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GEOLOGY AND HYDROLOGY OF YUCCA MOUNTAIN AND VICINITY, NEVADA TEST SITE

Final Report
March 1982

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Prepared for
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ABSTRACT

Yucca Mountain along the western boundary of the Nevada Test Site (NTS) in southeastern Nevada is a candidate site for the geologic disposal of radioactive waste. This report provides a summary of the geology and hydrology from available studies of the NTS region for the purpose of allowing application of the Sandia National Laboratories' (Sandia) risk assessment methodology to a realistic geologic system in which volcanic tuffs are the candidate disposal medium.

The western NTS contains a thick highly variable sequence of tertiary volcanic tuffs, block faulted during the past 26 to 27 million years. The tuffs unconformably overlie intensely deformed Paleozoic and Mesozoic carbonates and clastics. Groundwater recharge in the region is minor, producing very long, sluggish, groundwater flow systems. Boundaries between flow systems are poorly defined from existing data on water table configurations, and head distributions at depth are unknown. The hydrologic properties of geologic units in the region are partially known from some available testing, but must in large part be determined by assumption, analogy, and calculation. Modeling based on the summary presented in this report should consider the ranges of values presented for properties and should qualify results with elaboration on the uncertainties involved in characterization of a complex geologic system from a sparse data base.

The probability and consequences of the occurrence of several scenarios are considered. Future climatic change could produce up to 280 feet of rise in water table elevations. Future faulting that does not directly intersect a depository is unlikely to greatly alter flow in the system, which is already intensely faulted; however, the effects of existing faults on contaminant transport requires detailed analysis that considers the uncertainty of current knowledge of fault properties. Magmatic activity could greatly alter the flow system, but is unlikely to occur. Human-induced alterations of the system are mostly small scale or transient, and the contaminant releases from a repository in tuff attributable to human activity are probably small.

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1.0 INTRODUCTION

CGS, Inc. was contracted by Sandia National Labs to compile geologic and hydrologic information necessary to characterize in a general fashion a reference radioactive waste repository system in the volcanic tuffs at the Yucca Mountain, Nevada Test Site facility. The goal of this effort is to provide a realistic repository setting for exercise of the Sandia risk assessment methodology, allowing application of the methodology to an evaluation of EPA standards for radionuclide release in a tuff system.

The geology, and therefore the hydrogeology, of the NTS is quite complex. There are two reasons for this. First, the tuffs comprising the upper portion of the stratigraphic section exhibit a large, natural variability in properties due to their mode of deposition and subsequent structural deformation. Second, the Paleozoic and Precambrian rocks comprising the lower portion of the section have been severely deformed by several regional tectonic events and do not overlie each other in a simple layered fashion. This complexity would require an intense field program to provide the data needed to clarify many of the uncertainties related to inadequacies in the currently available information. At present, the field mapping, drilling and testing programs have not progressed to the stage where this system can be considered adequately understood from the viewpoint of site characterization for actual waste disposal, and much important data necessary for reference system definition is inadequately developed. We have made many assumptions (such as lateral and vertical continuity of rock properties and geometrical simplifications of stratigraphy) to bridge gaps in the available information, but these have been necessary to carry through on the analysis. The assumptions made and conclusions drawn in this report are explicitly stated and must be considered preliminary. Any modeling efforts based upon them should be appropriately qualified. We have used English units throughout this report to be consistent with previous report drafts and with most of our sources.

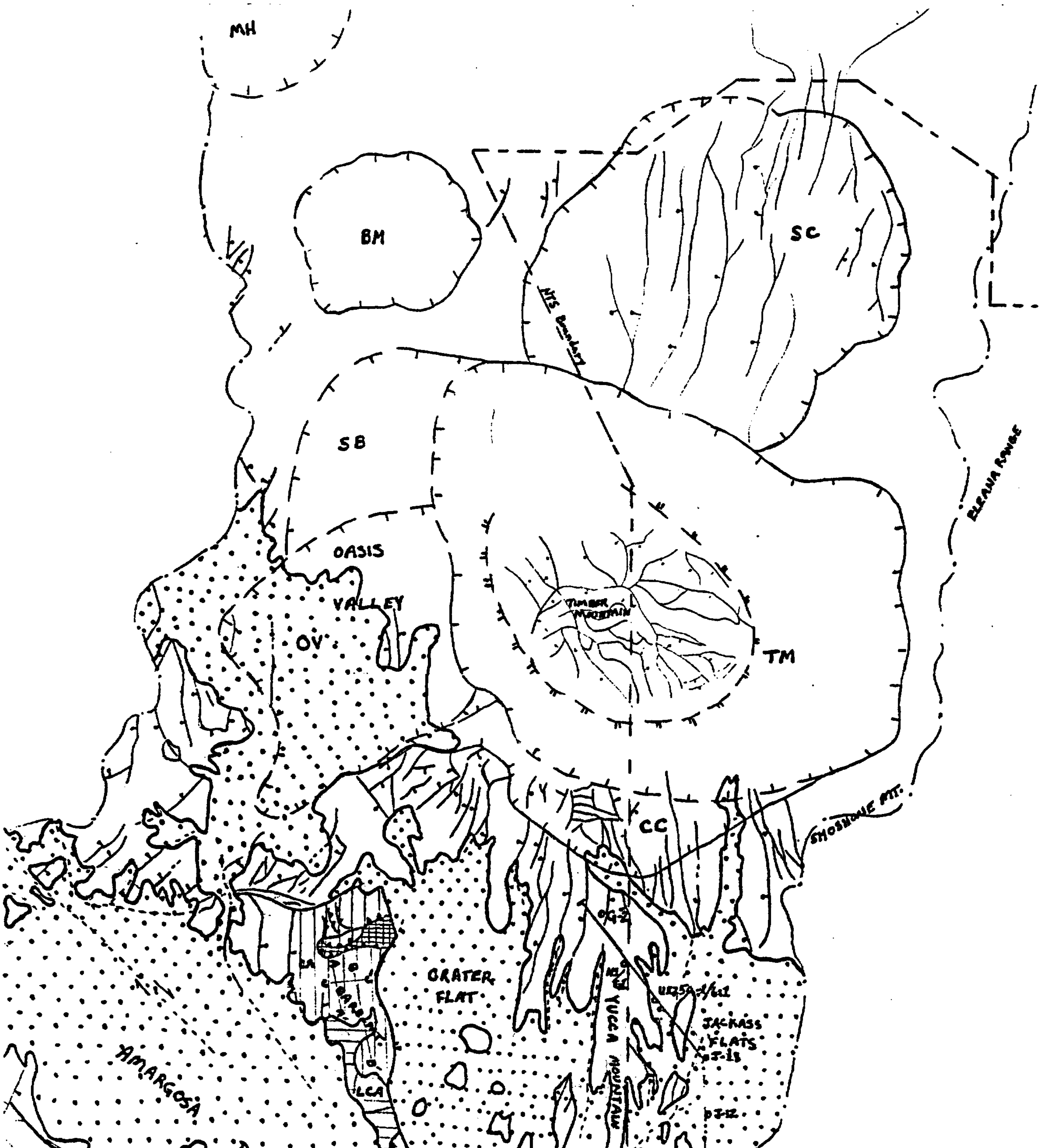
2.0 REGIONAL GEOLOGY

2.1 Stratigraphy and Unit Descriptions

On a regional basis, the major hydrostratigraphic units are, from oldest to youngest, (1) the lower clastic aquitard (Precambrian to lower Cambrian), (2) the carbonate aquifer (mid-Cambrian through mid-Devonian), (3) the upper clastic aquitard (upper Devonian through Mississippian), (4) the tuff aquitard (Oligocene through mid-Miocene), (5) the tuff and lava flow aquifer (upper Miocene through Pliocene), and (6) the alluvial aquifer (Pliocene to Recent). The regional distribution of these units is shown on Figure 1.

The rocks of unit 1, largely siltstones and quartzites, are up to 10,000 feet thick and probably exist throughout the Nevada Test Site (NTS) and vicinity except in the caldera regions shown on Figure 1 (Winograd and Thordarson, 1975, pp. C9-C11). Major outcrops occur in the Groom Mountains east of the NTS, in the Spring Mountains to the southeast and in the Funeral Mountains to the southwest (Winograd and Thordarson, 1975, Plate 1; Carr, 1974, Figure 2). The contact between the relatively impermeable rocks of unit 1 and the overlying Paleozoic sedimentary rocks represents the hydraulic basement or basal no-flow boundary of the regional groundwater system.

The Paleozoic sedimentary rocks of units 2 and 3 were deposited in a very broad, subsiding trough on what was the western edge of the continent. These rocks thicken in a westerly direction from a maximum of 17,000 feet near the Utah/Nevada border to a maximum of 32,000 feet in central Nevada (Nevada Bureau of Mines, 1964, pp. 20-25). Unit 2 rocks outcrop extensively east and southeast of the NTS, but are also found in Bare Mountain and the Funeral Mountains to the southwest


MH
BM
SC
NTS Boundary
SB
OASIS
VALLEY
OV
TIMBER MOUNTAIN
TM
ELEANA RANGE
SHOSHONE MT.
CC
CRATER
FLAT
YUCCA MOUNTAIN
JACKASS
FLATS
J-13
J-12
LCA
AMARGOSA

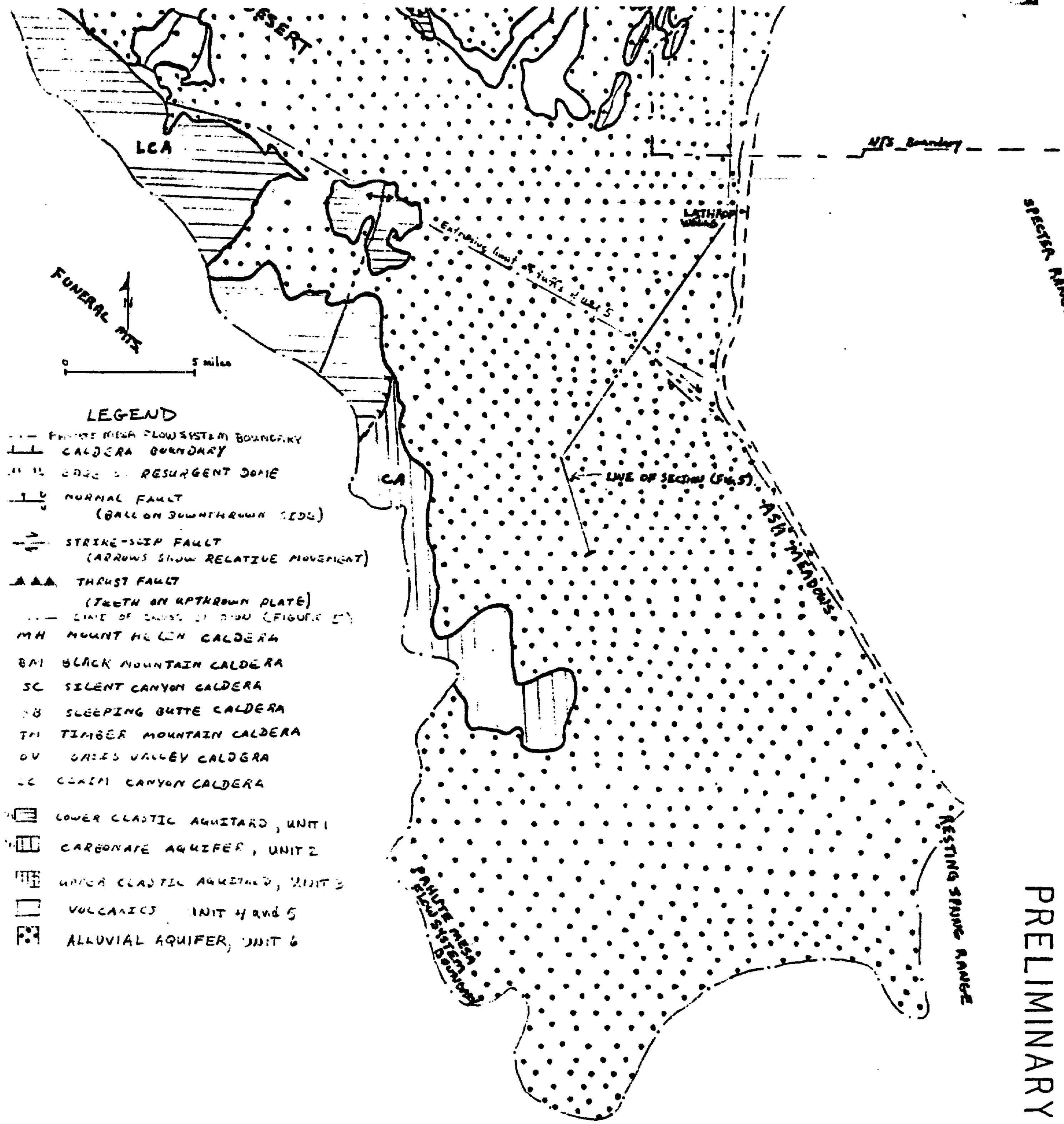


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FIGURE 1. GEOLOGY OF PAHUTE MESA FLOW SYSTEM

(Figure 1). The carbonate section at Bare Mountain is approximately 11,000 feet thick (Cornwall and Kleinhampl, 1961), and in the Funeral Mountains it is as much as 7,000 to 8,000 feet thick (Hunt and Mabey, 1966, Plate 1). These rocks probably exist throughout the NTS and vicinity, except in the caldera regions (Figure 1).

Unit 3 is comprised of upper Devonian and Mississippian age Eleana Argillite. In the eastern part of the NTS, thick sequences of the Eleana are found. Outcrops occur in the Eleana Range and in the Calico Hills northeast and east of Yucca Mountain, respectively (Winograd and Thordarson, 1975, Plate 1; Carr, 1974, Figure 2). In the Eleana Range, 8000 feet of argillite is reported. In the Calico Hills, over 2300 feet was penetrated by borehole UE25a-3 (Maldonada et al, 1979, pp. 7-9 and Plate 1). A thinner section (approximately 300 feet) of argillite is present at Bare Mountain to the southwest of Yucca Mountain (Cornwall and Kleinhampl, 1961). In many other areas to the east, southeast, and southwest of the NTS, the rocks of this age are represented not by argillite, but by facies dominated by carbonate lithologies. These are included in unit 2. Unit 3 is expected to be moderately thick at Yucca Mountain and to pinch out to the south due to a facies change and thrust faulting.

