CONCEPTUAL HYDROLOGIC MODEL OF FLOW IN THE

UNSATURATED ZONE, YUCCA MOUNTAIN, NEVADA

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4345

Prepared in cooperation with the

U.S. DEPARTMENT OF ENERGY

OBLIQUE AERIAL VIEW OF YUCCA MOUNTAIN, LOOKING NORTH.
YUCCA CREST AND SOLITARIO CANYON IN LEFT CENTRAL PART OF PHOTOGRAPH,
AND FORTYMILE CANYON IN UPPER RIGHT-HAND CORNER OF PHOTOGRAPH.

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Lakewood, Colorado

1984

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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METRIC CONVERSION TABLE

For those readers who prefer to use inch-pound rather than metric units, conversion factors for the terms used in this report are listed below:

| Metric unit | Multiply by | To obtain inch-pound unit |
|---|---|---|
| centimeter (cm) | $3.937 \times 10^{-1}$ | inch |
| meter (m) | 3.281 | foot |
| kilometer (km) | $6.214 \times 10^{-1}$ | mile |
| cubic meter ($m^3$) | $6.102 \times 10^{4}$ | cubic inch |
| cubic meter per year ($m^3$/yr) | $2.642 \times 10^{2}$ | gallon per year |
| centimeter per second (cm/s) | $1.367 \times 10^{-3}$ | foot per day |
| millimeter per year (mm/yr) | $3.937 \times 10^{-2}$ | inch per year |
| kilopascal (kPa) | $1.00 \times 10^{-2}$ | bar |
| | $1.45 \times 10^{-1}$ | pound per square inch |
| degree Celsius (°C) | F = 9/5°C + 32 | degree Fahrenheit (°F) |
| meter per day (m/d) | 3.281 | foot per day |
| meter squared ($m^2$) | $1.076 \times 10$ | foot squared |

CONCEPTUAL HYDROLOGIC MODEL OF FLOW IN THE UNSATURATED ZONE, YUCCA MOUNTAIN, NEVADA

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## ABSTRACT

The unsaturated volcanic tuffs beneath Yucca Mountain, Nevada, are being evaluated by the U.S. Department of Energy as a host rock for a potential repository for high-level radioactive waste. Proper assessment of the site suitability needs an efficient and focused investigative program. A conceptual hydrologic model is needed to guide the program and to provide a basis for preliminary assessment of site integrity. This report proposes a conceptual model to describe the flow of fluids through the unsaturated zone at Yucca Mountain.

Yucca Mountain consists of a series of north-trending fault-block ridges composed of volcanic rocks that have an eastward tilt of about 5 to 30 degrees. Thickness of the unsaturated zone is about 500 to 750 meters. Three formations of ash-flow tuff occur beneath the alluvium: Paintbrush Tuff, tuffaceous beds of Calico Hills, and Crater Flat Tuff. Based on physical properties, the rocks in the unsaturated zone are grouped for the purpose of this report into five informal hydrogeologic units: Tiva Canyon welded unit, Paintbrush nonwelded unit, Topopah Spring welded unit, Calico Hills nonwelded unit, and Crater Flat unit. Welded units have a mean fracture density of 8 to 40 fractures per cubic meter, mean matrix porosities of 12 to 23 percent, matrix hydraulic conductivities with geometric means ranging from $2 \times 10^{-6}$ to $3 \times 10^{-6}$ meter per day, and bulk hydraulic conductivities of 0.1 to 10 meters per day. The nonwelded units have a mean fracture density of 1 to 3 fractures per cubic meter, matrix porosities of 31 to 46 percent, and variable hydraulic conductivities, with geometric means ranging from $8 \times 10^{-6}$ to $9 \times 10^{-3}$ meter per day. The central block (the primary repository area being evaluated by the U.S. Department of Energy) is bounded by steeply dipping faults or by fault zones. The central block is relatively intact and is transected by a few normal faults.

A hypothetical model is proposed for flow through porous layers intercalated with double-porosity layers. In this model, flow through fractures can occur at almost all stages of saturation, but the flux magnitude in fractures is largely a factor of the contrast between the matrix and fracture hydraulic properties and the magnitude of the perturbation of flux at the flow boundaries. In this model, flow is retarded by capillary barriers that occur at the contacts between nonwelded and welded units. The effectiveness of this capillary barrier depends on the magnitude of flux and hydraulic-head distribution. Hysteresis during wetting phases and air entrapment may result in greater flux in fractures than would otherwise be predicted. Initiation of lateral flow also results. Both vapor transport and liquid flow can occur simultaneously within the fractured layers in this model.

Average annual precipitation at Yucca Mountain is estimated to be 150 millimeters per year, of which about 0.5 to 4.5 millimeters per year becomes net infiltration. Surface runoff is infrequent and of short duration, and no perennial streams exist in the area. Precipitation occurs during a few intense storms. Water infiltrates principally into the Tiva Canyon welded unit, but also into alluvium, Paintbrush nonwelded unit and Topopah Spring welded unit where they are exposed at the land surface. Eastward lateral flow occurs within and above the upper contact of the Paintbrush nonwelded unit. The lateral flow is intercepted by structural features, which transmit most of the infiltrated water to the water table.

Percolation through the matrix occurs principally vertically in the welded units and both laterally and vertically in the nonwelded units. Fracture flow is predominant in the Tiva Canyon welded unit during intense pulses of infiltration and is insignificant in the Topopah Spring welded unit except near the upper contact and near the structural features. Temporary development of perched water is possible near the structural features within and above the nonwelded units. This water drains into the structural flow paths and much of it travels directly to the water table.

Flux in the Paintbrush nonwelded unit is variable. Vertical flux may range from 0.1 to 98.6 millimeters per year, and the capacity to transmit lateral flux is more than 100 millimeters per year in this unit. The ratio of vertical to lateral fluxes depends on the effectiveness of the capillary barrier at the lower contact of this unit. From $1 \times 10^{-7}$ to 0.2 millimeter per year of downward flux could be occurring in the matrix of the Topopah Spring welded unit, but the net flux probably is about 1.0 to 2.0 millimeters per year upward in this unit. Downward flux in the Calico Hills nonwelded unit is variable but probably is limited to about 0.006 millimeter per year. These flux values are uncertain because of various alternative interpretations of the data.

