L 6.0), and the 1992 Little Skull Mountain, Nevada (M_L 5.6) near the proposed site (see Table 7-3).

Seismic Distribution

Studies of the large Great Basin earthquakes suggest faulting on steeply dipping fault planes that penetrate the upper 15 kilometers of crust as the focal mechanism for many of the earthquakes observed. In general, mainshock hypocenters for earthquakes of magnitude seven or greater in this region can be located on the down-dip projection of the surface rupture observed along faults identified in the field, suggesting that large Great Basin events occur on steeply dipping planar faults at depths less than about 15 kilometers.

Three—with perhaps two additional possible—seismic gaps (areas of no recent seismic activity) have been identified in the western Great Basin. These gaps occur between the rupture zones of major historic earthquakes and contain structures that show evidence of prehistoric activity. Seismic gaps are generally considered to be significant in plate-boundary regions but their relevance for interplate regions such as the Great Basin is not clear. These gaps may represent areas of prolonged low or no seismic activity or areas where stresses are not being released by fault movements.

Significant Historical Earthquakes

Figure 7-14 depicts the epicenters for earthquakes of magnitude 3 and greater occurring within 320 kilometers of the proposed site from 1850 through 1992. These data show a clustering of seismicity in the CNSB and the SNGBZ, as well as in the southern Mojave Desert and along the San Andreas fault zone. In addition to those identified in the figure, numerous small magnitude earthquakes have occurred in clusters or as isolated events throughout much of Nevada. The Garlock Fault and a large portion of the southern Great Basin appear to show relatively little seismic activity during this period.

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[20] M_L is a measurement of the magnitude of the seismic event. See Table 7-4 for a definition of this and other magnitude measures.

Table 7-4. Significant Earthquakes within 320 km of Yucca Mountain Site Since 1850 (Continued)

Table 7-4. Significant Earthquakes within 320 km of Yucca Mountain Site Since 1850

Owens Valley, CA, 1872	March 26, 1872; estimated at M_w 7.8 to M_s 8.0[*a]; considered largest historic event of the Basin and Range; surface ruptures along 90 to 110 km on Owens Valley fault; average net oblique slip of 6.1 ±2.1 m and up to four m vertical displacement; liquefaction of unconsolidated sediments.
Wonder, NV, 1903	Fall 1903; estimated magnitude 6.5; rupture of the Gold King fault; ruptures of five to 16 km with fissures up to 1.5 m wide and 1.5 m deep in alluvium; in the same area as the 1954 Fairview Peak-Dixie Valley earthquakes.
Cedar Mountain, NV, 1932	December 21, 1932; M_s 7.2; about 61 km of discontinuous faulting in a belt six to 14 km wide; displacements up to 1.8 m horizontal and 0.5 m vertical; analysis indicated main shock was two sources occurring about 20 seconds apart; an M_w 6.7 event and a second M_w 6.6 event; series of seven moderate events in this part of the CNSB from 1932 to 1939.
Excelsior Mountains, NV, 1934	January 30, 1934; M_L 6.3 (M_w 6.1); on Excelsior-Coaldale section of the Walker Lane belt; about 60 km west-southwest of the 1932 event; foreshock of M_L 5.6 preceded mainshock by 45 min.; surface rupture 1.4 km in length and less than 13 cm vertical displacement. An M_L 5.5 earthquake occurred on August 9, 1943, approximately 40 km southeast.
Rainbow Mountain, Stillwater, NV, 1954	July 6, 1954; two events of M 6.6 and M 6.4 in Rainbow Mountain area were followed on August 24 by the Stillwater M 6.8 event initiating a six-year period of 10 events greater than M 5.5 in the CNSB.
Fairview Peak-Dixie Valley, NV, 1954	December 16, 1954; an M_L 7.3 event on the Fairview fault followed four minutes later by an M_L 6.9 event rupturing the Dixie Valley fault; diffuse fracture zone covering an area 100 km by 30 km from Mount Anna to the northern part of Dixie Valley; displacements four m right lateral and three m vertical on Fairview Peak fault and over two m vertical in Dixie Valley.
Caliente-Clover Valley, NV, 1966	On August 16, 1966; M_L 6.0; near Caliente, Nevada, about 210 km east-northeast of Yucca Mountain. The source depth is estimated at 6 km; with the focal mechanism a strike-slip motion on steeply dipping plates oriented either north-northeast or west-northwest.
Mammoth Lakes, CA, 1978-1980	An M_L 5.8 earthquake midway between Bishop and Mammoth Lake in October, 1978, was followed 18 months later (May, 1980) by a swarm-like sequence of four events (M_L 6.5, M_L 6.0, M_L 6.7, M_L 6.3) within two days. This sequence was accompanied by inflation of the resurgent dome in the Long Valley caldera. Activity continued with moderate earthquake swarms in the southern part of the caldera with spasmodic tremor sequences usually associated with magma injection at depth. The Chalfant sequence, discussed below, occurred to the east in 1986.