It should be emphasized that the thicknesses reported in the literature for the upper Precambrian and Paleozoic rocks are largely composite stratigraphic thicknesses. This means that because the units do not overlie each other in a simple layered fashion, but rather exist in a very complicated structural pattern, thicknesses have been composited from observations in different areas. To illustrate the structural complexity, we have included three cross sections through Bare Mountain, located approximately 10 miles west of Yucca Mountain (Figure 2). These sections

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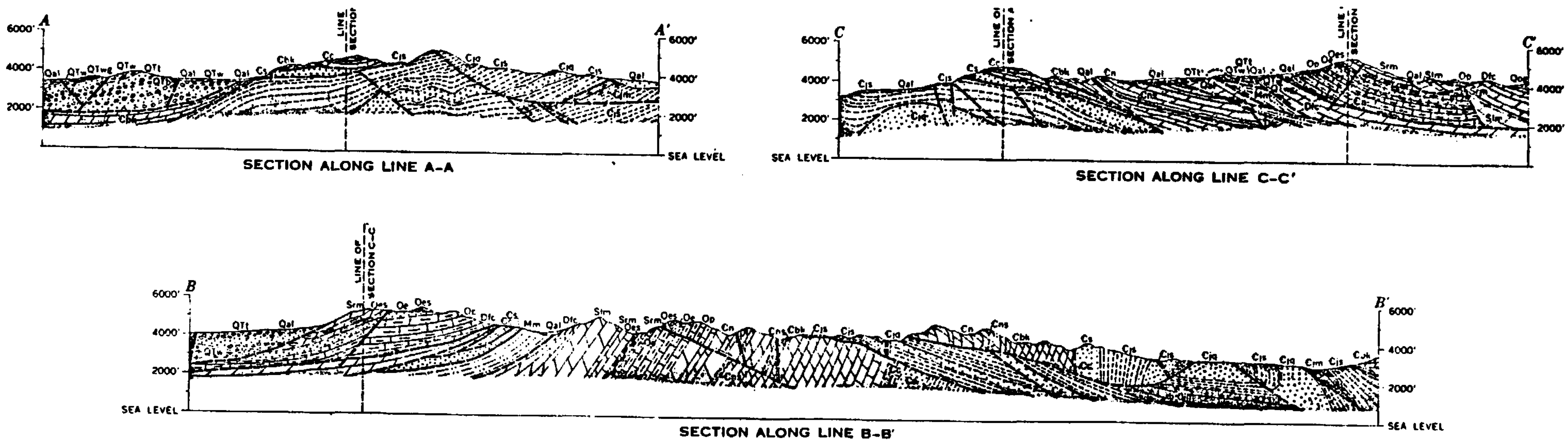


FIGURE 2. Cross sections of Bare Mountain showing the structural complexity of the pre-tuff Paleozoic section (from Cornwall and Kleinhampl, 1961).

emphasize the difficulty in attempting to evaluate the distribution and thickness of upper Precambrian and Paleozoic rocks in the region. We believe that these sections are representative of the complexity of the pre-Tertiary geology in and to the south of the NTS; however, this geology is largely obscured in the NTS by the thick overlying deposits of tuff and alluvium.

The tuffs of units 4 and 5 (Figure 1) are at least 3,000 feet thick in the Yucca Mountain region in boreholes UE25a-1 and J-13 (Heiken and Bevier, 1979, pp. 4-12; Doyle and Meyer, 1973, p. 2; Spengler et al, 1979, p. 10). Geophysical investigations indicate that the tuffs in this region are much thicker than 3,000 feet and may be as much as 6,000 to 10,000 feet thick (Oliver, 1981). Unit 4 includes the lower two thirds of the cored tuffs (approximately 2,000 feet) and, for the sake of simplification, we have assumed that it includes all underlying tuffs (an additional 3,000 to 7,000 feet) below the deepest Yucca Mountain borehole and overlying unit 3. Unit 4 is predominantly non-welded to moderately-welded ash flow tuffs and bedded ash fall tuffs. Unit 5 is approximately 1,000 feet to 1,300 feet thick in boreholes in the Yucca Mountain region. It is composed largely of densely welded ash flow tuffs with minor sections of moderately welded to non-welded ash flow tuffs.

The tuffs of units 4 (non-welded aquitard) and 5 (welded aquifer) become thinner with increasing distance from the centers of volcanism around Pahute Mesa. Tuffs that comprise unit 5 in Yucca Mountain apparently pinch out about 10 miles south of Lathrop Wells in the Amargosa Desert (Smith et al, 1981, Figure 5; Byers et al, 1976, Figures 4, 8, 10, 14, and 16). There is some evidence that the tuffs of unit 4 exist at least 10 to 15 miles farther south near the spring line in the

Ash Meadows region and that no welded tuffs occur in that area (Winograd and Thordarson, 1975, pp. C75 to C78). The volcanic tuffs are extremely variable in lithology. The variation is primarily in the degree of welding that occurred as the tuff was deposited. In general, the degree of welding should increase with proximity to the source caldera and with greater thickness of individual ash flows, but variability of this type cannot be reconstructed from data available to us.

Within the volcanic caldera regions in the northern parts of the study area (Figure 1), the only rocks present are thick tuffs and lava flows underlain by granitic batholiths. Most pre-tuff rocks within the caldera region were destroyed or massively altered by the eruptive events of the Tertiary.

The alluvial aquifer, unit 6 (Figure 1), is thin and discontinuous in mountain ranges, but attains thicknesses of 1000 feet in central Jackass Flats (Young, 1972, p. 5 and Plate 1) and perhaps as much as 2500 feet in the central Amargosa Desert (Walker and Eakin, 1963). The alluvial aquifer is a surficial unit that is composed of coarse sand, gravel, and cobbles near uplands, which act as source areas for the stream-transported sediment, and finer deposits farther south in the Amargosa Desert and in the central portions of some large valleys.

2.2 Mineral Resources

The mineral resources in the NTS and vicinity are of two categories. These are epigenetic (formed later than the enclosing rocks) and syngenetic (formed at the same time as the enclosing rocks).

In the NTS and vicinity, the principal epigenetic minerals are ores of mercury, gold, silver, and fluorspar (Nevada Bureau of Mines, 1964, Figures 12 and 13). Minor amounts of lead, zinc, uranium and pegmatite minerals are also present (Kral, 1951). These epigenetic minerals formed during the intrusion of igneous rocks. The minerals occur as veins and fissure fillings in the igneous rocks and in fractures in the surrounding sedimentary and metamorphic rocks (Nevada Bureau of Mines, 1964, p. 39; Kral, 1951). One major region for production of several of these minerals is Beatty, Nevada, in southern Oasis Valley (Nevada Bureau of Mines, 1964, Figures 12 and 13; Kral, 1951, pp. 28-40, 60-69, Maps 6 and 8). Mineral deposits might also be found in Yucca Mountain, but they are less likely to exist farther from the caldera region.

The principal syngenetic resources in the region are clay materials. These are found principally in the alluvium of the southwestern part of Amargosa Desert near Ash Meadows (Kral, 1951, pp. 13-16, Map 8; Nevada Bureau of Mines, 1964, pp. 185-189). Sand, gravel, limestone, and pumice cinders are also economic resources; these materials are abundant in the near surface environment of the region.

There are only a few low-grade coal deposits found in Nevada far west of the study area. No commercial coal deposits have been found (Nevada Bureau of Mines, 1964, pp. 49-53).

Petroleum may exist throughout eastern Nevada in the sedimentary rocks beneath the younger volcanics and alluvium. The complicated geology, however, makes exploration extremely difficult (Nevada Bureau of Mines, 1964, pp. 50, 54-56).

Thermal waters may constitute a valuable energy resource. In the test site area, high temperature waters occur in the southern part of Oasis Valley, in Jackass Flats, and in the Amargosa Desert (Garside and Schilling, 1979, Plate 1). In Oasis Valley, springs with temperatures up to 150°F are present. In Jackass Flats, the thermal waters are from wells and do not exceed 100°F. In the Amargosa Desert, springs with waters up to 100°F are common in the Ash Meadows region. Just northwest of this site some wells contain water with temperatures up to 100°F. None of these waters could be considered commercially useful except on a very small scale.

2.3 Geologic Structure

Thrust faulting of Paleozoic rocks occurred in the Jurassic and Cretaceous Periods during the Laramide Orogeny. As discussed in Section 1.1, these deformations are largely obscured by younger deposits in the study area but are found everywhere that younger rocks are absent (Figures 1 and 2). Portions of major thrust plates exist in the Eleana Range and Yucca Flat in the east part of the NTS, in the Specter Range and Spring Mountains to the south, and in the Panamint Range and Funeral Mountains around Death Valley to the southwest (Winograd and Thordarson, 1975, Plate 1, Carr, 1974, Figure 2; Hunt and Mabey, 1966, p. A55 and Plate 1). Several thrusts are shown on Figure 1. These thrust faults, and others farther to the east, southeast and southwest, are probably remnants of large, arcuate belts of major thrusting, with a root zone northwest of NTS, the details of which have been obscured by later block faulting, volcanism and sedimentation (Barnes and Poole, 1968). The thrust faults in the region are no longer active.

Most of the faulting observed in the study area is normal faulting associated with and responsible for the development of the Basin and Range topography. Displacements on these faults are usually less than 500 feet, but can be up to thousands of feet on some of the faults (Winograd and Thordarson, 1975, p. C-13). This faulting probably began at the onset of Tertiary volcanism, 26 to 27 million years ago along northwest and northeast trends, and 17 to 18 million years ago along a northerly trend (Ekren et al, 1968). There is evidence that this deformation is still active. Historical movements have occurred on some normal faults northwest of the NTS area, and fault scarps cutting Quaternary alluvial fans occur in the eastern part of study area (Carr, 1974, pp. 12-13).

There are major strike-slip faults east and southeast of the study area, but only one major fault of this type is postulated to exist in the study area (Figure 1). This fault trends along the axis of the Amargosa Desert (Carr, 1974, Figure 2). These strike-slip faults are probably part of or related to the Walker Lane zone of major right lateral faulting that is approximately 50 miles wide and trends northwest along the southern Nevada border. Some faults in this region, such as the Las Vegas Valley Shear zone, have experienced lateral displacements of more than 20 miles (Carr, 1974, p. 7). It is not known if this zone is still active, although the youngest evidence of strike-slip movement found in the NTS and vicinity is about 11 million years old (Carr, 1974, pp. 6-7).

There are major anticlines and synclines associated with the Mesozoic orogenic deformation of southern Nevada. Most of the known folds are found east of the NTS and have trends similar to large thrust faults (Winograd and Thordarson, 1975, Plate 1). These types of structural features probably occur at depth in the study area but are obscured, as are the deep thrust faults, by the thick sequence of overlying tuffs and alluvium.

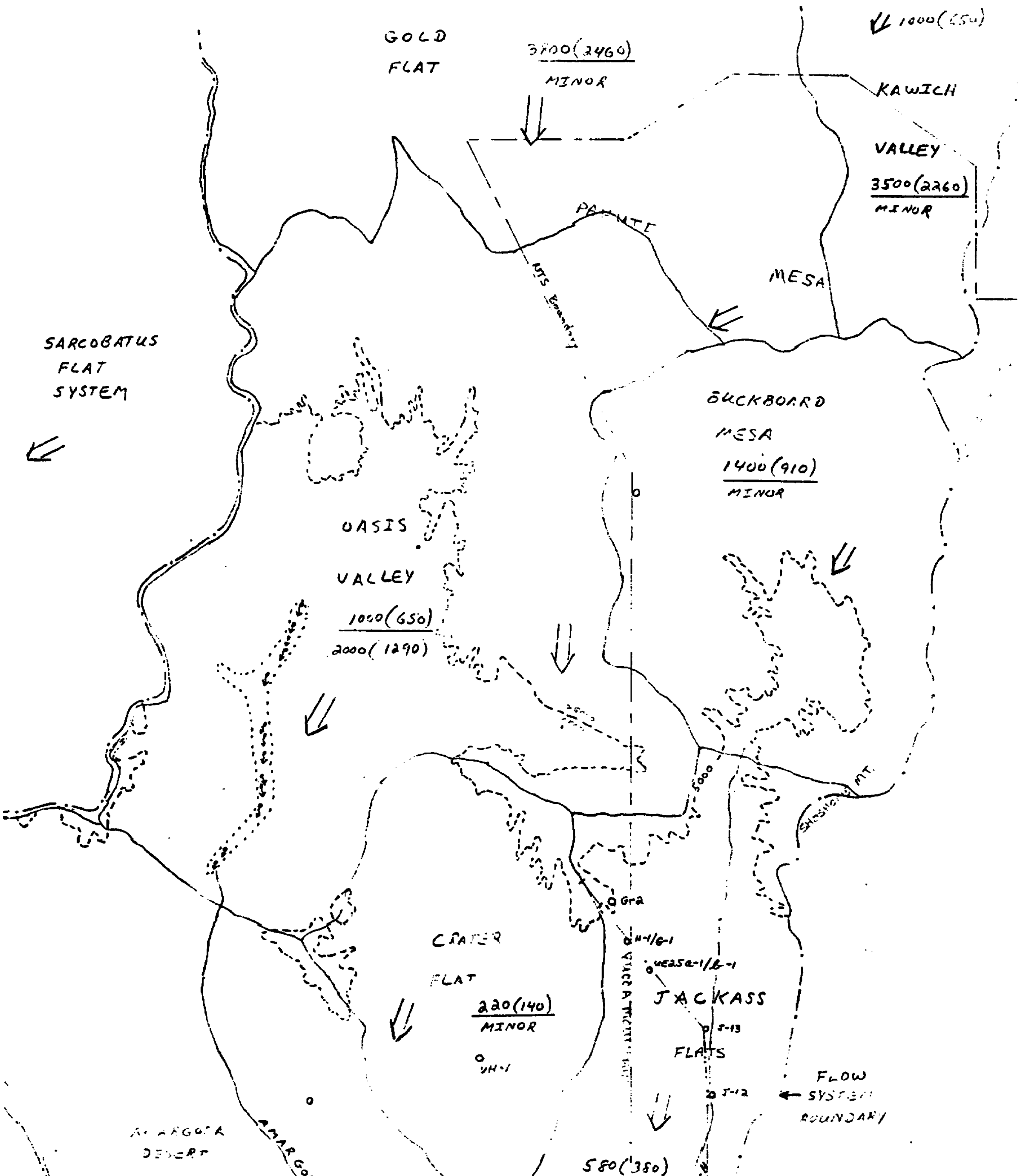
3.0 REGIONAL HYDROLOGY

3.1 System Boundaries

Yucca Mountain lies within the regional hydrologic system that has been called the Pahute Mesa groundwater system by some and the Oasis Valley-Forty Mile Canyon system by others (Figure 3). This system includes the western one-third of the Nevada Test Site and adjacent areas to the north, west, and south. The physiographic areas included in the system are Gold Flat, Kawich Valley, Reveille Valley, Buckboard Mesa, Oasis Valley, Crater Flat, Western Jackass Flats, and the Amargosa Desert. Yucca Mountain straddles the Crater Flat/Jackass Flats boundary, but the portion of the flow system that is of particular interest because it is down-gradient of Yucca Mountain lies within Jackass Flats and the Amargosa Desert.