The model provides a basis for conducting preliminary assessment of the hydrogeologic integrity of a potential repository at this site. Comprehensive numerical modeling, in-situ testing, and laboratory experiments would provide suitable tests of these hypotheses.

## INTRODUCTION

Yucca Mountain, Nevada, is one of several sites under consideration by the U.S. Department of Energy as the Nation's first mined geologic repository for storing high-level nuclear wastes. The U.S. Geological Survey has been conducting hydrologic, geologic, and geophysical investigations at Yucca Mountain and the surrounding region in order to help assess the suitability of the site for a repository. These investigations are part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project and are conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

Under current conceptual designs, the waste would be placed within the thick section of unsaturated volcanic tuff that underlies Yucca Mountain. Investigations are underway to evaluate the hydrologic conditions, processes, and properties of the unsaturated zone at this site. This report proposes a conceptual flow model that has been developed from preliminary investigative results and from a general understanding of principles of unsaturated-zone flow.

## Concept of a Repository in the Unsaturated Zone

The initial focus of the NNWSI in the late 1970's was to evaluate the suitability of placing a repository in the saturated zone beneath Yucca Mountain. However, the concept of storing waste in the unsaturated zone had been noted in the literature for nearly a decade (Winograd, 1972, 1974). Later, Winograd (1981) summarized the advantages associated with thick unsaturated zones, with special reference to the Nevada Test Site. Roseboom (1983) expanded on the concept and proposed design features that could enhance the isolation potential of this environment. At Yucca Mountain, as an understanding of the hydrologic system began to develop, and as a result of the urging by various components of the scientific community, more careful consideration was given to the unsaturated zone. In 1982, investigative emphasis was shifted to the unsaturated zone.

One of the features of Yucca Mountain that permits consideration of a repository in the unsaturated zone is the very deep water table, generally about 500 to 750 m below land surface (Robison, 1984). As proposed, the repository would be constructed in the lower part of a densely welded fractured tuff, the Topopah Spring Member of the Paintbrush Tuff. These rocks appear to have geomechanical properties that permit the construction of stable openings and geochemical and thermal properties that are suitable for storage of waste (Johnstone and others, 1984). In addition, these rocks have a fracture density (Scott and others, 1983) that probably promotes rapid drainage of water. Moreover, a waste package and underground facility probably can be designed to enhance water drainage into the surrounding rocks with only minimal contact of the water with the waste package (Roseboom, 1983).

At the Yucca Mountain site, the unsaturated zone could be a natural barrier to radionuclide migration that would add to the barriers that exist in the saturated-zone system. The first component of the unsaturated-zone barrier is the very slow flux of water that occurs at Yucca Mountain. Next, a sequence of nonwelded porous tuffs that overlies the Topopah Spring Member probably are a natural capillary barrier to retard the entrance of water into the fractured tuffs. A similar sequence of nonwelded tuffs underlies the Topopah Spring Member. These underlying nonwelded tuffs locally contain sorptive zeolites and clays that could be an additional barrier to the downward transport of radionuclides from a repository to the water table.

Although the general conditions described above probably exist, details of the hydrologic processes, conditions, and properties in the unsaturated zone are unknown. These details need to be known to characterize the site properly. The current lack of knowledge is the result of: (1) Lack of data, because of the newness of the focus on the unsaturated zone; (2) inadequacy of the general state of understanding of the physics of flow in thick, fractured-rock unsaturated zones in arid environments; and (3) lack of well established techniques for testing and evaluating the hydrology of such unsaturated zones. To develop the information and understanding needed to assess the suitability of the unsaturated zone at Yucca Mountain within the time frame imposed by the national site-selection effort, an efficient and focussed investigative program needs to be conducted, and preliminary results need to be obtained quickly. A conceptual hydrologic model is needed to guide the program and to provide a basis for useful preliminary assessment of site integrity.

### Purpose and Scope

The purpose of this report is to propose a conceptual hydrologic model that reasonably describes the flow of fluids through the unsaturated zone at Yucca Mountain, for use as a basis for preliminary site-performance assessment and as a guide to further investigations. Scott and others (1983) presented an initial conceptual hydrogeologic model for the unsaturated zone at Yucca Mountain, based on detailed geologic, but very limited hydrologic, information. In this report, some of their concepts are examined and either supported or modified, and new concepts are developed.

The model describes the manner in which flow probably occurs at Yucca Mountain and is based on: (1) Current understanding of the hydrogeologic framework; (2) application of the principles of unsaturated flow; and (3) interpretation of some preliminary data from ongoing field and laboratory investigations. Included are extensive geologic information but relatively few hydrologic data that currently exist from the unsaturated zone in the Yucca Mountain area. Many uncertainties remain to be resolved concerning hydrologic conditions and processes. As a result, most of the concepts presented are intentionally descriptive and conjectural, with little quantitative basis provided. However, for the sake of directness and simplicity of expression, the model is presented as if it were a true expression of the facts. The authors recognize, and the reader should be aware, that the proposed model probably is not the only reasonable description that could be made at this point, and it certainly is subject to revision and quantification as more data become available. Although various alternative models probably could be developed, the one described in this report seems to fit current understanding of the unsaturated flow through a section of layered, fractured-rock formations with contrasting hydrologic properties, such as occurs at Yucca Mountain.

## GENERAL HYDROGEOLOGIC SETTING

Yucca Mountain lies in and west of the southwestern part of the Nevada Test Site (NTS) (fig. 1). The NTS, used principally by the U.S. Department of Energy for underground testing of nuclear devices, is in Nye County, Nevada, about 105 km northwest of Las Vegas. The part of the mountain of principal interest is informally termed the central block, as outlined in figure 2. The central block approximately corresponds to the area under consideration by the U.S. Department of Energy for a repository, or the primary repository area.