Table 7-4. Significant Earthquakes within 320 km of Yucca Mountain Site Since 1850 (Continued)

Chalfant Valley, CA, 1986	On July 21, 1986, an M_L 6.6 earthquake occurred in the Chalfant Valley in eastern California about 15 km north of Bishop with about 10 km of rupture along the White Mountains fault zone. The source-depth was located 11 km below the surface and the focal mechanism indicates right lateral slip on a plane oriented north-northwest dipping 70° southwest.
Landers, CA, 1992	The Landers sequence began April 23rd with the M_L 6.2 Joshua Tree earthquake, followed by a sequence of 6000 events. On June 28, 1992, an M_s 7.6 earthquake near Landers, California, ruptured sections of several mapped north- to northwest-trending faults and several concealed unmapped north-trending faults in the south-central portion of the Mojave block. An extensive aftershock sequence followed, extending 85 km north of the mainshock and 40 km to the south. The sequence included the M_s 6.7 Big Bear earthquake three hours after and 30 km west of the mainshock. Surface rupture extended for 85 km, with displacement averaging two to three meters across the rupture zone, up to 6.7 m on the Emerson fault, and minor rupture of faults within 30 km of either side of the main rupture zone. The Lander event was followed by a sudden increase in seismic activity in the western U.S. up to 1250 km from the mainshock, with an intense cluster of events in the Walker Lane belt. This included the M_L 5.6 Little Skull Mountain earthquake on June 29, 1992, approximately 20 km SE of Yucca Mountain.
Eureka Valley, CA, 1993	On May 17, 1993, an M_L 6.1 earthquake occurred 30 km southeast of Bishop, California. The hypocenter was located nine kilometers below the surface in the southern part of Eureka Valley. Preliminary analysis indicates normal faulting on a northeast striking plane, perhaps paralleling a north-northwest trending inferred Quaternary fault in the area.

[*a] Terms used for earthquake magnitude in the table above include:

- M_L Local magnitude; this is the original Richter scale, developed in California for earthquakes with epicentral distances less than 600 km and focal depths less than 15 km; uses waves with periods of about 1 s; saturates at M = 7.25;
- M_s Surface-wave magnitude; suitable for global distance; uses waves with 20 s periods; saturates at about M = 8.6;
- M_w Moment magnitude; based on seismic moment ($M_0 = \mu AD$), where μ = shear modulus, A = area of fault rupture, and D = fault displacement; $M_w = 2/3 \log M_0 - 10.7$; does not saturate;
- M This is assumed to be local magnitude.