The boundaries of the Pahute Mesa flow system are, in part, geologic, hydrologic and physiographic. Highly impermeable clastic rocks of units 1 and 3 underlie the topographic divide east of Yucca Mountain that trends southward along the Belted Range, the Eleana Range, Shoshone Mountain, the Specter Range, the northwest Spring Mountains and Resting Spring Range (Figure 3). Major thrust faults and normal faults border most of these regions and are the reason that these units dominate the subsurface geology. The eastern limits of the flow system probably coincide with this divide (Blankennagel and Weir, 1973, Plate 3; Carr, 1974, Figure 2; Winograd and Thordson, 1975, Plate 1).

The western boundary of the flow system is not as well defined. In Sarcobatus Flat, some head data indicate that groundwater is flowing west to southwest (Malmberg and Eaken, p. 14), and therefore, this area is not considered to be part of the Pahute Mesa flow system. It is


GOLD FLAT
3700(2460)
MINOR
1000(650)
KAWICH VALLEY
3500(2260)
MINOR
PAIUTE
MESA
NTS Boundary
SARCOBATUS FLAT SYSTEM
BUCKBOARD MESA
1400(910)
MINOR
OASIS VALLEY
1000(650)
2000(1290)
5000
SHOSHONE MT.
Gra
CRATER FLAT
220(140)
MINOR
JACKASS FLATS
UE25a-1/b-1
J-13
J-12
VH-1
FLOW SYSTEM BOUNDARY
AMARGOSA DESERT
AMARGOSA
580(350)

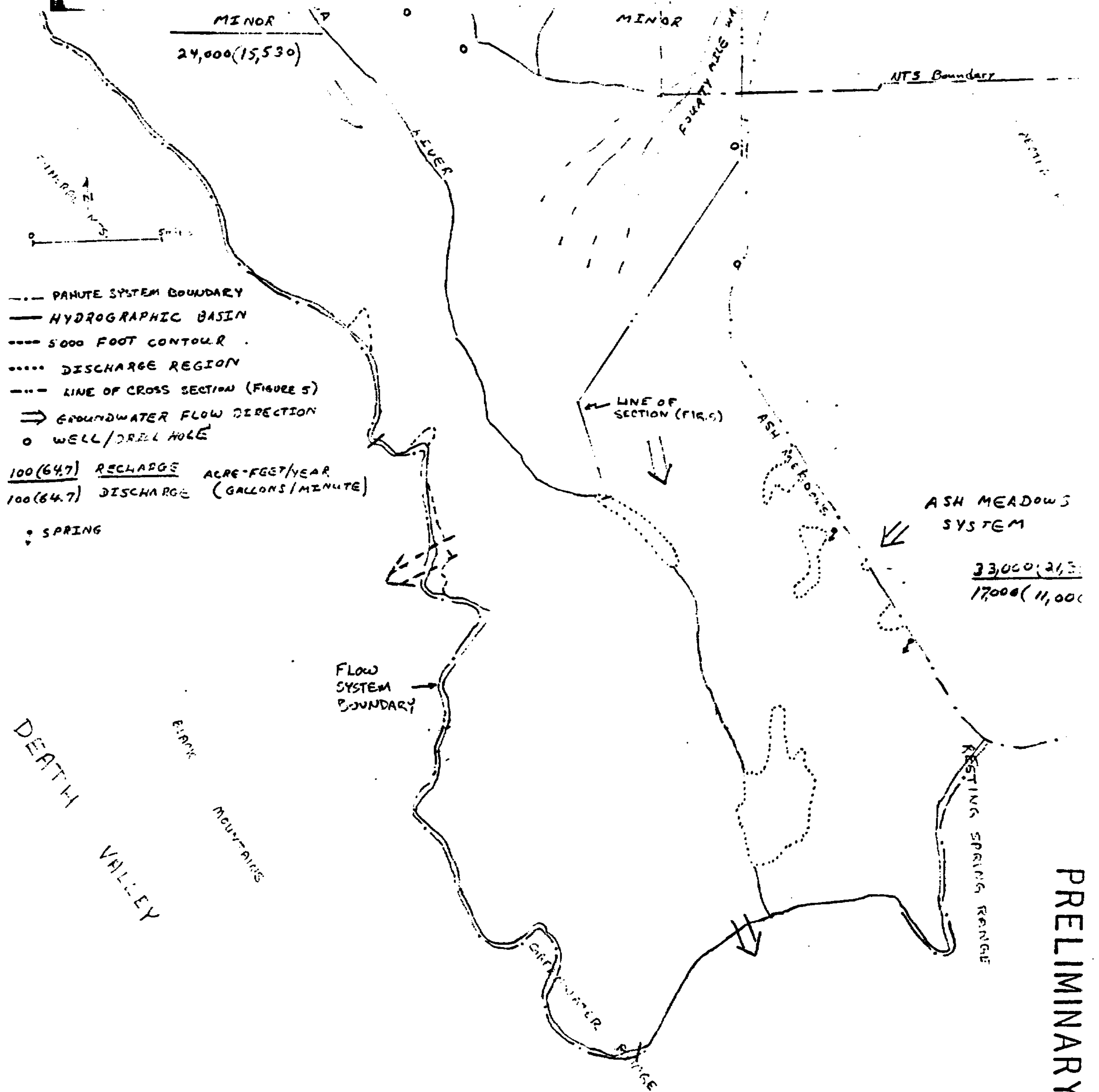


FIGURE 3. PAHUTE MESA GROUNDWATER SYSTEM

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believed that Gold Flat and Reveille Valley north of Pahute Mesa define the northern boundary of the flow system (Rush, 1970, p. 11 and Plate 1).

The thick sequence of clastic rocks in the Funeral Mountains probably defines the southwestern boundary of the flow system (Figure 3). The water table gradient, based on numerous wells in the Amargosa Desert, shows a southeasterly flow of water parallel to this boundary. However, some underflow is suspected to occur through the Funeral Mountains, This is discussed further in Section 3.2.

3.2 Recharge, Discharge, and Groundwater Movement

The Pahute Mesa groundwater system is recharged by infiltration of precipitation and by localized underflow from the Ash Meadows groundwater system located to the east.

No large perennial streams or lakes are found in the region. The Amargosa River is considered intermittent (Walker and Eakin, 1963, p. 6). The only other surface expressions of water are dry washes, areas of evapotranspiration, and some springs (Winograd and Thordarson, 1975, Plate 1).

Precipitation varies from 2.5 to 15 inches per year in the area, and depends primarily upon longitude and altitude (Winograd and Thordarson, 1975, p. C-8; Rush, 1970, p. 15). Potential lake evaporation in the region is approximately 60 to 82 inches and everywhere exceeds precipitation (Winograd and Thordarson, 1975, p. C-6).

The high evaporation potential is the reason that very little precipitation enters the groundwater system. Virtually no recharge from precipitation occurs below elevations of 5,000 feet, and a maximum of 15 percent of 15 inches per year infiltrates to the water table at elevations above 7,000 or 8,000 feet (Rush, 1970, p. 15). The only recharge in the Yucca Mountain region occurs in a small area that extends above 5,000 feet (Figure 3). Using techniques similar to those used by Rush (1970, p. 15), we estimate that the recharge in that area is 0.24 to 0.36 inches per year (3 percent of the 8 to 12 inches of precipitation).

The volume of groundwater recharging the various subsystems of the Pahute Mesa system, excluding the underflow from the Ash Meadows system to the southeast, is shown in Figure 3. These contributions from the various basins total approximately 11,500 acre-feet per year, and are very small in comparison to the 1,888,000 acre (2,800 square mile) area of the drainage system (Rush, 1970, pp. 6 and 15).

The general direction of regional groundwater flow in the Pahute Mesa system is toward the south and southwest. The evidence for this consists of water table elevation data and hydrochemical data from wells and springs (Winograd and Thordarson, 1975, Plates 1 and 3).

The waters in Pahute Mesa, Oasis Valley, western Jackass Flats, and the central and western parts of the Amargosa Desert are of a sodium-potassium-bicarbonate type, indicating movement through volcanic rocks. The dissolved solids content of water samples increases to the south. In the eastern part of the Amargosa Desert, the water samples have a "mixed" signature of calcium-magnesium-sodium-bicarbonate, indicating an influx of water from the Ash Meadows flow system that has passed through carbonate rocks.

Groundwater discharge from the Pahute Mesa flow-system occurs mostly by evapotranspiration and regional underflow to adjacent basins (Figure 3). Evapotranspiration largely occurs in central Oasis Valley and southeast Amargosa Desert. Most of the remaining groundwater flow follows the Amargosa River Valley in an arcuate path around the Funeral Mountains, Greenwater Range and Black Mountains and into Death Valley, the topographically lowest basin in the entire region and the likely discharge point for all groundwater that does not escape elsewhere by evapotranspiration.

There is a considerable discharge of water from springs on the southwest side of the Funeral Mountains in Death Valley. The waters have a volcanic rock "signature" similar to those in the Amargosa Desert on the northeast side of the Funeral Mountains (Winograd and Thordarson, 1975, Plate 3). The amount of this discharge is approximately 4900 acre-ft per year or 3150 gallons per minute (Hunt et al, 1966, p. B-38). This is a substantial fraction of the 11,500 acre feet of water recharging the Pahute Mesa system. It is suspected that much of this spring discharge is fed by groundwater moving southwest from the Pahute Mesa system under the Funeral Mountains through a thick sequence of carbonate rocks or along major fracture zones that exist in this region.

Because of the small amount of recharge mentioned previously, the groundwater system is sluggish, i.e., the flux through the system is low. The hydraulic gradients, indicated by water table elevations, are low to moderate, except in regions where the rocks in the saturated zone are relatively impermeable. Thus, the lower gradients (values of .0001 to .005, shown on Winograd and Thordarson, 1975, Plate 1, and Rush, personal communication, 1981) are found principally in the southern part of the system where groundwater is moving through the fractured carbonates and alluvium. Similar gradients are found locally in areas of intense fracturing of otherwise impermeable rock, such as in the Topopah Springs tuff unit on the east side of Yucca Mountain.

The higher gradients (0.005 to 0.05, shown on Winograd and Thordarson, 1975, Plate 1, and Rush, personal communication, 1981) are predominantly in the northern part of the system, where the rocks in the saturated zone are principally low permeability tuffs and granites. These gradients are also the result of the greater amounts of recharge to the system in these upland areas. High gradients are also found locally in the southern part of the system where localized bodies of low permeability rock or major faults create hydraulic impedence to groundwater movement. In addition, the gradient is steeper where groundwater is moving through low permeability lake deposits in the southeastern part of the Amargosa Desert.

In the Pahute Mesa system, the major aquifers are the Paleozoic carbonates (unit 2), the densely welded tuffs (unit 5) in the upper part of tuff section, and the alluvial materials (unit 6). In various locations, any of all of these three units may be partly unsaturated or lie completely above the water table.

3.3 Regional Hydrologic Cross Section

The six major hydrostratigraphic units discussed in Section 2.1 are shown on a diagrammatic hydrologic cross section that approximately follows flow lines from Yucca Mountain to the region of natural groundwater discharge in the southeastern Amargosa Desert (Figure 4). The trace of the line of cross section is shown on Figures 1 and 3. The following discussion presents the methodology used to construct the cross section.

The topographic information in Figure 4 was taken from Winograd and Thordarson (1975, Plate 1). The thickness and extent of alluvium (unit 6) in western Jackass Flats was taken from Young (1972, Plate 1) and extrapolated to 2,200 feet at the south end of the section. The extrapolated value is based upon estimates of alluvial thickness of 2,500 feet in central Amargosa Desert (Walker and Eakin, 1963).

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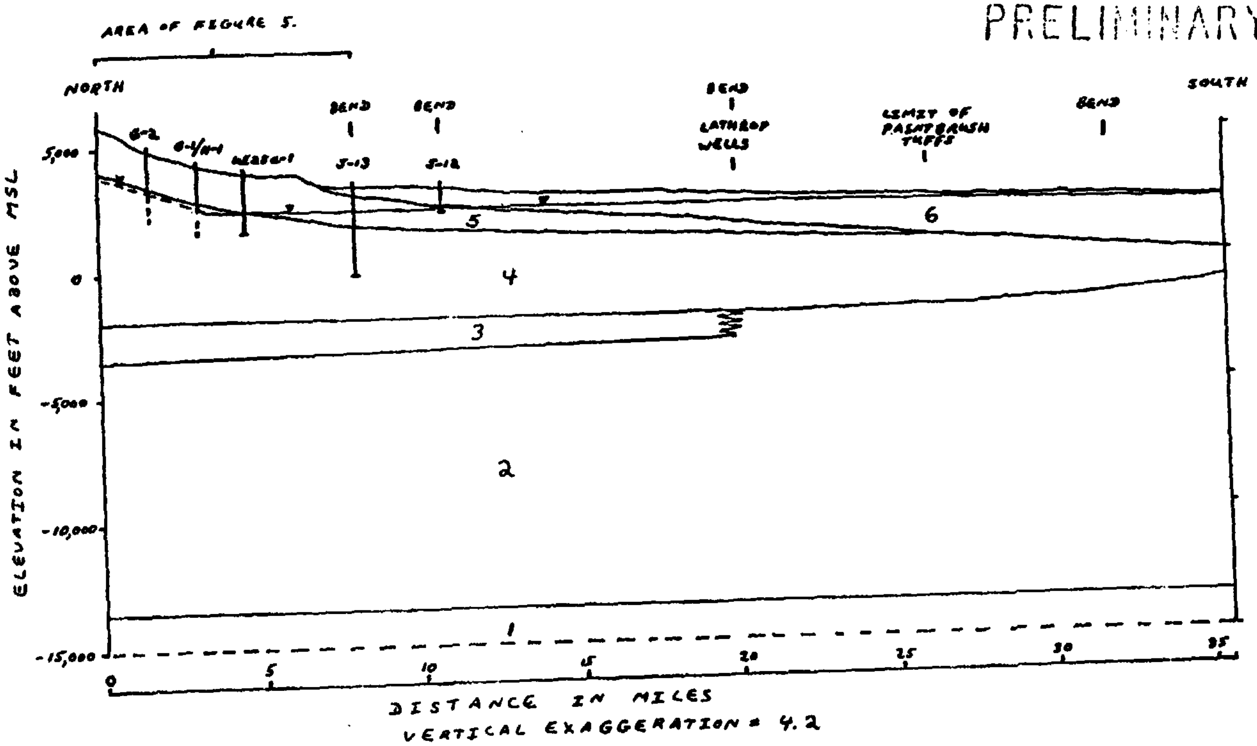


UNIT 1 - LOWER CLASTIC AQUITARD
UNIT 2 - CARBONATE AQUIFER
UNIT 3 - UPPER CLASTIC AQUITARD
UNIT 4 - TUFF AQUITARD
UNIT 5 - TUFF AQUIFER
UNIT 6 - ALLUVIAL AQUIFER

FIGURE 4. REGIONAL HYDROLOGIC CROSS SECTION FROM YUCCA MOUNTAIN TO AMARGOSA DESERT.