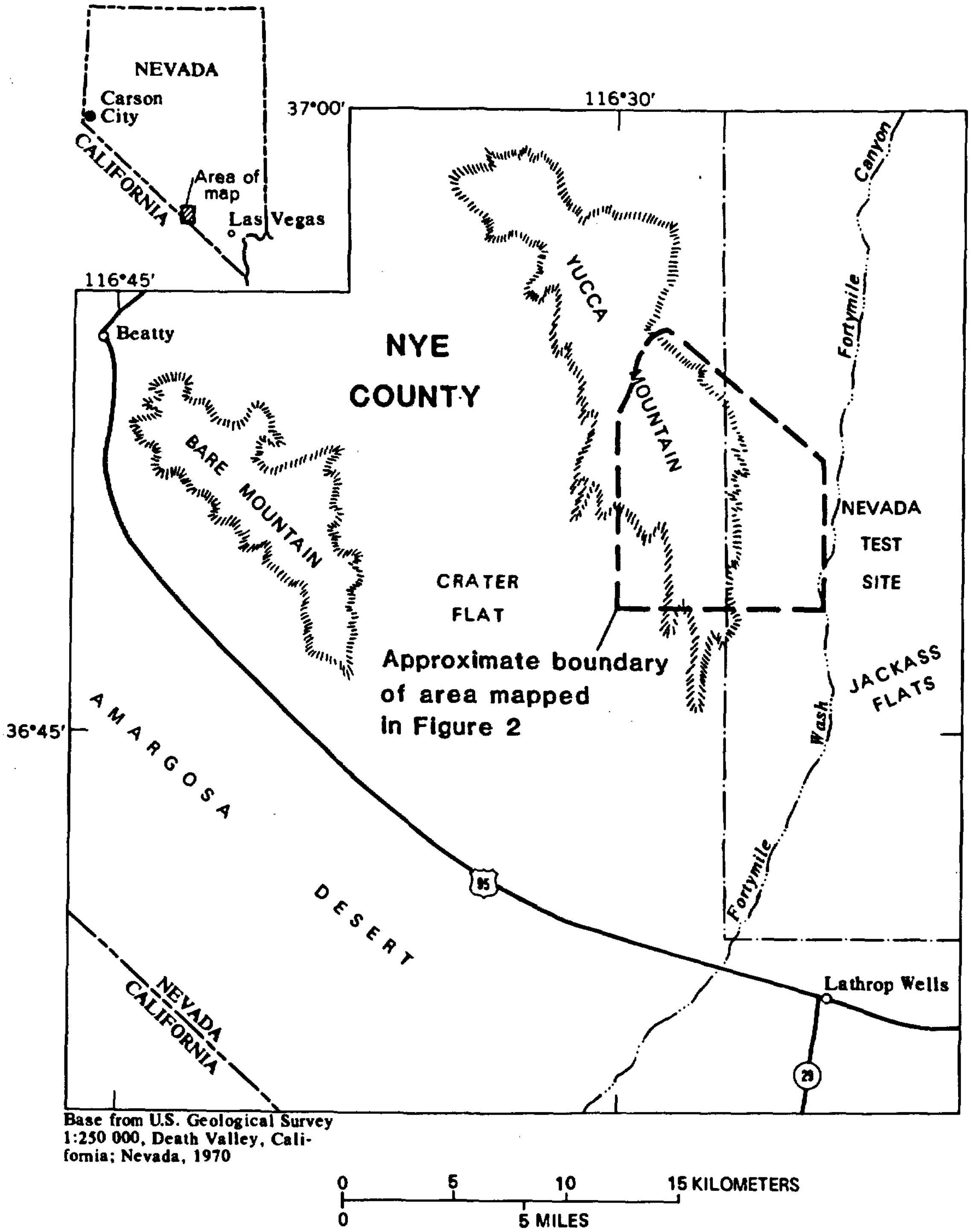



Figure 1.--Location of Yucca Mountain.