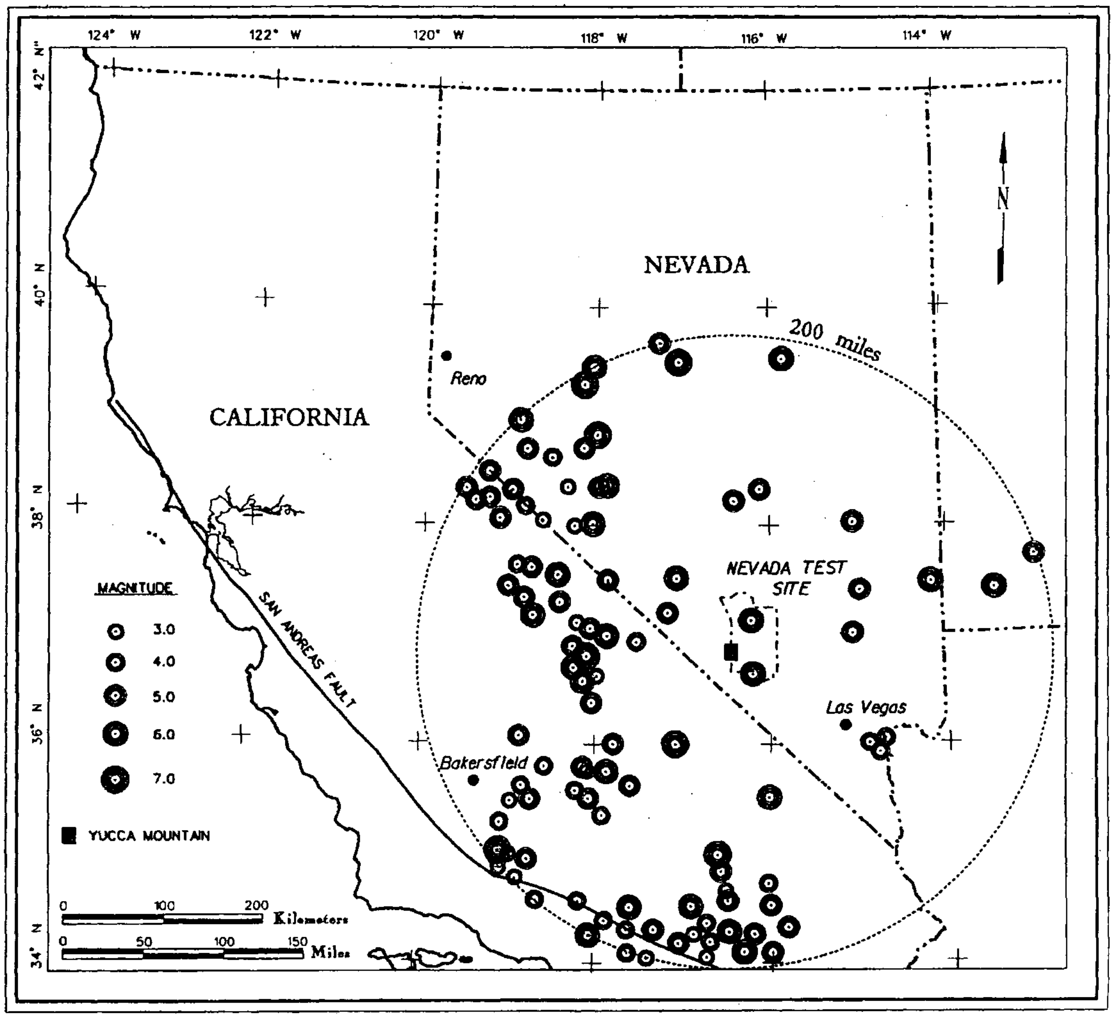

Figure 7-14. Magnitude 3 or Greater Earthquakes Within 320 Km (200 Miles) of Yucca Mountain from 1850 to 1992 (Modified from DOE95a)

Earthquakes occurring since 1850 within 320 km of the Yucca Mountain site with magnitudes greater than 6 are summarized in Table 7-3. These either resulted in surface rupturing or represent the largest event in a particular seismic-source zone. The most recent strong earthquake (M_L =5 or greater) in the vicinity of Yucca Mountain was the Little Skull Mountain (M_L = 5.6) event in June 1992, associated with the Landers, California earthquake earlier that year.

Studies of ground motion from recorded seismic activity around Yucca Mountain and of surface features susceptible to ground motion effects, suggests that Yucca Mountain has not been subject to ground accelerations at the surface in excess of 0.2 g for over several tens of thousands of years. At the depth at which waste is likely to be emplaced in the repository, the effects of ground motion would be expected to be significantly less. These ground accelerations do not present excessive demands on seismic facility design requirements for the repository or its associated surface facilities.

The largest seismic event in the immediate area of Yucca Mountain since 1978 was an M_L 2.1 event on November 18, 1988, centered 12 km northwest of the proposed repository location. An earthquake of magnitude M_W 5.7 occurred on June 29, 1992, beneath Little Skull Mountain approximately 20 km southeast of Yucca Mountain. This earthquake is the largest ever recorded (in about 100 years of records) in the vicinity of the site. It caused minor structural damage to the Yucca Mountain project field office near Yucca Mountain but had no apparent effect on geologic features near the mountain.

Based on a return period of 12,700 years, Bechtel Nevada estimates that for the adjacent Nevada Test Site there is a 0.55 probability of at least one earthquake of magnitude 6.8 or greater occurring in the next 10,000 years (SHO97).

DOE has not considered seismicity to be a significant factor in repository safety performance. Seismic effects are not considered in previous total system performance assessments (DOE94a, DOE95b) because DOE believes that they will have virtually no effect underground. Dowding and Rozen (DOW78) examined empirical evidence of damage to 71 rock tunnels in Alaska, California and Japan from earthquake shaking. From this analysis, the authors concluded that, for peak surface accelerations which would cause heavy damage to above ground structures, there was only minor damage to tunnels. No tunnel damage was observed for peak surface accelerations of less than approximately 0.2g and only minor tunnel damage occurred when the peak surface acceleration was less than 0.5g.

DOE quantitatively analyzed the variation of ground motion with depth using both stochastic and empirical methods (DOE94e). Peak surface accelerations were shown to be reduced by a factor of two at a depth of about 400 m.