The thickness and extent of the tuff aquifer (unit 5) comes from several sources. In Yucca Mountain, borehole information limits the thickness to 1,300 feet at well UE25a-1 and 1,000 feet at well J-13 (Spengler et al, 1979, p. 10; Doyle and Meyer, 1963; p. 2). The stratigraphic units that comprise the tuff aquifer are thought to pinch out about 10 miles south of Lathrop wells (Smith et al, 1981, Figure 5).

The total thickness of the tuff aquitard (unit 4) is not known. Geophysical work indicates the tuffs have a total thickness of 6,000 to 10,000 feet at Yucca Mountain (Oliver, 1981), and the tuff aquitard, therefore, is 5,000 to 9,000 feet thick.

The tuff aquitard, like the tuff aquifer, should become thinner with increasing distance from the source calderas to the north. Winograd and Thordarson (1975, pp. C75-C78) present evidence that non-welded tuffs are present below the alluvium as far south as the Ash Meadows spring area. This is at the southern limit of the cross section. If it is assumed that the alluvium is approximately 2,500 feet thick in the region, then there would be approximately 1,000 feet of tuff aquitard at the south end of the cross section (Winograd and Thordarson, 1975, Plate 1, cross section A-A'). Thus, we have chosen a thickness of 6,000 feet for the aquitard at the north end of the cross section and thinned the unit to 1,000 feet at the southern end. Because there is very likely some relief on the pre-Tertiary surface in the region, the rising of the bottom of unit 4 to higher elevations toward the south end of the cross section is reasonable.

There is no direct measurement of the thickness of the upper clastic aquitard (unit 3) along the line of section. In the Calico Hills, approximately 6 miles northeast of the cross section, over 2,300 feet of this unit is found in borehole UE25a-3 (Maldonado et al, 1979, pp. 7-9 and

Plate 1). At Bare Mountain, approximately 9 miles west of the cross section, only 300 feet of unit 3 exists (Cornwall and Kleinhampl, 1961). As stated in Section 1.1, unit 3 is expected to pinch out to the south due to a facies change and thrust faulting. We have given unit 3 a thickness of 1,500 feet, an extrapolation between 2,300 feet at UE25a-3 and 300 at Bare Mountain, at the north end of the section and decreased its thickness to 1,000 feet near Lathrop Wells. At this point a facies change to a carbonate lithology is indicated on the cross section, and the thickness of rock of the same age as unit 3 is included with the carbonate aquifer (unit 2) south of Lathrop Wells.

The carbonate aquifer (unit 2), like unit 3, has not been measured directly along the line of section. At Bare Mountain, the carbonates attain a thickness of 11,000 feet (Cornwall and Kleinhampl, 1961). In the Funeral Mountains on the southern edge of the Amargosa Desert, these rocks are as much as 7,000 to 8,000 feet thick (Hunt and Mabey, 1966, Plate 1). In the Specter Range east of the cross section, unit 2 is probably at least 10,000 feet thick (Winograd and Thordarson, 1975, Plate 1). A thickness of 10,000 feet was assigned to unit 2 at the north end of the cross section. The bottom boundary was extended as a horizontal line to the south edge of the cross section, creating 12,500 feet of unit 2 at this location (Figure 4).

The lower clastic aquitard (unit 1) is thought to be approximately 10,000 feet thick and probably exists throughout the NTS site and vicinity (Winograd and Thordarson, 1975, pp. C9-C11). Only 1,500 feet of this unit is represented on the cross section because the upper surface of this unit is considered to be a regional no flow boundary.

The locations and depths of wells along the cross section are shown (Figure 4). Well G-2 and the pair of wells G-1/H-1 are projected a short distance to the cross section. G-2 is about 2,300 feet northeast of the cross section, and wells G-1 and H-1 are about 700 feet on either side of the cross section (Rush, personal communication, 1981). The total depths of wells G-2, G-1 and H-1 are not known. We know only that they must extend at least to the water table elevations that are given for each well.

The water table elevations from well J-13 to the south end of the cross section (Figure 4) are taken from Winograd and Thordarson (1975, Plate 1). The elevations of this surface north of well J-13 come from information supplied by F. Eugene Rush (personal communication, 1981) and from data for well UE25a-1 (Spengler et al, 1979).

The water table is a very flat surface except in the vicinity of wells G-1, H-1 and G-2. The water table in well H-1 is 2,393.4 feet above MSL. This is consistent with the gradients to the south of the well. However, the water table in well G-1, only 1,400 feet from H-1, is 62 feet higher. A water table elevation equal to the average of the elevations at G-1 and H-1 was chosen for representation on the cross section.

At well G-2, the water table is 3,384.3 feet. This value is about 930 feet higher than that at well G-1 and represents a gradient of 0.1 between those two wells.

It is perhaps more than coincidence that the steeper water table slope roughly follows the structural slope of the hydrostratigraphic units and occurs in the region of the section where the saturated zone lies entirely in the lower portion of the tuff sequence that has been characterized as having a relatively low permeability. However, it is not known if this is the sole cause of the change in gradient. The steeper gradient might be caused by some other, as yet unidentified, local inhomogeneity in the tuff section that is acting as an impediment to movement of groundwater. Such an impediment might be caused by significant inhomogeneity in the degree of welding of a unit or by larger vertical offset on a fault than is indicated on the cross section.

The nearest location with water table information north of the cross section is in Oasis Valley about 10 miles to the northwest. There, the water table elevation is 3,800 feet (Winograd and Thordarson, 1975, Plate 1). Given the regional southward decrease in water table elevation, the water table at the north end of the cross section is almost certainly somewhat less than 3,800 feet. This is consistent with the water table on Figure 4 that intersects the north end of the section at an elevation of 3,750 feet. What is not known is if the water table gradient is relatively uniform over the entire distance between the known values or if it has local abrupt changes, due to the presence of local inhomogeneities such as those mentioned above.

Most of the geological details or complexities that are known or suspected to exist cannot be shown on the cross section in Figure 4. In particular, at this scale, the extensive block faulting of the tuffs at Yucca Mountain cannot be shown. The complexities of thrust faulting, block faulting and erosion in the pre-Tertiary sequence, such as that indicated by Figure 2, also cannot be shown, because the details are simply not known. Thus, the simple layering of units 1, 2, and 3 in Figure 4 is a very generalized depiction of the real geology. No basis exists at this time for further refinement of this part of the cross section.

4.0 LOCAL GEOLOGY AND HYDROLOGY OF YUCCA MOUNTAIN

4.1 Mineralogy

The primary and secondary mineralogy of the tuffs at Yucca Mountain have been the subject of only two detailed studies. Both of these studies were carried out on cores from borehole UE25a-1 (see location on Figure 1). The analysis techniques used were thin section petrography, x-ray diffraction, and electron microprobe. For detailed summaries of the results, the reader is referred to Sykes (1979, p. 5-10, 12-14) and Spengler (1979, p. 10-23).

4.2 Fractures

Information concerning the nature and distribution of fractures in the Yucca Mountain area comes primarily from work by Spengler et al (1979) and Sykes et al (1979) on a single drill hole, UE25a-1 (Figure 1). Spatial variation in fracture characteristics within the study area is likely; however, the following section and other sections, which use UE25a-1 as a reference, are based on the simplifying assumption that data from UE25a-1 are representative of the average characteristics of the overall system. This is necessary to complete the task of system definition, because UE25a-1 is the only available well-documented borehole.

In the tuffs of the Yucca Mountain area, the densely welded zones are the most fractured, whereas the bedded and moderately welded zones are less fractured. In nonwelded tuffs, fractures are rare except where the unit is silicified. Loss of circulation fluid to densely welded tuff formations during drilling through fracture zones suggests fractures are open and interconnected. The overall average frequency of fractures for all of the UE25a-1 core is 0.38 per foot. There is a general decrease in fracture density with depth. About 80% of the fractures are partially coated or stained with secondary minerals; 18% of the fractures were open with no secondary minerals; and 3% of the fractures were closed with no secondary minerals. The secondary minerals, in decreasing percent abundance, are silica (47%), manganese and iron oxides (22%), calcite (16%--only in Tiva Canyon and Topopah Springs units), and manganese oxides and silica (15%). Table 1 shows the details of fracture density, orientation, aperture, and filling materials for individual members.

4.3 Detailed Hydrologic Cross Section

A detailed hydrologic cross section (Figure 5) has been constructed to show some of the structural and stratigraphic detail in the near field of Yucca Mountain that could not, because of scale, be shown on the regional cross section (Figure 4). The detailed section (Figure 5) is an expanded version of approximately the northernmost 7.5 miles of the regional section; both are oriented along the same line of section. In construction of the detailed cross section, geologic maps were used for topography, locations of faults, sense of movement on faults, surface contacts between units, and general dips of the units (Christiansen and Lipman, 1965; Lipman and McKay, 1965). Positions of faults at ground surface on the detailed cross section are fairly accurate. However, dips on faults and relative displacements on faults are not accurately known. Dips of 60° or greater are assumed for faults, and major offsets do not generally seem to be greater than 500 feet (Winograd and Thordarson, 1975, p. c-13).

Where our line of section deviated from cross sections presented on the geologic maps, diagrammatic cross sections contained in other reports (Johnstone and Wolfsberg, 1980, p. 31; Spengler et al, 1979, p. 9) were used in conjunction with borehole data at wells UE25a-1 and J-13 (Spengler et al, 1979, p. 10; Heiken and Bevier, 1979, p. 4-12; Doyle and Meyer,

TABLE 1. Properties of Fractures in Tuff from Borehole UE25a-1, Yucca Mountain

UNIT	FRACTURE DENSITY (Number/Foot)	FRACTURE DIP (Degrees)	FRACTURE APERTURE (Microns)	FRACTURE FILLING
TIVA CANYON	D.W.[1]-0.98	No Preferred Orientation	No Data	≥50% MN-FE Oxides 10-20% Calcite 10% Silica 15% Open, No filling 4% Closed, No filling
	M.W.[2]-0.10	Average=46°		
TOPOPAH SPRINGS	D.W.-0.43	Mostly 80° to 90°	≤15	60% Silica 20% Calcite 20% MN-FE Oxides and Silica 2% Open, No filling 2% Closed, No filling
	M.W.-0.40	Average=63°	Average=5-20	
CALICO HILLS	N/A [3]	N/A	N/A	N/A
PROW PASS	D.W.-N/A	No Preferred Orientation	≤40	No Data
	M.W.-0.25	Average 50°	Average=5-10	
BULLFROG		Mostly 40° to 50°	No Data	No Data
	M.W.-0.24	Average=56°		