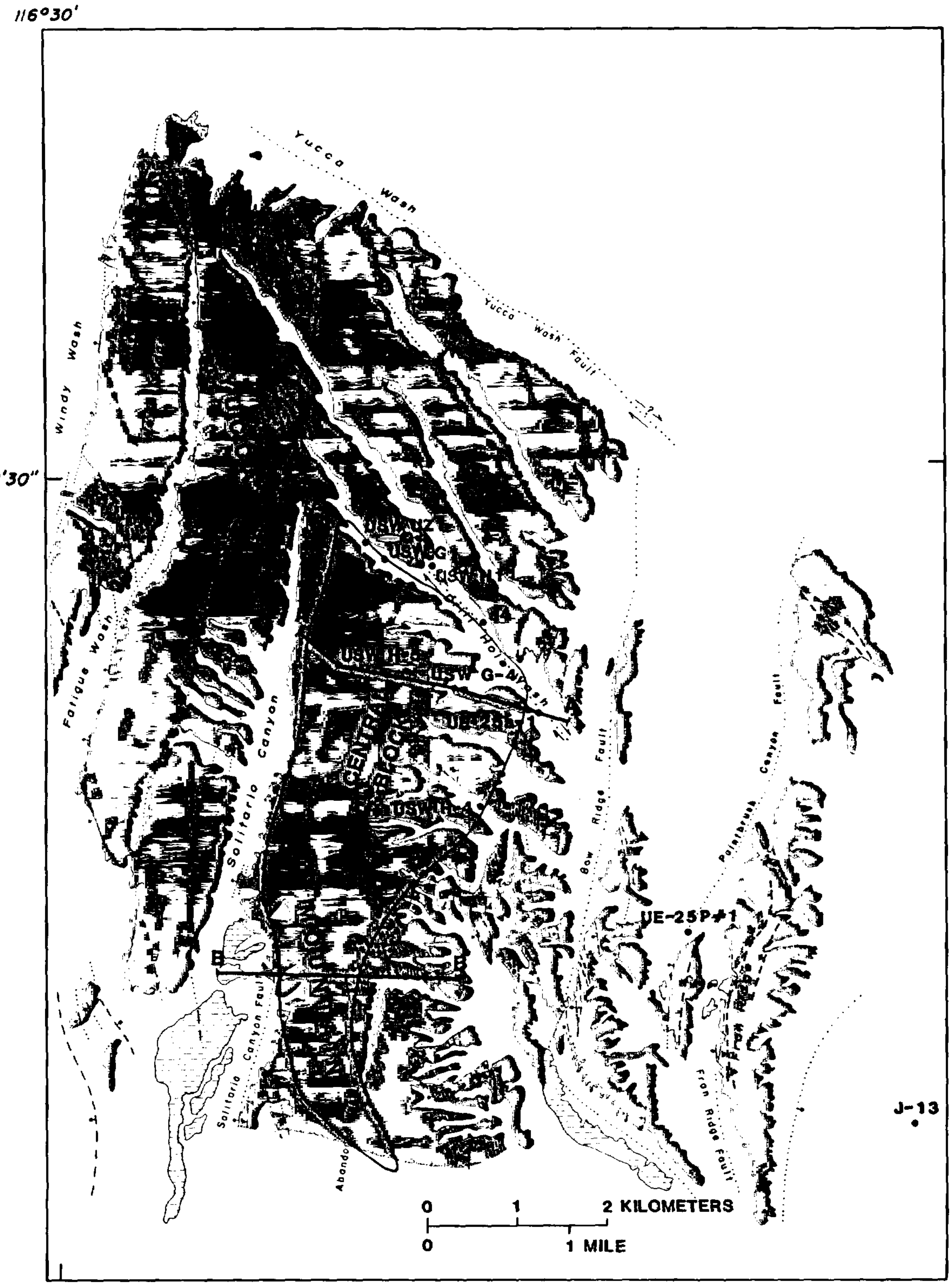



Figure 2.--Generalized geologic map of the Yucca Mountain central block and vicinity (modified from Scott and Castellanos, 1984).

## EXPLANATION

ALLUVIUM AND COLLUVIUM OF QUATERNARY AND TERTIARY AGE

RAINIER MESA MEMBER OF THE TIMBER MOUNTAIN TUFF OF MIOCENE AGE

PAINTBRUSH TUFF OF MIOCENE AGE

NORMAL FAULT--Dashed where known or inferred; dotted where concealed; bar and ball on downthrown side

STRIKE-SLIP FAULT--Dashed where known or inferred; dotted where concealed; arrows show direction of movement; queried where direction of movement is speculative

GEOLOGIC CONTACT

USW H-1 BOREHOLE SITE AND DESIGNATION REFERRED TO IN THIS REPORT

LINE OF HYDROGEOLOGIC SECTION IN FIGURE 3--From detailed geologic map of Scott and Bonk (1984); position is approximate and features transected by the line of section on this generalized map do not necessarily correspond precisely to those on the detailed map or on the section

BOUNDARY OF CENTRAL BLOCK

Yucca Mountain is in the Great Basin physiographic province. The maximum altitude of the central block is 1,509 m. Along the highest ridge within the central block (Yucca Crest, fig. 2), altitudes generally are between 1,465 and 1,475 m. The crest is about 460 m above Jackass Flats to the east, and about 180 m above Solitario Canyon to the west. Topography of the mountain is rugged, as illustrated by the photograph inside the front cover. The mountain consists of a series of north-trending fault-block ridges unerlain by volcanic rocks (fig. 2) that generally have an eastward tilt of 5° to 10° (Scott and Bonk, 1984). Washes, generally underlain by alluvium, dissect the mountain. The major washes in the northeastern part of the mountain are approximately parallel to a northwest-trending strike-slip fault system and drain southeastward to Fortymile Wash (figs. 1 and 2). The upstream reaches of most of the washes are parallel to the dips of the uppermost strata of the mountain.

The climate of the Yucca Mountain area is arid. Only recently have measurements of precipitation been made at Yucca Mountain itself. Average annual precipitation is estimated to be about 150 mm/yr, based on information presented by Quiring (1983). Nearly three-fourths of the annual precipitation occurs during the cool season (October-April), generally as rainfall resulting from frontal systems moving through the region, and occasionally as snowfall. The altitude of Yucca Mountain is too low for snow to persist for more than a few days. Warm-season precipitation generally occurs as thunderstorms. No perennial streams exist in the Yucca Mountain area. Surface runoff is infrequent and of short duration, occurring only as a direct result of intense precipitation or rapid snowmelt.

Geologically, Yucca Mountain is within the Basin and Range Province. The mountain is underlain for the most part by a thick sequence of silicic volcanic tuffs of Miocene age (fig. 2). In the unsaturated zone of the central block, three formations occur beneath the alluvium. In descending stratigraphic order, these are: Paintbrush Tuff, tuffaceous beds of Calico Hills, and Crater Flat Tuff. The Rainier Mesa Member of the Timber Mountain Tuff, which overlies the Paintbrush Tuff, also occurs locally in topographic lows near the central block (fig. 2). The Paintbrush Tuff is the only unit exposed in the central block (fig. 2). These formations and their component members are distinguished stratigraphically by their petrographic characteristics.

The physical properties within each formation vary considerably, which is largely due to variations in the degree of welding of the tuffs. The physical-property boundaries do not correspond to rock-stratigraphic boundaries in most cases. Because the physical properties largely control the characteristics of water occurrence and flow in the unsaturated zone, the rocks have been grouped into hydrogeologic units, based principally on the degree of welding. Beneath the alluvium, five hydrogeologic units have been identified: Tiva Canyon welded unit, Paintbrush nonwelded unit, Topopah Spring welded unit, Calico Hills nonwelded unit, and Crater Flat unit. The characteristics of these units and their relationships to rock stratigraphy are discussed in the section, "Hydrogeologic Units."

In detail, the structural geology of the Yucca Mountain area is very complex, as reflected in the geologic map (fig. 2) and the hydrogeologic sections (fig. 3). The volcanic plateau of Yucca Mountain is broken into structural blocks bounded by major north-striking and west-dipping normal faults with as much as 100 m of vertical separation (Scott and others, 1983). Northwest-striking strike-slip faults with minor horizontal separation form a second type of faulting. Two dominant sets of fractures occur on Yucca Mountain; one set strikes north-northwest, and the other strikes north-northeast. Both fracture sets have steep to vertical dips. Fracture densities are substantially greater in welded tuffs than in nonwelded tuffs (Scott and others, 1983).