DOE considered tectonism in the TSPA-VA released in 1998, including the effects of parameter variability (DOE98). NRC included the effects of fault displacement impacts and seismic rockfall impacts on waste packages in TPA 3.1 (NRC97c).

In its 1996 Phase 3, Yucca Mountain Total System Performance Assessment, the Electric Power Research Institute (EPRI) did not include consideration of earthquakes since it was concluded that "...tectonic activity is not expected to significantly impact repository integrity" (EPR96).

The National Academy of Sciences (NAS) supports DOE's view that seismic effects on underground excavations are usually less severe than on surface facilities (NAS95, p. 93). In addition, NAS states that while the timing of seismic effects is unpredictable, the consequences of such events are boundable for performance assessment purposes (Ibid., p. 94). The NAS further notes that it is possible for the hydrologic regime to be affected either adversely or favorably by seismic events.

The technical community did not agree with DOE's position on structural deformation and seismicity presented in TSPA-95. Subsequently, in May 1996, a meeting of involved groups was held to review and seek agreement on defensible tectonic models based on available data. The group included DOE, NRC, the Advisory Committee on Nuclear Waste (ACNW), the Nuclear Waste Technical Review Board, the USGS, the State of Nevada, the EPRI, and the Center for Nuclear Waste Regulatory Analyses (CNWRA) (NRC97a). Of 11 proposed models, the group agreed that only five were supported by existing data. Agreement on the five supportable models was not unanimous nor was agreement on the relative importance of the five models. In addition, some of the models may be independent and some may be subsets of others. The five viable alternative models are:

- Deep detachment fault (12-15 km)
- Moderate detachment fault (6-8 km)
- Planar faults with block deformation
- Pull-apart basin[21]
- Amargosa shear

The pull-apart basin model proposed by the USGS and the Amargosa shear model proposed by the State of Nevada are based on buried or blind seismic sources at Crater Flat and involve the greatest seismic risk. These seismic sources are not included in DOE's Probabilistic Seismic Hazards Analysis which was used as a partial basis for the conclusions reached in TSPA-95. Depending on proximity to the repository, the Amargosa shear could result in an earthquake with magnitude $M_w \geq 7.8$ and accelerations exceeding 1 g (NRC97a). More recently, CNWRA stated

[21] A pull-apart basin is a structural depression formed by localized extension along strike-slip fault zones. The basin is formed in the brittle upper crust above a horizontal detachment in the lower crust (NRC97a).

that apatite-fission-track dating from Bare Mountain and Striped Hills does not support the USGS reconstruction of the Amargosa shear model (McK96). CNWRA believes that the pull-apart basin model is more tenable but requires additional direct observations of basin-bounding and cross-basin strike-slip faults.

Additionally, DOE argued that future tectonic events are unlikely to significantly alter the hydrologic characteristics of the Yucca Mountain site. This argument is based on the position that the current state of faults and fractures at the site is the result of cumulative tectonic events. However, CNWRA posits that a single tectonic event can cause significant changes in hydrologic characteristics. The DOE argument is valid only for characteristics resulting from cumulative events and not for the most recent single tectonic event (NRC97a).

7.1.1.6 Fractures (Adapted from DOE95a)

Closely allied with tectonic issues is the consideration of fractures in the rocks surrounding the repository. An extensive fracture network can provide fast paths both for influx of water into the repository for overlying strata and egress of water potentially contaminated with radionuclides through underlying strata. To develop an understanding of fractures, studies have been conducted to examine the age and connectivity of fractures primarily in a portion of the Tiva Canyon Tuff. Outcrop studies were conducted for a number of units. The studies were designed to define the general orientations of fracture sets over all of Yucca Mountain and to establish the relationship of fracture sets to regional tectonic history. A few studies of the vertical continuity of fractures have been conducted in the Paintbrush nonwelded unit. These are designed to examine changes in fracture pattern as a function of stratigraphy (DOE95a).

Four sets of tectonic fractures with consistent orientation were identified within the Paintbrush Group. In addition, a set of sub-horizontal joints with variable strikes and dips of less than 10 degrees exists. These fracture sets may have originated as extension joints, many of which have been subsequently been reactivated. It has been postulated that the fractures developed as a mountain-wide response to far-field stresses rather than local movement of structural blocks. However, data to support this hypothesis conclusively are limited (DOE95a).

Fracture widths are defined both by rock wall separation and actual fracture aperture. Rock wall separation is the distance between the fractured surfaces without reference to any infilling with secondary minerals. Aperture includes the effects of any infilling and is the amount of open space remaining. Wall separations are typically one to 10 mm from the surface to a depth of about 200 m. Surface fractures are 50 to 75 percent filled with caliche which reduces the

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