1 D.W.-Densely Welded
2 M.W.-Moderately Welded
3 N/A-Not Applicable, Calico Hills completely non-welded

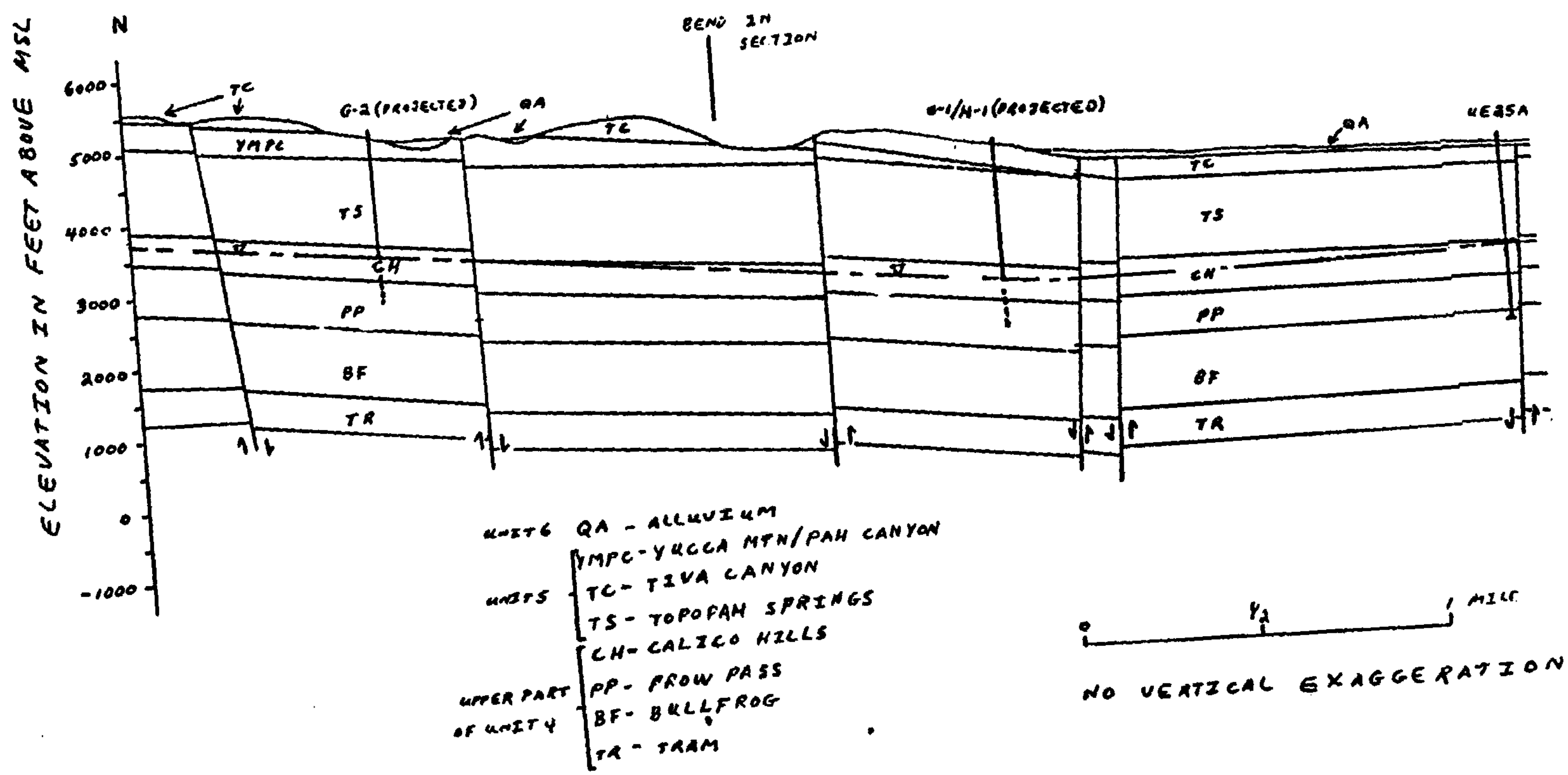
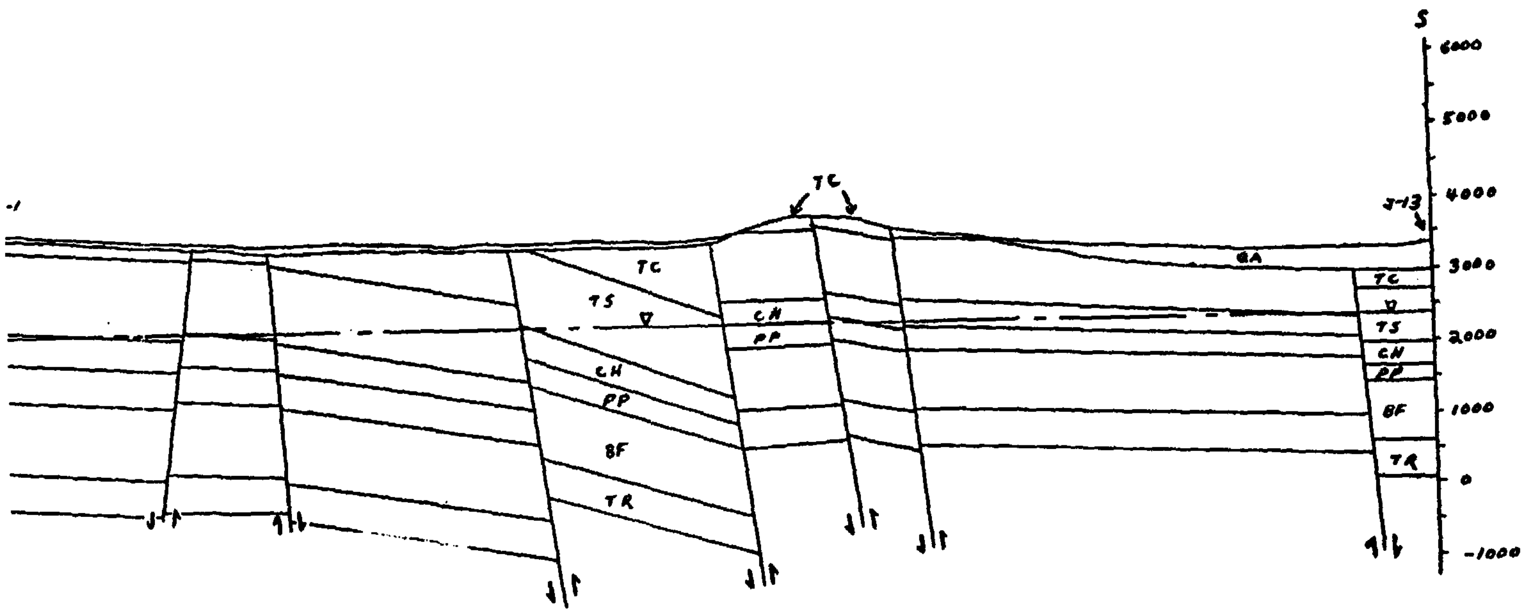


FIGURE 5. DETAILED HYDROLOGIC CROSS SECTION FROM YUCCA

PRELIMINARY



MOUNTAIN TO FORTY MILE CANYON.

1963, p. 2) to construct the cross section. The Tram unit has been added to the base of the section as a distinct unit identified at several locations. It has a fairly uniform thickness of about 500 feet (Gary Dixon, personal communication). Details of the change in thicknesses of units away from well UE25a-1 are not known, and there is considerable uncertainty about member thicknesses between control points. Any particular contact between individual units might be in error by as much as a few hundred feet. In addition to unpredictable variations in the thickness, the stratigraphic positions of zones exhibiting different degrees of welding are not known.

The locations of wells G-1, H-1, G-2, UE25a-1, and J-13 are shown on the cross section. Water table elevations are also indicated. Well locations and water table elevations were provided by F. Eugene Rush (personal communication).

5.0 ROCK PROPERTIES

5.1 Introduction

The following text is an explanation and documentation of the data on rock properties presented in Tables 2 and 3. The more important values in the tables are those which represent the properties of the rock mass, referred to here as the bulk properties. These are given for each lithology (densely welded etc.) and as composite values for the various stratigraphic units. The other data, such as matrix and fracture porosity, have been used to obtain the bulk and composite information. These may also be useful and are included for completeness. The data presented here are the result of a preliminary synthesis of available information and are intended to be used for comparative purposes only. Many additional data are needed to fully characterize the properties of rock units at the NTS.

5.2 Alluvium, Unit 6

Alluvial deposits, unit 6, constitute the uppermost unit across most of the regional and detailed cross sections (Figures 4 and 5). Table 2 shows the range of values for selected properties of these deposits that can be used in regional groundwater flow and transport calculations.

The range of values for porosity in Table 2 are taken from tests of 42 samples taken from boreholes and shafts in the region (Winograd and Thordarson, 1975, p. C37). These values are for measured total matrix porosity, and because the deposits are not fractured the effective matrix porosity is also the bulk effective porosity of the unit.

The range of values for horizontal hydraulic conductivity in Table 2 represent the range of results from 6 pump tests at the test site (Winograd and Thordarson, 1975, p. C23).

Table 2. Summary of Selected Properties of Units for the Regional Hydrologic Cross Section

UNIT	FRACTURE PROPERTIES			HYDRAULIC PROPERTIES									BULK DENSITY
				EFFECTIVE POROSITY			HORIZONTAL CONDUCTIVITY			VERTICAL CONDUCTIVITY			
	FREQUENCY (ft^{-1})	APERTURE (in)	GEOMETRY	MATRIX (%)	FRACTURE (%)	BULK (%)	MATRIX (ft/day)	FRACTURE (ft/day)	BULK (ft/day)	MATRIX (ft/day)	FRACTURE (ft/day)	BULK (ft/day)	(lbs/ft^3)
ALLUVIUM (Unit 6)	N/A(3)	N/A	N/A	16.0-42.0	N/A	16.0-42.0	$7x10^{-1}$-19.1	N/A	$7x10^{-1}$-19.1	$7x10^{-1}$-19.1	N/A	$7x10^{-1}$-19.1	99.9-112.4
TUFF AQUIFER (Unit 5)(1)	-	-	IV(4)	-	-	5.1-8.7	-	-	$3.0x10^{-2}$-$1.4x10^{1}$	-	-	$4.0x10^{-5}$-$4.9x10^{-1}$	133.0-145.3
TUFF AQUITARD (Unit 4)(2)	-	-	IV	-	-	21.8-36.8	-	-	$2.0x10^{-5}$-$2.7x10^{-1}$	-	-	$9.3x10^{-6}$-$1.1x10^{-1}$	118.2-136.1
UPPER CLASTIC AQUITARD (Unit 3)	1.4-4.1	$2.0x10^{-5}$ $6.0x10^{-4}$	IVH(5)	0.6-15.1	0.0007-0.06	0.6-15.1	$1.0x10^{-7}$-$1.0x10^{-6}$	$2.4x10^{-7}$-$1.8x10^{-2}$	$3.4x10^{-7}$-$1.8x10^{-2}$	$1.0x10^{-7}$-$1.0x10^{-6}$	$2.4x10^{-7}$-$1.8x10^{-2}$	$3.4x10^{-7}$-$1.8x10^{-2}$	155.4-171.6
CARBONATE AQUIFER (Unit 2)	0.3	$2.0x10^{-2}$-$4.0x10^{-1}$	IV	0.0-9.0	0.1-2.0	0.1-2.0	$3.0x10^{-6}$-$1.5x10^{-2}$	$2.6x20^{1}$-$2.1x10^{5}$	$2.0x10^{-1}$-$1.1x10^{1}$	$3.0x10^{-6}$-$1.5x10^{-2}$	$5.2x10^{1}$-$4.1x10^{5}$	$4.0x10^{-1}$-$2.1x10^{1}$	139.2-174.8
LOWER CLASTIC AQUITARD (Unit 1)	2.0-5.0	NEG(6)	IVH	0.6-5.0	NEG	0.6-5.0	$1.0x10^{-7}$-$1.0x10^{-6}$	NEG	$1.0x10^{-7}$-$1.0x10^{-6}$	$1.0x10^{-7}$-$1.0x10^{-6}$	NEG	$1.0x10^{-7}$-$1.0x10^{-6}$	155.4-171.6

1 Composite of Tiva Canyon and Topopah Springs Tuffs (Table 2)
2 Composite of Calico Hills, Prow Pass, and Bullfrog Tuffs (Table 2)
3 Not Applicable
4 Intersecting Vertical
5 Intersecting Vertical and Horizontal
6 Negligible

Table 3. Summary of Selected Properties of Tuffs for the Detailed Hydrologic Cross Section

UNIT LITHOLOGY		PERCENT OF TOTAL UNIT THICKNESS	FRACTURE PROPERTIES: APPARENT FREQUENCY (ft^{-1})	DIP (DEGREES)	TRUE FREQUENCY (ft^{-1})	APERTURE (in)	HYDRAULIC PROPERTIES: EFFECTIVE POROSITY: MATRIX (%)	FRACTURE (%)	BULK (%)	HORIZONTAL CONDUCTIVITY: MATRIX (ft/day)	FRACTURE (ft/day)	BULK (ft/day)	VERTICAL CONDUCTIVITY: MATRIX (ft/day)	FRACTURE (ft/day)	BULK (ft/day)	BULK DENSITY (lbs/ft^3)
TIVA CANYON	D.W.(1)	32	0.98	46	1.41	2.0×10^{-4}-5.9×10^{-3}	3-10	0.0047-0.14	0.0047 0.14	1.0×10^{-6}-3.0×10^{-5}	1.2×10^{-4}-3.2	4.0×10^{-2}-18.7	1.0×10^{-6}-3.0×10^{-5}	2.4×10^{-4}-6.4	8.0×10^{-2}-37.4	139.8-149.1
	M.W.(2)	8	0.10	46	0.14	2.0×10^{-4}-5.9×10^{-3}	10-25	0.00047-0.014	10-25	3.0×10^{-5}-3.0×10^{-3}	1.2×10^{-5}-3.2×10^{-1}	4.2×10^{-5}-3.2×10^{-1}	3.0×10^{-5}-3.0×10^{-3}	2.4×10^{-5}-6.4×10^{-1}	5.4×10^{-5}-6.4×10^{-1}	133.7-139.8
	N.W.(3)	60	N/A(5)	N/A	N/A	N/A	25-40	N/A	25-40	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6}-9.0×10^{-2}	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6}-9.0×10^{-2}	108.4-133.7
	COMP.(4)	100							*15.8-26.0*			*1.3×10^{-2}-6.1*			*1.2×10^{-5}-1.5×10^{-1}*	*129.3-143.4*
TOPOPAH SPRINGS	D.W.	86	0.43	63	0.94	2.0×10^{-4}-5.9×10^{-3}	3-10	0.003-0.093	0.003-0.093	1.0×10^{-6}-3.0×10^{-5}	8.4×10^{-5}-2.1	4.0×10^{-2}-18.7	1.0×10^{-6}-3.0×10^{-5}	1.7×10^{-4}-4.2	8.0×10^{-2}-37.4	139.8-149.1
	M.W.	5	0.40	63	0.88	2.0×10^{-4}-5.9×10^{-3}	10-25	0.003-0.087	10-25	3.0×10^{-5}-3.0×10^{-3}	7.9×10^{-5}-2.0	1.1×10^{-4}-2.0	3.0×10^{-5}-3.0×10^{-3}	1.6×10^{-4}-4.0	1.9×10^{-4}-4.0	133.7-139.8
	N.W.	9	N/A	N/A	N/A	N/A	25-40	N/A	25-40	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6}-9.0×10^{-2}	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6}-9.0×10^{-2}	108.4-133.7
	COMP.	100							*2.8-4.9*			*3.4×10^{-2}-16.2*			*8.1×10^{-5}-9.7×10^{-1}*	*135.2-145.8*
CALICO HILLS	N.W.	100	N/A	N/A	N/A	N/A	25-40	N/A	25-40	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6} 9.0×10^{-2}	7.5×10^{-6}-9.0×10^{-2}	N/A	7.5×10^{-6}-9.0×10^{-2}	108.4-133.7
	COMP.	100							*25-40*			*7.5×10^{-6} 9.0×10^{-2}*			*7.5×10^{-6}-9.0×10^{-2}*	*108.4-133.7*
PROW PASS	M.W.	16	0.25	50	0.39	2.0×10^{-4}-5.9×10^{-3}	10-25	0.0013-0.039	10-25	3.0×10^{-5}-3.0×10^{-3}	3.5×10^{-5}-9.0×10^{-1}	6.5×10^{-5}-9.0×10^{-1}	3.0×10^{-5}-3.0×10^{-3}	7.0×10^{-5}-1.8	1.0×10^{-4}-1.8	133.7-139.8
	N.W.	84	N/A	N/A	N/A	N/A	25-40	N/A	25-40	$75.\times10^{-6}$ 9.0×10^{-2}	N/A	7.5×10^{-6} 9.0×10^{-2}	7.5×10^{-6} 9.0×10^{-2}	N/A	7.5×10^{-6} 9.0×10^{-2}	108.4-133.7
	COMP.	100							*22.6-37.6*			*1.7×10^{-5}-2.2×10^{-1}*			*8.8×10^{-6}-1.1×10^{-1}*	*112.4-134.7*
BULLFROG	M.W.	100	0.24	56	0.43	2.0×10^{-4}-5.9×10^{-3}	10-25	0.0014-0.042	10-25	3.0×10^{-5}-3.0×10^{-3}	3.8×10^{-5}-9.7×10^{-1}	6.8×10^{-5}-9.7×10^{-1}	3.0×10^{-5}-3.0×10^{-3}	7.6×10^{-5}-1.9	1.1×10^{-4}-1.9	133.7-139.8
	COMP.	100							*10-25*			*6.8×10^{-5}-9.7×10^{-1}*			*1.1×10^{-4}-1.9*	*133.7-139.8*
TRAM(6)	COMP.								*21.8-36.8*			*2.0×10^{-5}-2.7×10^{-1}*			*9.3×10^{-6}-1.1×10^{-1}*	*118.2-136.1*

1 Densely Welded
2 Moderately Welded
3 Non-Welded
4 Composite
5 Not Applicable
6 No Data on Tram; it is given the composite values of the Tuff Aquitard (Table 3)

The valley-fill material tested is reported to be poorly sorted and poorly stratified to non-stratified, with particles ranging from clay to boulder size (Winograd and Thordarson, 1975, p. C37; Hoover et al, 1981). Therefore, this unit is assumed to be isotropic and has been assigned in Table 2 a vertical hydraulic conductivity with the same range as the horizontal hydraulic conductivity.