The central structural block (fig. 2) is approximately triangular-shaped. The structural geology of this block is less complex than in the surrounding area, although one extensive nearly vertical normal fault has been mapped in the block (Ghost Dance fault, fig. 2 and fig. 3, Section A-A'). The central block is bounded by a normal fault on the west (Solitario Canyon fault), by zones of normal faults on the east and southeast, and by a strike-slip shear zone underlying Drill Hole Wash on the northeast (figs. 2 and 3).

A very thick unsaturated zone occurs beneath Yucca Mountain. The water table ranges in altitude from about 730 to about 780 m (Robison, 1984). This depth range, combined with the rugged topography of the mountain, gives a range of unsaturated-zone thickness of about 500 to 750 m.

Infiltration of water at Yucca Mountain probably occurs either directly into fractures within bedrock exposures or from surface runoff seeping into alluvium beneath the channels of washes. The amount of water that is not evapotranspired and that percolates downward and laterally in the unsaturated zone probably is very small, because of the minor amount of precipitation and the rapid evapotranspiration rates.

## HYDROGEOLOGIC UNITS

Rocks in the unsaturated zone beneath Yucca Mountain are grouped in this report into informal hydrogeologic units, based on their physical properties. The relationship of these units to rock-stratigraphic units and a summary of some of their properties are shown in table 1. The classification generally is the same as that described by Scott and others (1983) and as that used informally within the NNWSI project. Hydrogeologic units consisting of vitrophyres and moderately to densely welded devitrified tuffs alternate with hydrogeologic units consisting of nonwelded to partially welded tuffs and bedded tuffs. The Topopah Spring welded unit generally is the thickest unit in the section and is the one under consideration by the U.S. Department of Energy as the potential host rock for a repository. Fracture density and fracture permeability are greater in the welded units than in the nonwelded units. The welding process generally results in small matrix porosity and small pore sizes; thus, matrix permeability is less in the welded units than in the nonwelded units.

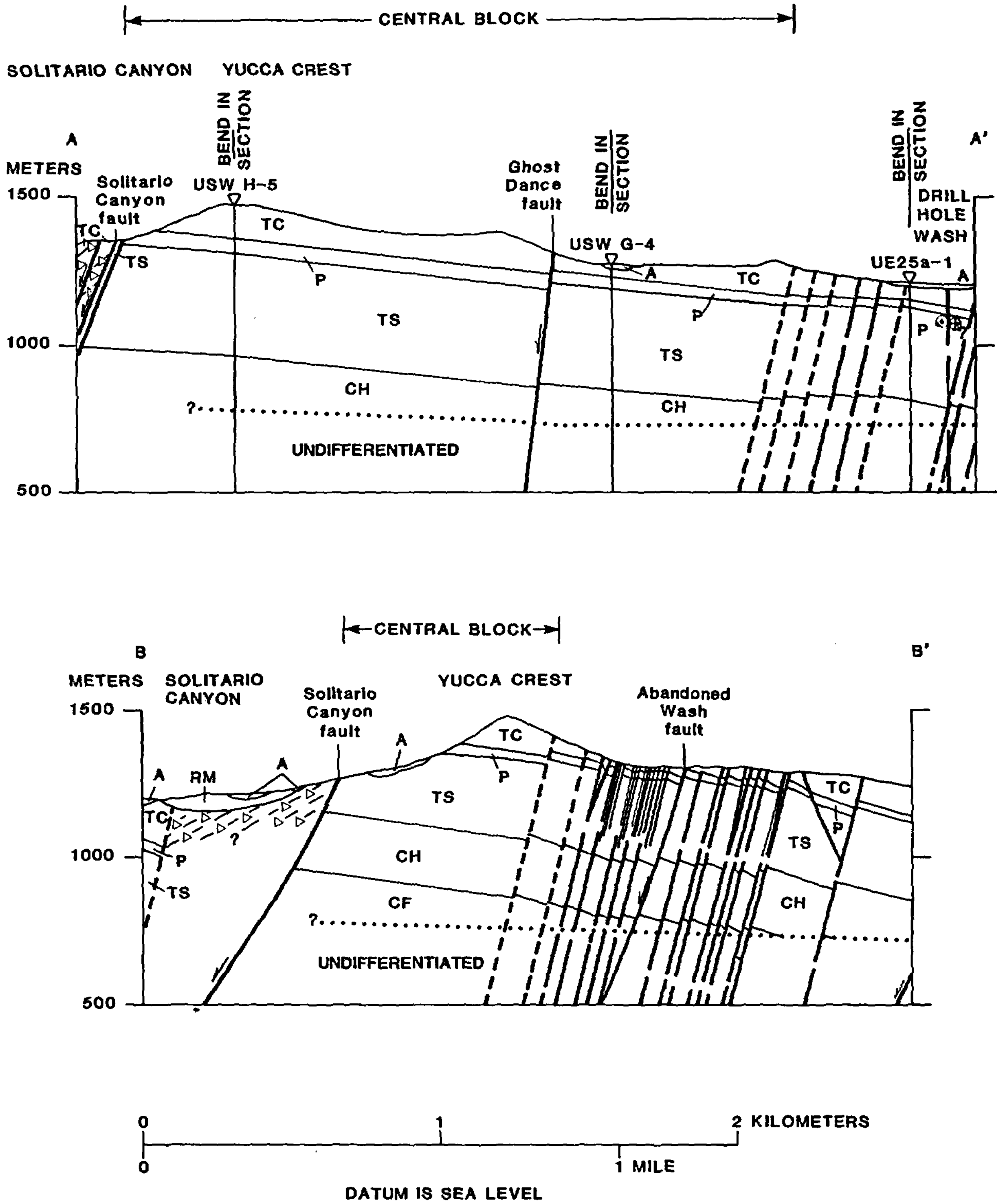



Figure 3.--Hydrogeologic sections across Yucca Mountain (modified from Scott and Bonk, 1984).