The reported values for bulk density are taken from gravity studies performed in the Calico Hills region east of Yucca Mountain (Snyder and Oliver, 1981, p. 7).

5.3 Tuff Aquifer and Tuff Aquitard, Units 4 and 5

The tuff aquifer (unit 5) is composed of zones of densely welded, moderately welded, and non-welded ash-flow and ash-fall tuffs from the Tiva Canyon and Topopah Springs members. Hydraulic properties of the rock mass (bulk properties) of these units have not been measured and must for this report be largely estimated from data available from cores. Analysis of cores and geophysical logs from borehole UE25a-1 show that the densely welded and moderately welded tuffs exhibit a significant amount of fracturing, with the densely welded tuff having the greater amount of fracturing (Spengler et al, 1979, p. 24-26; Sykes et al, 1979, p. 15). These same reports give information on fracture frequencies, fracture apertures, fracture orientations and whether the fractures are open or filled. This work shows that the fractures in the tuffs exhibit a preferred vertical orientation. For the purpose of estimation of fracture porosity and conductivity, properties that have not been measured directly, we have approximated this fracture network with a system of vertical fractures consisting of two sets that intersect in an orthogonal fashion. This fracture geometry gives the rock mass an anisotropic hydraulic conductivity. Inspection of this fracture geometry shows that it behaves hydraulically as a system of parallel fractures (planar) in the horizontal direction and as a double system of parallel fractures (double planar) in the vertical direction.

Expressions exist for calculation of the hydraulic conductivity and effective porosity of a simple system of open planar fractures such as just described. In addition to incorporating geometric relationships, these expressions are functions of the fracture frequency (fractures per foot) and fracture aperture (Snow, 1968). For a system of planar fractures (one set of parallel fractures in any orientation), the expressions are:

$$K_f = \frac{\rho g}{\mu} \frac{Nb^3}{12}$$

for the hydraulic conductivity in the fracture plane and $n_f = Nb$ for the effective porosity, where ρ = density of water, g = acceleration due to gravity, μ = viscosity of water, N = fracture frequency and b = fracture aperture. For the double planar situation (two intersecting sets), these expressions are multiplied by two.

Because the reported range of values for fracture frequencies are from cores taken from vertical boreholes that were used to sample nonvertical and usually nonhorizontal fractures, the fracture frequencies are not a true representation of fracture spacing. Knowing the average dip of the fractures and the reported frequencies, the true fracture frequency or spacing can be obtained from a simple geometrical argument. The appropriate expression for this conversion is:

$$N_a \times \sin (90^\circ - \theta) = N_t$$

where N_a = apparent fracture frequency, N_t = true fracture frequency, and θ is the dip of the fracture set. The values reported in Table 3 for true fracture frequency have been determined using this expression. The values for fracture frequency and fracture aperture, along with appropriate constants for viscosity, density, and acceleration due to gravity, have been used to calculate fracture horizontal hydraulic conductivity. In the type of fracture system assumed here, the values of fracture vertical hydraulic conductivity are double the values of horizontal conductivity. The same values for aperture and fracture frequency are used to calculate the effective fracture porosities.

The range of values for matrix vertical hydraulic conductivity and matrix porosity for the densely welded, moderately welded and non-welded tuffs in Table 3 are taken from laboratory tests of 20 core samples from the Topopah Springs, Tiva Canyon and Rainier Mesa members of the tuff sequence and from 32 cores of the tuff aquitard in Yucca Flat and Rock Valley (Winograd and Thordarson, 1975, p. C32, C34, and C45).

The tuff matrix is assumed to be isotropic and, therefore, the matrix horizontal hydraulic conductivities for the different tuff zones are given the same range of values as for the matrix vertical hydraulic conductivities.

The bulk horizontal hydraulic conductivity values for densely welded tuffs in Table 3 come from data for four pump tests conducted at the NTS (Winograd and Thordarson, 1975, p. C22-C23). They are considered bulk values because these tests should include the combined effects of flow through both the matrix and fractures and be representative of rock mass properties. Comparison of the matrix, fracture, and bulk horizontal hydraulic conductivities of the densely welded tuffs (Table 3) shows that the values for the fracture conductivity are closer than the matrix conductivity to the bulk horizontal conductivity determined by pumping. This supports the conclusion that the fracture system dominates the flow in the densely welded tuffs. In this case, the fracture porosity comprises essentially all the effective porosity, and we have given the bulk effective porosity a range of values equal to the calculated fracture effective porosity.

A comparison of matrix and fracture horizontal and vertical hydraulic conductivities for the moderately welded tuffs in Table 3 shows that both the fractures and the matrix contribute substantially to the overall conductivity. We have assigned the bulk horizontal and vertical conductivities of the moderately welded tuffs a range of values in Table 3 that reflects the significant contributions of the fractures and matrix.

Since the flow through the matrix of the moderately welded tuffs is probably never completely abandoned in favor of the flow through the fractures, the porosity of the matrix cannot be excluded from and, moreover, dominates the bulk effective porosity, as we have indicated in Table 3.

Non-welded tuff zones exhibit negligible fracturing and, therefore, are assigned ranges of bulk porosity and conductivity that are equal to the range of available matrix values.

The values of the bulk density of the three types of tuff are from interpretations of geophysical logs in borehole UE25a-1 (Hagstrum et al, 1980, Table 1).

Each composite value given in Tables 2 and 3 represents a weighted average of the contributions of various tuff zones to the appropriate property. The composite values for the bulk effective porosity, bulk horizontal hydraulic conductivity and bulk density values are obtained by the formula

$$Cv = \sum_i P_i \times d_i/D$$

where Cv = composite value, P_i = parameter value for zone i, d_i = thickness of zone i and, D = total unit thickness. The expression for composite bulk vertical hydraulic conductivity is slightly different and is of the form

$$Cv = D/(\sum_i d_i/P_i) \ .$$

These values were calculated using the total thicknesses of units in borehole UE25a-1 (Spengler, 1979, p. 10, and Sykes et al, 1979), and the percentages of zones of different degrees of welding in each unit as reported by Spengler et al (1979, Plate 1).

The range of values for properties of the zones of different degrees of welding in the tuff aquitard in Table 3 are the same as those for similar zones in the tuff aquifer. The main difference between the two hydrostratigraphic units is that there are essentially no densely welded zones in the tuff aquitard. This alters significantly the composite values for the different properties of the tuff aquitard with respect to those for the tuff aquifer. The tuffs comprising the lower unsampled portion of the aquitard are assumed to have properties similar to those of the upper sampled portion of the aquitard.

5.4 Upper Clastic Aquitard, Unit 3

The Upper Clastic Aquitard, mostly the Eleana Formation, includes several different rock types, with argillite being the dominant lithology (Winograd and Thordarson, 1975, p. C43; Hoover and Morrison, 1980, pp. 9-17; Maldonado et al, 1979, pp. 5-10).

Recent work (Maldonado et al, 1979, p. 16; Hoover and Morrison, 1980, p. 60) indicates that the argillites are fractured and that the majority of these fractures are open to some degree at all depths. The presence of open fractures at depth might be due in part to the presence in the argillite of substantial amounts (up to 45%) of fine-grained quartz that impart a higher strength than would be characteristic of rock richer in clay minerals (Hoover and Morrison, 1980, pp. 13 and 15). These same reports give information on fracture frequency, fracture orientation, and whether the fractures are open or filled (Maldonado et al, 1979, pp. 16-23; Hoover and Morrison, 1980, pp. 58-59). The fractures in the Eleana Formation do not show any preferred orientation. For the purpose of simplification and to allow calculation of properties, this fracture network can be represented by a system of three sets of fractures that all intersect in an orthogonal fashion (cubic system). This fracture geometry gives the rock mass isotropic hydraulic conductivity.

No data are available to us on the fracture apertures in the Eleana Formation. We have assumed in our calculations that the fracture apertures for the upper clastic aquitard are less than the apertures for the tuff aquifers, because the tuffs are welded and more brittle than the deeply buried, somewhat plastic argillite. We have assigned a range of values for the fracture apertures of the upper clastic aquitard (Table 2) that is an order of magnitude lower than the values for the fracture apertures of the welded tuffs in Table 3.

For a system of cubic fractures, the expressions are

$$K_f = \frac{\rho g}{\mu} \frac{Nb^3}{6}$$

for the hydraulic conductivity and $n_f = 3\ Nb$ for the porosity, where all the variables are as defined in Section 5.3 of the text.

The values of fracture frequency and fracture aperture have been used to calculate fracture porosity and horizontal fracture conductivity in Table 2. Because the fracture system is isotropic, the range of values for vertical fracture conductivity is the same as the range for horizontal fracture conductivity.

Winograd and Thordarson (1975, p. C41) report conductivity values for argillite and siltstone determined from 9 tests on cores of the lower clastic aquitard taken from a well in Yucca Flat. These values are measurements of matrix conductivity. Matrix conductivity for the upper clastic aquitard in the Yucca Mountain area is assumed to be similar (Winograd and Thordarson, 1975, p. C43). This assumption is reflected in the range of values for matrix conductivity of our Unit 3 (Table 2).

The matrix of the upper clastic aquitard is assumed to be isotropic and, therefore, the matrix vertical conductivity is equal to the matrix horizontal conductivity.

No field tests in wells are known to have been performed on the argillite to determine its bulk hydraulic conductivity. A few well tests have been performed in the more conductive dolomites and quartzites present in the Eleana Formation (Winograd and Thordarson, 1975, p. C43; Dinwiddie and Weir, Jr., 1979, p. 7). These rocks constitute a small percentage of the Eleana Formation, and their properties cannot be considered representative of the formation.

Comparison of the matrix and fracture conductivities for the upper clastic aquitard in Table 2 shows a situation in which both the fractures and the matrix appear to contribute to the overall conductivity. Following the argument used for the moderately welded tuffs, we have given the bulk horizontal and vertical hydraulic conductivities of the upper clastic aquitard a range of values in Table 2 that reflects the significant contributions of both the fractures and the matrix. Also, the same argument used for determination of the bulk effective porosity of the moderately welded tuffs is invoked to obtain the range of values for the bulk effective porosity of the upper clastic aquitard reported in the table.

The effective matrix porosity of the upper clastic aquitard in Table 2 is taken from data reported for lab tests performed on 22 outcrop samples of the Eleana Formation (Winograd and Thordarson, 1975, p. C43).

The values for bulk density come from data reported for the analysis of cores from borehole UE25a-3 in the Calico Hills region and from borehole logs and analysis of cores from the Syncline Ridge area (Maldonado et al, 1979, pp. 27 and 30; Hoover and Morrison, 1980, pp. 63 and 66).

5.5 Carbonate Aquifer, Unit 2

The carbonate aquifer is a very thick, substantially fractured rock unit. Winograd and Thordarson (1975, p. C18) indicate that only a small percentage of the fractures are open, and that these fractures exhibit a preferred vertical orientation. This same study gives information on fracture frequency and fracture apertures. We have approximated this fracture system with the same fracture geometry used for the densely and moderately welded tuffs (two vertical orthogonal sets) and have used the same expressions and arguments to calculate the true fracture frequency, fracture horizontal and vertical conductivity, and effective fracture porosity for the carbonate aquifer.

The values for effective matrix porosity and matrix vertical conductivity of the carbonate aquifer in Table 2 are taken from data reported for lab tests of cores obtained from the test site region (Winograd and Thordarson, 1975, p. C17). We have assumed that matrix conductivity is isotropic and assigned values for horizontal matrix conductivity that are equal to measured vertical matrix conductivities.

The values for bulk horizontal conductivity of the carbonate aquifer in Table 2 come from transmissivity data calculated from the drawdown curves of six pumping tests performed at the test site (Winograd and Thordarson, 1975, p. C22).

Comparison of the matrix, fracture, and bulk horizontal conductivities shows that the fracture conductivities are nearer to the bulk or true conductivity values reported for the pump tests. The fracture network is therefore the major transmitter of groundwater in the carbonate aquifer. The unusually high values in the range of horizontal fracture conductivity might represent very localized karstic or brecciated zones in the aquifer, and they are not considered representative of the aquifer in general.

Because the carbonate aquifer is dominated by fracture flow, the effective bulk porosity is given a range of values equal to that of the effective fracture porosity.

Data for the bulk density of the carbonates is not available for the NTS region. Values in Table 2 are taken from data on limestones and dolomites from other regions (Clark, 1966, pp. 23-24).

5.6 Lower Clastic Aquitard, Unit 1

The lower clastic aquitard, although intensely deformed and fractured, probably exhibits little fracture conductivity because of the tendency for fractures in these rocks to be closed at the great depths at which they exist (Winograd and Thordarson, 1975, pp. C40-C41). For this reason, the matrix values of porosity and conductivity based cn analysis of 43 cores from the lower clastic aquitard (Winograd and Thordarson, 1975, p. C41) are considered representative of the bulk values for the unit (Table 2). The unit is assumed to be isotropic, with vertical conductivity being equal to horizontal conductivity.

The bulk density of the lower clastic aquitard is unknown but is assumed to be similar to that of the upper clastic aquitard.

6.0 SCENARIO SELECTION AND DESCRIPTION

6.1 Introduction

There are a large number of phenomena, both natural and human-induced, that might alter the expected confinement capability of a geologic repository system. These phenomena can be termed release mechanisms if they lead to release of contaminants from confinement, and the analysis of the effects of one or more specific release mechanisms on a repository system constitutes a scenario analysis.