## EXPLANATION

| Symbol | Description | Age |
|---|---|---|
| A | ALLUVIUM AND COLLUVIUM | QUATERNARY AND TERTIARY |
| RM | RAINIER MESA MEMBER OF TIMBER MOUNTAIN TUFF | TERTIARY (MIOCENE) |
| TC | TIVA CANYON WELDED UNIT | |
| P | PAINTBRUSH NONWELDED UNIT | |
| TS | TOPOPAH SPRING WELDED UNIT | |
| CH | CALICO HILLS NONWELDED UNIT | |
| CF | CRATER FLAT UNIT | |

CONTACT

FAULT WITH MAJOR DIP-SLIP DISPLACEMENT--Position known or concealed at land surface; arrows show direction of relative displacement. Average dip of fault planes at surface is 70° and subsurface drill-hole data indicate a decrease to about 60° below a depth of 1 kilometer. Some faults cut older A but do not cut younger Quaternary deposits shown by partial penetration of fault through A to surface

FAULT WITH MINOR DIP-SLIP DISPLACEMENT--Position known or concealed at land surface; No evidence to indicate a decrease in dip with depth; average dip is 76° at land surface and in drill holes

UNMAPPED AND INFERRED FAULTS OF SMALL DISPLACEMENT REQUIRED BY GEOMETRIC CONSTRAINTS IN LAND-SURFACE EXPOSURES AND DRILL HOLES

STRIKE-SLIP FAULTS--

⊕ Indicates displacement toward the reader;

⊙ Indicates displacement away from the reader;

? Queried where relative displacement is doubtful

? ZONE OF WEST-DIPPING STRATA CONTAINING ABUNDANT BRECCIA AND FAULTS TOO COMPLEX TO DRAW INDIVIDUALLY--Stratigraphic units shown only near surface

USW H-5 BOREHOLE USED FOR CONTROL

?...... WATER TABLE--Queried where extended beyond drill-hole data control; measured prior to December 1983

Table 1.--*Summary of hydrologic*

[fractures/m³, fractures per cubic meter; Std. dev., standard
NP, nonwelded to partially welded;

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

[1]Thicknesses from geologic sections of Scott and Bonk (1984).
[2]Scott and others (1983).
[3]Inferred from physical properties.
[4]Sources: Anderson (1981); R. Peters (Sandia National Laboratories, written commun., 1983); Rush and others (1983); Thordarson (1983); Weeks and Wilson (1984).
[5] [6]Single values of relative permeability from Weeks and Wilson (1984) (5) and from G. Gee (Pacific Northwest Laboratories, written commun., 1983) (6) were applied to the geometric means of saturated hydraulic conductivity.

*properties of hydrogeologic units*

deviation; m/d, meters per day; MD, moderately to densely welded; (V), vitric; (D), devitrified; B, bedded]

| Matrix properties (from analyses of core)[4] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Porosity (percent) | | | Saturation (percent) | | | Water content by weight (percent) | | | Hydraulic conductivity (m/d) | | |
| | | | | | | | | | Saturated | | Effective |
| Number of samples | Mean | Std. dev. | Number of samples | Mean | Std. dev. | Number of samples | Mean | Std. dev. | No. of samples | Geometric mean | Estimate[5,6] |
| -- | -- | ---- | -- | -- | -- | -- | ---- | ---- | -- | ------ | --------- |
| 12 | 12 | 7.6 | 6 | 67 | 23 | 6 | 5.7 | 6.5 | 11 | $2x10^{-6}$ | -------- |
| 14 | 46 | 11 | 9 | 61 | 15 | 9 | 19 | 11 | 5 | $9x10^{-3}$ | [5]$3x10^{-4}$ |
| 56 | 14 | 5.5 | 44 | 65 | 19 | 29 | 5.5 | 2.8 | 27 | $3x10^{-6}$ | [5]$1.6x10^{-7}$ |
| (V) 5 | (V) 37 | (V) 8 | (V) 1 | (V) 90 | (V) -- | (V) -- | (V) ---- | (V) ---- | (V) 4 | (V) $4x10^{-3}$ | (V) [6]$1.5x10^{-4}$ |
| (D) 34 | (D) 31 | (D) 7.5 | (D) 25 | (D) 91 | (D) 6 | (D) 26 | (D) 16 | (D) 5 | (D) 22 | (D) $8x10^{-6}$ | (D) [6]$1.6x10^{-8}$ |
| 42 | 23 | 6.4 | 39 | 88 | 75 | -- | ---- | ---- | 19 | $5x10^{-5}$ | -------- |

Specific data on matrix porosity, saturation, water content, and hydraulic conductivity also are shown in table 1. These data are based on results of laboratory analyses of cores and are combined from a variety of sources. The following discussion of individual units is based in part on the information contained in table 1; geologic information is based mostly on descriptions of Robert B. Scott (U.S. Geological Survey, written commun., 1984).

## Alluvium

Unconsolidated alluvium underlies the washes that dissect Yucca Mountain and forms the surficial deposit in broad inter-ridge areas and flats near Yucca Mountain. Thickness, lithology, sorting, and permeability of the alluvium are quite variable; particles range in size from clay to boulders, and in places the unit is moderately indurated by caliche. However, the permeability of alluvium generally is substantial compared to the tuff units.

## Tiva Canyon Welded Unit

The Tiva Canyon welded unit is the densely to moderately welded part of the Tiva Canyon Member of the Paintbrush Tuff. This unit is the uppermost stratigraphic layer that underlies much of Yucca Mountain; it dips 5° to 10° eastward within the central block, resulting in a relatively planar eastward-sloping, dissected land surface. The unit is absent in some washes and is about 150 m thick beneath Yucca Crest. This unit has a fracture density of 10 to 20 fractures/$m^3$ and small matrix permeability (table 1).