This section presents a brief description of selected scenarios that we feel may compromise the integrity of a repository system in tuff at the NTS. The level of detail presented here reflects the availability of information on hydrologic and geologic processes and features at the NTS. We have, where time has permitted, drawn on information from outside the site to supplement the available data.

Analysis of those scenarios with a high probability of occurrence or with severe consequences are most relevant to risk assessment. To aid in the selection of a group of scenarios for application to the tuff repository system, we have first compiled a list of scenarios that have been considered for repository systems in general or for repositories in other specific geologic media. Our sources for this list were Claiborne and Gera (1974), the APS Study (1977), Campbell et al (1978), and Arnett et al (1980). From this list we have selected those release mechanisms that have, in our opinion, a higher probability of occurrence in the tuff repository system and/or potentially more severe consequences if they were to occur. Table 4 lists both the scenarios selected and those considered but rejected. The following paragraphs present our selected scenarios and the justification for selection of each. Important features of the selected scenarios

Table 4 List of Scenarios Considered for Use in the Tuff System

SELECTED SCENARIOS

Natural Phenomena

1. Climatic change that produces a pluvial period

2. Faulting

3. Magmatic activity (intrusion)

Human-Induced Phenomena

4. Boreholes/shafts (future resource recovery, waste disposal, degradation of seals)

5. Hydrologic perturbations (irrigation, artificial recharge or new ground-water withdrawals)

ADDITIONAL SCENARIOS CONSIDERED BUT REJECTED

Natural Phenomena

1. Meteorite impact
2. Earthquakes
3. Landslides
4. Storms
5. Long-term changes in system properties caused by dissolution or precipitation
6. Thermal effects related to changes in the natural geothermal gradient
7. Changes in the tectonic stress field
8. Erosion or sedimentation
9. Regional subsidence or uplift
10. Flooding
11. Undetected aquifers or aquitards
12. Inadequately characterized geologic media (uncertainty in geometry and properties of units)

Human-Induced Phenomena

13. Effects of the engineered repository (subsidence, caving, thermal or excavation stresses, radiation effects, chemical effects, thermally induced groundwater buoyancy)
14. Reservoirs
15. Nuclear explosions
16. Sabotage

are shown in Table 5. Further discussion of the rejected scenarios is not within the scope of this report.

6.2 Climatic Change

Many topographic basins in southern Nevada contain deposits and shoreline features of ancient pluvial lakes. These exist in an area that is arid today, and they provide unmistakable evidence for substantial variation in ancient climatic patterns. Mifflin and Wheat (1979) have mapped the extent of pluvial lakes in Nevada and have attempted to quantify past climatic variation in terms of specific climatic factors.

Pluvial lakes were formed under paleoclimatic conditions that provided moisture input into closed topographic basins that exceeded moisture loss. No closed basins exist in the proximity of Yucca Mountain or along the regional cross section from Yucca Mountain to the Amargosa Desert and no lakes have been mapped in that area (Mifflin and Wheat, 1979, Plate 1). Regardless of the absence of lakes, the other possible influences of climatic change on the repository system and the likelihood of future climatic change will be considered here.

Although a large number of studies have attempted to estimate the amount of precipitation and temperature variation required to produce and sustain a pluvial lake system, the Mifflin and Wheat (1979) study appears to use the most quantitative approach. Their results suggest increases of precipitation that range from 52 to 80 percent above modern values, and only minor, 5°F or less, temperature differences between the present and the cooler pluvial climates (Mifflin and Wheat, 1979, p. 49).

Evidence for several cycles of lake formation and disappearance in Nevada (Mifflin and Wheat, 1979, Table 1) along with the long-term cyclicity of Pleistocene world climate (Bowen, 1978, p. 193-199) suggests that these

Table 5 Summary of Features and Characteristics Proposed for Scenario Analysis in a Tuff Repository System

Scenario	Type of Disruption	Proposed Location/Geometry	Proposed Properties of Disruptive Feature			
			K_V(Ft/Day)	K_H(Ft/Day)	n_{eff}	γ(Lbs/Ft^3)
1. Pluvial	Water table rise	280 foot rise throughout region	........................no change................................			
2. Faulting	Properties of existing faults	All existing faults	10^{-4} to 10^{3}	10^{-4} to 10^{3}	0.1 to 0.4	99.9 to 112.4
3. Magmatic activity	Igneous dike intrusion	Major fault between boreholes UE25a-1 and J-13; 100 feet in width; Terminates at base of alluvium	10^{-7} to 10^{-6}	10^{-7} to 10^{-6}	0.001 to 0.01	179.1 to 190.3
4. Boreholes and shafts	a. Depository access shafts	a. 5 shafts along line perpendicular to detailed section; Diameter 12 feet; Penetrates to depository level	a. 2.8×10^{-7} to 1.1×10^{-5}	2.8×10^{-7} to 1.1×10^{-5}	0.21 to 0.28	99.9 to 141.7
	b. Repository exploration boreholes	b. 1 mile apart on detailed section; 3 miles apart on regional section; One foot in diameter; Penetrates to base of tuff aquitard	b. 4×10^{-7} to 2×10^{-5}	4×10^{-7} to 2×10^{-5}	0.17 to 0.28	114.4 to 156.6
	c. Resource recovery shafts	c. 2 shafts along 2 major faults in detailed section; 12 foot diameters; 2,000 feet deep	c. 0.7 to 19.1	0.7 to 19.1	16 to 42	99.9 to 112.4
	d. Resource exploration boreholes (minerals)	d. One along each fault in detailed section; One foot in diameter; 2000 feet deep	d. 0.7 to 19.1	0.7 to 19.1	16 to 42	99.9 to 112.4
	e. Resource exploration and recovery boreholes (oil and gas)	e. One for each structural block in detailed section; One each mile for regional section; one foot in diameter; penetrates to top of carbonate aquifer	e. 0.7 to 19.1	0.7 to 19.1	16 to 42	99.9 to 112.4
5. Hydrologic perturbation	Groundwater withdrawal	Change in water table gradient between J-13 and fault directly west of well to a straight line segment from current water table at fault to base of Topopah Springs unit at J-13	..........................no change................................			

precipitation variations have occurred repetitively in the past. The Pleistocene climatic cycles, each consisting of a warm interglacial and a cold glacial episode, are known from a variety of sedimentological and paleontological records and appear to have an average length of about 100,000 years (Bowen, 1978, p. 75).

The major pluvial periods in Nevada correlate in general with glacials rather than interglacials, but the exactness of the correlation and the duration of the pluvial are poorly known (Mifflin and Wheat, 1979, p. 11). During the early and late Wisconsinan (the last glacial stage), high lake levels were reached several times, suggesting that the pluvial climate lasted for several tens of thousands of years and had a complex history (Mifflin and Wheat, Table 1).

The evidence for past climatic change and the repetitive and cyclic nature of that change during the recent geologic past suggest that pluvial climates will recur in southern Nevada and will probably last for a period of several tens of thousands of years during the next 100,000 years.

Direct evidence at the NTS shows that periods of past climatic change produced water table levels that were higher than exist today. The position of these levels can be inferred from the presence of zones of zeolitization in partly welded and non-welded tuffs that are above the modern water table. It is extremely unlikely that other mechanisms, such as downward percolation of ground water through the unsaturated zone, could have given rise to the massive zeolitization of these tuff layers.

In borehole UE25a-1, mineralogic and petrologic studies indicate a zone of zeolitization that extends as much as 280 feet above the present water table (Sykes et al, 1979, p. 14). It is not clear whether this ancient water level represents the most recent pluvial period or older pluvials. Nevertheless, we estimate that the next pluvial period could give rise to water tables that are elevated approximately 280 feet above the existing levels. This estimate falls within the range of the rise in the potentiometric surface of the carbonate aquifer (20 to 295 feet) that Winograd and Doty (1980, p. 82-85) have predicted for a renewed pluvial period.

An increase in water table elevation of 280 feet, or any substantial amount, would have two major consequences. First, the area of discharge of the regional flow system would be greatly expanded. Along the line of the regional cross section, the water table would approach the ground surface in the vicinity of Lathrop Wells, about 15 miles north of the discharge area for the undisturbed case. Second, increased volumes of ground water would flow through a previously unsaturated portion of the more transmissive upper section of the tuffs, i.e., the Tiva Canyon and Topopah Springs units, the tuff aquifer or unit 4. Both of these situations could greatly affect the travel time of a contaminant, one by shortening the flowpath and the other by increasing the average velocity of a non-retarded contaminant particle.

6.3 Faulting

The ubiquitous nature of faults in the NTS and vicinity necessitates consideration of future fault movement as a possible release mechanism and the properties of fault zones as pathways for or barriers to radionuclide migration.

The energy of ground motion associated with fault movement or other energy sources, such as nuclear testing, could possibly cause a disruption of the engineered depository during its operational phase, but is unlikely to affect it adversely after closure (Pratt et al, 1978). This ground motion could also create significant local fracturing of the rock mass and thus alter the hydrologic properties. Although an in-depth analysis of this type of scenario is beyond the scope of the report, some data from nuclear testing at the NTS can be used to examine the possible location and scale of future fracturing and faulting.

A 200 kiloton detonation, known as the Bilby event, took place at the NTS in 1963 and is well documented. This explosion created a crater with a maximum diameter of about 1,600 feet (Borg et al, 1976, p. 96). At distances of 3.5 to 5.2 times the crater radius, the compressive stress of the shock wave was too small to fracture the rock (Borg et al, 1976, p. 84). Thus, for the Bilby event, fracturing was limited to a distance of 2,800 to 4,160 feet from ground zero.

Larger events, up to 1.1 megaton, have taken place at the NTS (a one megaton event is equivalent to an earthquake of magnitude 6.5), and could be expected to produce larger zones of fracturing. Explosion-induced earthquake shocks of relatively small magnitude (up to 4.0) have been measured on faults up to 8 miles, but mostly less than 3 miles, from ground zero (Smith, 1973, p. 212-213). Carr (1974, p. 12) reports that geologic evidence indicates that very few large earthquakes have occurred in the NTS region in the last few thousand years. Carr states that stress is relieved continuously by smaller earthquakes, and that seismic monitoring has detected only low-level earthquake activity up to magnitude 4.0 at the NTS (Carr, 1974, p. 33).

In summary, neither natural earthquake activity nor human-induced explosions is likely to produce significant new fracturing, except in a very localized region (several thousand feet) around the explosion source or adjacent to existing faults. Therefore, a scenario that includes new faulting through the depository due to natural or human-induced energy sources will not be further considered here.

A situation more likely to occur in the repository system is that of continued or renewed movement on pre-existing faults. The potentially significant effect of this scenario is further offset of geologic units, causing a change in the groundwater flow field configuration. In addition, the major faults present in the tuff system, even without further movement, may have higher hydraulic conductivity than the surrounding rock and thus may act as avenues for rapid movement of contaminants. Fault zones characterized by lower hydraulic conductivity can be equally disruptive because they may act as "dams" in the groundwater flow field (Schwartz and Donath, 1980).

Ekren and others (1968) report that the youngest fault set in the NTS began forming about 17 million years ago and may still be active today. These authors also state that the general form of the present Basin and Range topography, which is controlled by faulting, took shape as recently as 7 million years before present. The normal faults observed at the site commonly exhibit approximately 100 feet of vertical displacement with some faults having as much as 1,000 feet of vertical displacement. If one assumes a uniform amount of fault movement over time, this information on relative offsets and ages of normal fault movement give rates of fault displacement that range from 0.06 to 1.0 feet of displacement in 10,000 years. Even if a very non-uniform rate of movement over time is assumed, displacements greater than several feet to several tens of feet in the next 10,000 years are probably unlikely. This amount of relative movement should not create offsets of the hydrologic units in the detailed or regional cross section that are larger than the offsets that already exist.

Nuclear explosions probably assist faults in releasing accumulated tectonic stress (Dickey, 1968, p. 231). Because this stress would have eventually been released by natural means, these human events should not increase the long-term rates of natural fault movement.

In summary, we feel that neither natural nor human-induced movement on pre-existing faults will produce sufficient offset of the hydrogeologic units to disrupt the flow system during the next 10,000 years.

Finally, we must consider the properties of fault zones that already exist in the geologic system at the NTS.

The hydraulic conductivity of a fault zone filled with granular material can be estimated by the Kozeny-Carmen equation which relates conductivity to mean grain size (Freeze and Cherry, 1979, p. 351). This equation takes the form of

$$K_f = \frac{\rho g}{180\mu} d_m{}^2 \frac{n^3}{(1-n)^2} ,$$

where K_f is fracture conductivity, ρ is density of water, g is acceleration due to gravity, μ is viscosity of water, d_m is the mean grain diameter and n is the porosity.

Spengler (1979, p. 26) reports grain diameters for granulated shear zones in borehole UE25a-1 that range from 0.08 to 3.0 inches (2 to 76 millimeters). The material is reported to be friable and uncemented. Porosities of these zones have not been reported, but we assume them to be in the range of 0.1 to 0.4 based on the reported grain-size distribution.

Using the largest values for estimated porosity and reported mean grain size, conductivity equals 1.58×10^6 feet per day. For the smallest values of the same parameters, conductivity equals 7.6×10^1 feet per day. It is clear that the result is very sensitive to grain size. Although these values seem quite large, it should be noted that these materials are gravel size. Reported ranges of conductivity for gravel-sized material is 2.83 x

10^2 to 2.83×10^5 ft/day (Freeze and Cherry, 1979, p. 29). It should be pointed out that the above equation assumes a well-sorted material of uniform grain size. The fault zone material may be much more poorly-sorted with finer material filling the interstices between the coarser material. In this case, porosity and mean grain diameter of the poorly-sorted material will be lower and the Kozeny-Carmen equation will overestimate the fault conductivity. As an example, assume the fault gouge has a significant proportion of silt size material. Silt has a median grain size diameter of 1.2×10^{-3} inches (3×10^{-2} mm) (Folk, 1974, p. 25), three orders of magnitude smaller than the 1.2 inches (30 mm) average for the data reported above by Maldonado. If the mix of gravel to silt were 50/50, the mean grain diameter would decrease by one and a half orders of magnitude and the calculated conductivity would decrease by approximately 3 orders of magnitude. It would be still lower, perhaps 5 orders of magnitude lower, if the fine-grained material was clay rather than silt. Fault gouge material can be expected to differ in mean grain size and grain size distribution for different geologic units. Depending upon the conductivity and mechanical properties of the unfaulted rocks, the fault conductivity could be higher or lower than the rock conductivity.