## Paintbrush Nonwelded Unit

The Paintbrush nonwelded unit consists of the nonwelded and partially welded base of the Tiva Canyon Member, the Yucca Mountain Member, the Pah Canyon Member, the nonwelded and partially welded upper part of the Topopah Spring Member, and associated bedded tuffs. All are part of the Paintbrush Tuff. Within the central block, the unit consists of thin, nonwelded ash-flow sheets and bedded tuffs that thin to the southeast from a maximum thickness of 100 m to a minimum thickness of about 20 m. The unit dips to the east at 5° to 25°; the dip at any location depends on the tilt of the faulted block at that site. In the central block, the dip rarely exceeds 10° (Scott and Bonk, 1984). In the vicinity of the central block, this unit crops out only in a narrow band along the steep west-facing scarp along Solitario Canyon (Scott and Bonk, 1984).

Tuffs of this unit are vitric, nonwelded, very porous, slightly indurated, and, in part, bedded. The unit has a fracture density of 1 fracture/$m^3$. Saturated hydraulic conductivities of five core samples of the matrix have a geometric mean of about $9.0 \times 10^{-3}$ m/d (table 1). For two samples, the hydraulic conductivity is an order of magnitude larger than the mean; for one other sample, the hydraulic conductivity is three orders of magnitude smaller than the mean. Air-permeability tests were conducted at test well UE-25a#4, using barometric-pressure changes as a driving force.

Results indicate an equivalent hydraulic conductivity of $4.2 \times 10^{-2}$ m/d (E. P. Weeks, U.S. Geological Survey, written commun., 1984). This hydraulic conductivity is the bulk hydraulic conductivity for the non-wetting phase (air), and indicates that the bulk hydraulic conductivity of this unit is at least one order of magnitude greater than the average represented by the core samples. If the core sample with very small permeability were eliminated from the analysis, the other four samples would have a geometric mean within the same order of magnitude as the bulk hydraulic conductivity of this unit. This similarity could indicate that the fracture permeability is insignificant in this unit.

Porosities average about 46 percent, but some porosities are as much as 60 percent. The rocks of this unit are moderately saturated, with an average value of about 61 percent. However, water contents are relatively large; the mean volumetric water content is about 27 percent, and the mean water content by weight is about 19 percent. The maximum values reported are: saturation, 80 percent; volumetric water content, 42 percent; and water content by weight, 36 percent.

## Topopah Spring Welded Unit

The Topopah Spring welded unit consists of a very thin upper vitrophyre, a thick central zone consisting of several densely welded devitrified ash-flow sheets, and a thin lower vitrophyre of the Topopah Spring Member of the Paintbrush Tuff. At Yucca Mountain, the unit: (1) Is densely to moderately welded and devitrified throughout its central part; (2) contains several lithophysal cavity zones that generally are continuous but vary appreciably in thickness and stratigraphic position; and (3) is intensely fractured (table 1). The unit crops out along the scarp west of Yucca Crest and in some other fault blocks east of the mountain (Scott and Bonk, 1984).

The Topopah Spring Member is the thickest and most extensive ash-flow tuff of the Paintbrush Tuff. The central and lower densely welded, devitrified parts of the Topopah Spring welded unit are the candidate host rock for a repository. This part of the unit contains distinctive subunits that have abundant lithophysal gas cavities within the central block. The saturated hydraulic conductivity of the matrix of this unit generally is small and has a mean of about $3.0 \times 10^{-6}$ m/d. However, for two samples, the hydraulic conductivity is two orders of magnitude greater. No major variations are known in the lateral distribution of the saturated hydraulic conductivities of the matrix in this unit.

Because of the densely fractured nature of this unit, bulk hydraulic conductivity is substantially greater than matrix hydraulic conductivity. Saturated horizontal hydraulic conductivity of the rock mass is about 1.0 m/d for a 120-m interval of the Topopah Spring welded unit that was packed off and tested at well J-13, about 6 km east of Yucca Mountain (Thordarson, 1983). Vertical hydraulic conductivity of the upper 30 m of the Topopah Spring welded unit at borehole UE-25a#4 ranges from 0.6 to 10 m/d (E. P. Weeks, U.S. Geological Survey, written commun., 1984). The values from UE-25a#4 were obtained by converting air permeability, determined from air-permeability tests using barometric fluctuation as a driving force, to equivalent vertical hydraulic conductivity, assuming an equivalent porous medium.

Permeability values determined by flow of air through fractured rocks could be much greater than the "intrinsic" permeability because of the slip phenomenon (Klinkenberg effect) and lubrication effect (Montazer, 1982). In addition, borehole UE-25a#4 is in Drill Hole Wash, along which a permeable fault zone probably occurs (Scott and Bonk, 1984). Therefore, the bulk hydraulic conductivities of the relatively unfaulted central block probably are smaller than the equivalent hydraulic conductivities reported by E. P. Weeks (U.S. Geological Survey, written commun., 1984). Nonetheless, the values of equivalent hydraulic conductivity reported by E. P. Weeks (U.S. Geological Survey, written commun., 1984) probably are within an order of magnitude of the likely hydraulic conductivities of the upper part of this unit. Because of the marked contrast between the matrix and the bulk hydraulic conductivities in this unit, values of the bulk hydraulic conductivity from well J-13 and borehole UE-25a#4 probably represent the hydraulic conductivity of the fractures in this unit. The large bulk hydraulic conductivity of this unit probably promotes rapid drainage of water.

From an analysis of the same test results, E. P. Weeks (U.S. Geological Survey, written commun., 1984) also obtained values for drained (air-filled) porosities that ranged from 2 to 4 percent. The average matrix porosity of the unit is about 14 percent, of which about 5 percent is drained (table 1). This comparison could mean that the fracture porosity in the upper part of this unit probably is much less than 1 percent. Analyses that treat the unit as a double-porosity media (E. P. Weeks, U.S. Geological Survey, written commun., 1984) and in-situ test results are expected to provide better estimates of the fracture porosity in this unit.

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

## Calico Hills Nonwelded Unit

The Calico Hills nonwelded unit includes the following components, in descending order:

1. A nonwelded to partially welded vitric layer, locally zeolitic, that is the lowermost part of the Topopah Spring Member of the Paintbrush Tuff.
2. Tuffaceous beds of Calico Hills.
3. The Prow Pass Member of the Crater Flat Tuff, which is nonwelded to partially welded where it occurs in the unsaturated zone beneath the central block.
4. The nonwelded to partially welded upper part of the Bullfrog Member of the Crater Flat Tuff, where it is above the water table.