Based upon the above discussion, we suggest an appropriate range of horizontal and vertical hydraulic conductivity of the fault zones to be 10^{-4} to 10^3 feet per day. We also suggest an appropriate range of porosity to be 0.1 to 0.4. The bulk density is assumed to be the same as that of the alluvium. This range is 99.9 to 112.4 pounds per cubic foot.

Fault zones in the Syncline Ridge area east of Yucca Mountain are reported to be up to 66 feet in width (Hoover and Morrison, 1980, p. 33). Spengler (1979, p. 26) reports a thickness of 15 to 30 feet for a granulated shear zone in borehole UE25a-1. We would recommend that the sensitivity of the behavior of a modeled system to fault zone width be assessed for zones ranging from 15 to 66 feet thick. The average width of such zones should be assumed to be about 30 feet. Figure 5 shows the representative spacing of faulting near Yucca Mountain. This same spacing can be assumed for the entire regional cross section.

6.4 Magmatic Activity

Great Basin volcanism has been temporally and spatially extensive. Within the NTS, the major volcanic source areas have been Timber Mountain, Oasis Valley and related calderas north of Yucca Mountain (Figure 1). This volcanic activity has been largely of the silicic variety with minor associated basaltic events. The major silicic volcanic activity spanned a period of approximately 16 to 6 million years before present (Christiansen et al, 1977, p. 947). There has not been any large-scale volcanic activity of this type since that time. However, basaltic eruptions preceded, occurred with and postdated the silicic eruptions. These basalts were erupted first around the edge of the main caldera complex and, later, within as well as around the complex (Christiansen et al, 1977, p. 953-957). More specifically, areas of Quaternary (<2 million years old) basalt are rare within the Great Basin. One of these regions is in Crater Flat and southern Yucca Mountain (Figure 1) where lava flows suspected to be as young as 240,000 years are observed (Crowe and Carr, 1980, p. 3-4; Cornwall and Kleinhampl, 1961; Burchfield, 1966).

The frequency of the Pliocene and Pleistocene magmatic and volcanic events in an area within a 15 mile radius centered around Yucca Mountain has been estimated to be 10^{-6}/year (Crowe and Carr, 1980, p. 6-7). These point-source volcanic eruptions are surface expressions of one or more dike intrusions of magma at depth. The dikes are most likely intruded along preexisting zones of weakness in the rock mass such as faults. Many faults intersect the line of cross section and, thus, a magmatic body in the form of a dike could intrude the cross section under consideration. The location of such an intrusive body on the cross section might be along one of the major faults flanking the west side of Forty-Mile Canyon about halfway between boreholes UE25a-1 and J-13.

Surface studies of dissected volcanic centers indicate that the dikes or dike zones can be as much as 100 feet in width (Crowe and Carr, 1980, p. 7). The level in the subsurface to which such a dike zone would rise is uncertain. It may rise to the unconformity at the base of the alluvium where faults typically terminate or to the surface.

No direct measurements of the hydraulic and mechanical properties of igneous dikes at the NTS or elsewhere are known to exist. Measurements of these properties have, however, been performed on large granitic plutons such as the Climax Stock in the NTS and a pluton in the Sand Springs Range of west-central Nevada. Intrusive bodies of this type typically experience some contraction and fracturing upon cooling. The development of fractures depends on the mechanical properties, composition, rate of cooling, and confining pressure. Some amount of fracture of these rocks, except at very great depths, is inevitable.

Testing of a slightly fractured core sample of granite from the Sand Springs Range gave a conductivity value of 8.5×10^{-6} ft/day (Fryer et al, 1981, p. 35 and 37). Murray (1981) reports conductivity values in the Climax Stock for intact granite at $<2.7 \times 10^{-9}$ ft/day and for moderate-to-highly fractured granite at 2.7×10^{-4} to 2.7×10^{-1} ft/day. These values are probably on the extremes of what would be representative for slightly fractured igneous rocks. Conductivity of an outcrop sample of the Climax Stock is reported as 2.7×10^{-7} ft/day (Maldonado, 1977, p. 11).

We estimate the conductivity of an intrusive igneous dike to be in the range of 10^{-7} to 10^{-6} ft/day.

Effective bulk porosity values are estimated to be in the range of 0.001 to 0.01 based upon analogy with dense basalts in the Columbia Plateau (La Sala and Doty, 1970; Atlantic-Richfield Hanford Company, 1976). These values compare well with cored-rock porosities for Climax Stock granite (Maldonado, 1977, p. 9).

Dry bulk density values of gabbro and diabase, which are the intrusive equivalents of basalts, are reported from various locations to be in the range of 179.1 to 190.3 lbs/ft^3 (Clark, 1966, p. 20, 21, 198, 199, 201, 469-471).

6.5 Boreholes and Shafts

There are several situations that could lead to emplacement of boreholes and shafts in the vicinity of the proposed tuff repository system at the NTS. The most plausible situations are (1) system characterization and facility construction, (2) other types of waste disposal, and (3) resource recovery.

Although the spatial configuration of the underground facility with its boreholes and shafts is uncertain, an analogy can be drawn with the drilling and testing programs and conceptual depository designs for the Hanford site in Washington state. The average density of geologic and hydrologic boreholes in the vicinity of the Hanford depository siting area is approximately one per mile (Gephart et al, 1979, p. III-30; Myers et al, 1979, p. III-21; Spane, 1980, p. III-17). The dimensions of the depository are approximately 7,800 feet by 10,500 feet by 40 feet (Ritchie et al, 1980, p. VI-16 and VI-18). Five shafts from 10 to 14 feet in diameter are located in the center of the depository with an average separation distance of approximately 325 feet (Ritchie et al, 1980, p. VI-12 to VI-14). Typical borehole diameters are 8 to 24 inches (Fernandez et al, 1976). We will assume an average borehole diameter of 12 inches.

If a radioactive waste facility is constructed in the Yucca Mountain region, the boreholes and shafts excavated for the project will likely be sealed with various materials such as compacted earth backfills, cements, grouts, etc. We shall assume, in the absence of any information to the contrary, that the boreholes will be plugged with a grout and the shafts will be filled with compacted earth materials.

Koplick (1979) reports attainable ranges of conductivity for grouts and compacted earth materials to be 4.0×10^{-7} to 2.0×10^{-5} ft/day and 2.8×10^{-7} to 1.1×10^{-5} ft/day, respectively. He also reports porosities for grouts and earth materials to be 0.17 to 0.28 and 0.21 to 0.28, respectively. Fernandez (1976) reports bulk density for compacted earth materials to be in the range of 69 to 141.7 pounds per cubic foot. This is a wide range and it is probably possible to, at a minimum, backfill to the natural density of the overlying alluvium. For this reason, we would assign the bulk density within a range of 99.9 to 141.7 pounds per cubic foot. Bulk density of grout is reported to be in the range of 114.4 to 156.6 pounds/cubic foot (Gullick et al, 1980). Koplick (1979) states that some degradation of the sealing materials is expected to occur with time, and that this could lead to an increase in conductivity of up to two orders of magnitude. The length of time for this degradation to occur is unknown.

In order for this scenario to be properly analyzed, a depository location must be assumed. The largest, unfaulted structural block on the detailed cross section in the Yucca Mountain region is the one which contains borehole UE25a-1 (Figure 5). Because this block cannot incorporate a depository with the dimensions mentioned above for the BWIP site, we would give the depository a width of 5,000 feet and position it in the middle of the block. We will assume that the shafts would be oriented along the long dimension of the depository and perpendicular to our line of section. Therefore, only one of the five shafts would appear along the cross section and this would be centered about the midpoint of the structural block. The shaft might be given a diameter of 12 feet. We will also assume boreholes spaced one mile apart with the nearest holes being one mile on either side of the midpoint of the structural block.

Two of the constraints for location of the underground facility in this system are emplacement (1) below the water table and (2) within a zone of moderate to densely welded tuff. Given these constraints, the unit in the Yucca Mountain region most suitable for a depository would be the Bullfrog Tuff (Figure 5). Of all the units below the water table in this area, the Bullfrog has the largest known percentage of welded tuffs (Spengler et al, 1979, Plate 1). The underground facility might be assumed to be in the center of the Bullfrog unit. All the shafts will likely penetrate to the level of the excavated cavity and all boreholes might be assumed to penetrate the entire thickness of the detailed cross section (Figure 5).

On the regional cross section south of well J-13 we can assume a borehole spacing of three miles. For a worst case situation, all boreholes will be assumed to penetrate the entire thickness of the tuff aquitard (Figure 4).

The other major type of waste disposal practice that may affect a nuclear waste depository is deep injection of liquid wastes. Injection depths of 6,500 feet are not uncommon and depths as great as 13,000 feet are sometimes used (Freeze and Cherry, 1979, p. 454). The two main constraints on the use of a formation for injection of wastes are (1) that its transmissivity be sufficient to accept the injected waste and (2) that it is not a source of potable water. Freeze and Cherry (1979, p. 84) report that waters with less than 2,000 to 3,000 mg/liter of dissolved solids can be considered potable. In some circumstances, livestock, agricultural and industrial uses could tolerate even higher TDS concentrations (Hem, 1970, p. 324-336). The TDS concentrations of all waters in the NTS region are reported to be under these limits (Winograd and Thordarson, 1975, p. 100-101), and must therefore be considered potable. Based upon the above discussion, we conclude that deep injection of liquid wastes at the NTS and vicinity is an unrealistic scenario.

We have stated in section 2.2 that economic mineral deposits are associated with magmatic activity in the Yucca Mountain region and surrounding area. In the past, mining as deep as 2,000 feet for these minerals was not uncommon, whereas today, strip mining comprises virtually all the mineral recovery operations in Nevada (Larry Garside, Nevada Bureau of Mines, 1981, personal communication). Because of changing economics and technology, future underground mining should not be ruled out.

Because these types of deposits are associated with the magmatic intrusions north of Yucca Mountain, we assume that any future mining operations along the length of the cross section will be confined to the region north of well J-13. Farther from the magma body these minerals tend to be deposited along zones of weakness in the country rock. Exploration for the minerals might thus be concentrated along known fault zones with the largest faults being the most likely areas of mineral deposits.

Based upon the above discussion, we might assume there to be boreholes with a diameter of one foot and a depth of 2,000 feet along any one or several fault zones in the detailed cross section. We further assume that in the future shafts with a diameter of 12 feet and a depth of 2,000 feet might be excavated along any of the fault zones with the larger amount of relative offset. Once the boreholes and shafts have served their purpose, a worst case scenario would be that the openings will be allowed to cave in or will be backfilled with a loose aggregate of earth materials. This backfill material might have the same range of values for conductivity, porosity and bulk density as the alluvium (unit 6) in the cross sections.

We have stated in section 2.2 that there is a possibility that petroleum is present in the Paleozoic sedimentary rocks in southern Nevada. Future exploration and production of petroleum or perhaps groundwater, cannot be dismissed. For this scenario it is possible that a borehole with a diameter of one foot might penetrate the entire thickness of any unfaulted structural block in the detailed cross section (Figure 5). For the regional cross section, an exploratory borehole might be drilled every mile along the line of section, and these holes might penetrate to the top of the carbonate aquifer, unit 2 in the cross section. The properties of the boreholes will be the same as for the mineral recovery scenario discussed above.

6.6 Hydrologic Perturbations

There are several types of transient perturbations of the hydrologic system that might affect the containment characteristics of a radioactive waste disposal facility in tuff. These situations are irrigation, artificial recharge (surface spreading or well injection) and groundwater withdrawals.

In order for irrigation to occur there must be an economical source of water. The nearest perennial source of surface water is the Colorado

River, which is approximately 300 miles southeast of the Nevada Test site. It is unlikely that water would be transported this far for irrigation purposes. Ground water might be locally withdrawn for irrigation. An unknown percentage of this water would infiltrate back down to the water table. Because of the high evaporation rates in this region (60 to 82 inches of potential lake evaporation per year, section 3.2), only a small percentage of irrigation water would infiltrate to the saturated zone. In the Pasco Basin of Washington, where the water table is much closer to ground surface and evaporation is lower, it is estimated that 20 to 40 percent of irrigation water recharges the groundwater system (Gephart et al, 1979, p. II-140). For the region near Yucca Mountain, a very small amount, perhaps no more than 10 percent, of irrigation water would recharge the groundwater system. Because the amount of future irrigation and the unsaturated hydrologic properties of the system are unknown, we cannot quantify the effect of irrigation on the water table. Nevertheless, we consider the potential hydrologic perturbations due to irrigation to be insignificant in terms of their effects on the repository system.

Artificial recharge of the groundwater system involves diversion of water from outside the area of interest and thus is considered a very unlikely scenario because of the great distance to a perennial surface water supply.

Groundwater withdrawals in Jackass Flats, east and southeast of Yucca Mountain, have been taking place since 1957 in association with the Nuclear Rocket Development station in the southwest part of the NTS (Young, 1972, p. 3 and 10). The water table in this area is within the Topopah Springs tuff, and this unit is the only important water-producing unit. The underlying ashfall tuffs of the Calico Hills are poorly transmissive and function as aquitards. The detailed cross section (Figure 5) shows that low permeability rocks are in lateral contact with the Topopoah Springs tuff along the fault zone immediately west of well J-13. The growth of a cone of depression caused by pumping at J-13 would be effectively halted by this barrier although the drawdown cone would be free to grow farther in other directions. Therefore, induced inflow from a steepening of the hydraulic gradient is unlikely to occur west of this fault zone. Similar effects should occur if pumping were initiated in other fault blocks.

From known saturated thickness, historic pumping rates, estimated values for specific yield and approximate areal dimensions of the aquifer, Young (1972) has estimated the time to dewater the Topopah Springs aquifer to be 76 to 380 years. At this point in time, and probably somewhat earlier, it would be become necessary for the well user to move the well field, thus allowing a return to natural conditions.

It can be seen from the above discussion that extensive pumping of this system can only be a very short-lived phenomenon. The only significant adverse effect that pumping could have on the containment characteristics of this repository system would occur after the contaminants had escaped the depository. If radionuclides entered the Topopah Springs tuff and migrated southward to the vicinity of the west boundary of the aquifer, they would be available for removal by a pumping well. In the case of well J-13 the water table gradient produced by pumping might be 0.45 between well J-13 and the nearest fault zone. This value represents a drop in water table elevation of 450 feet (total dewatering at the well bore) over the 1,000 feet separating the fault and the well. This is an extreme value because it is very unlikely that the aquifer could or would be totally dewatered. During pumping, well J-13 would be the point of discharge for shallower groundwater flowing from Yucca Mountain in the Topopah Springs tuff.

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