The unsaturated thickness of the Calico Hills nonwelded unit is determined in part by the position of the water table. At some distance east of the central block, the thickness is zero, because the water table occurs within the overlying Topopah Spring welded unit. In the southeast, this situation occurs east of Bow Ridge fault (fig. 2). Beneath the northern one-half of the central block, the water table is within the Calico Hills nonwelded unit and forms the base of the unit. Thickness in this area ranges from about 140 to about 250 m. Beneath the southern one-half of the block, the water table is within the underlying Crater Flat unit, and the full thickness of the Calico Hills nonwelded unit is unsaturated. Thickness in this area ranges from about 200 to about 250 m.

Both vitric and devitrified facies occur within the Calico Hills nonwelded unit. As described below, the permeability of the vitric facies is substantially greater than that of the devitrified facies. Thus, the distribution of these two facies in the Calico Hills nonwelded unit could significantly affect the flow of water below the potential repository host rock. Beneath the southern two-thirds of the central block, the Calico Hills nonwelded unit contains some vitric facies (fig. 4). However, even in this area, the lower part of the unit is devitrified and altered, whereas the upper part is vitric. Thus, the entire central block is underlain by a devitrified and altered layer of small permeability.

Alteration products in the devitrified facies include zeolites (most abundant), clay, and calcite (rare). Because this facies commonly is pervasively zeolitic, this facies of the unit is hereafter referred to as the zeolitic facies. Zeolitization probably is the result of a water table that formerly occurred higher in the section, according to Scott and others (1983). Thickness of the zeolitic facies generally increases from the southwest to northeast beneath Yucca Mountain. Beneath the northern and northeastern parts of the central block, the entire unit is devitrified and altered (fig. 4).

Both the vitric and zeolitic facies of the Calico Hills nonwelded unit are very porous, with a mean porosity of about 37 percent for the vitric facies, and 31 percent for the zeolitic facies (table 1). Although only a small difference appears to exist in porosities between the two facies, data have been reported from only five samples from vitric facies; thus, the data set may not be representative.

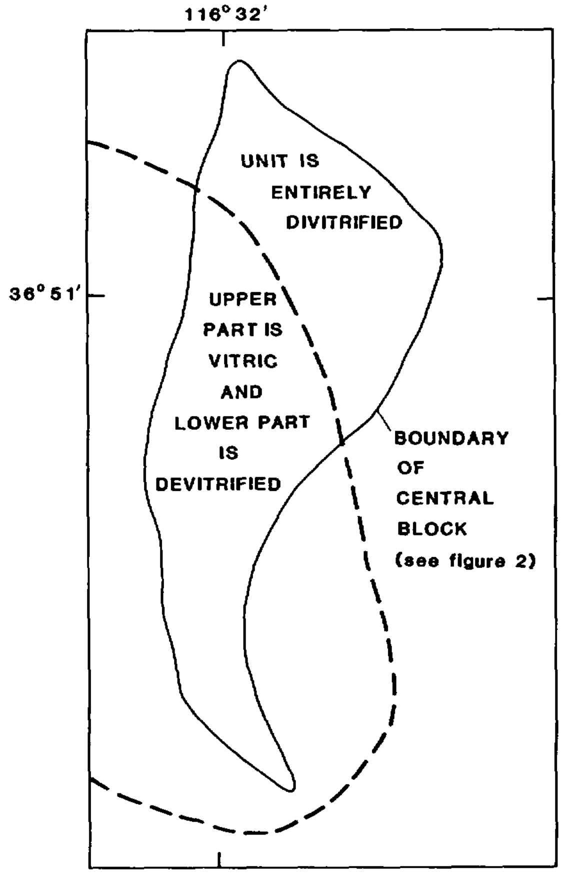



Figure 4.--Approximate distribution of devitrified and vitric facies in the Calico Hills nonwelded unit (modified from R. W. Spengler, U.S. Geological Survey, written commun., 1984).

The distribution of values of effective porosity of the Calico Hills nonwelded unit needs to be known to evaluate velocity and travel time of water through the unit. Preliminary laboratory porosimetry studies from a core sample of the vitric facies show that only a small percentage (about 5 percent) of the pore space is large enough to contribute significantly to flow under saturated conditions (G. W. Gee, Battelle Pacific Northwest Laboratories, written commun., 1984). If these large pores were the only ones contributing to flow, effective porosity would be 1.6 percent ($0.05 \times 0.31 = 0.016$). However, under unsaturated conditions, these large pores probably are drained and do not contribute to water flow. About 75 percent of the pores have a very narrow range in size, but these probably are the principal pores involved in unsaturated flow. The remaining 20 percent of pores probably are too small to contribute to flow. Under these conditions, effective porosity of the vitric facies of the Calico Hills nonwelded unit is about 23 percent ($0.75 \times 0.31 = 0.232$). Thus, a value of 1.6 percent may be assumed as an absolute minimum for unsaturated-zone effective porosity for this unit; 23 percent is a more probable value. As is discussed in the section, "Concepts of unsaturated flow," the effectiveness of fractures in transmitting water through this unit probably is insignificant under the ambient conditions of saturation.

Saturations in this unit generally are greater than 85 percent, with a mean value for the zeolitic facies of about 91 percent and a standard deviation of about 6 percent (table 1). Only one value (90 percent) is available from the vitric facies. A large percentage of the pores has a small diameter and only a small percentage is drained. Because of the substantial porosity and saturation, the zeolitic facies also has a large water content (16 percent by weight) (table 1). However, these data are from cores that were obtained by wet-drilling techniques. Therefore, an artificially large saturation value may have resulted from imbibition of water into the small pores during drilling operations. Currently, no sample that has been dry-cored is available from this unit; therefore, the accuracy of the data and the potential artificial exaggeration of the saturation values cannot be estimated accurately. A comparison of data available from the drill cuttings of the Paintbrush nonwelded unit in borehole USW UZ-1 (obtained using a dry-drilling method) with samples collected from other boreholes (using wet-drilling methods) indicates no significant differences in the moisture contents between the samples. This observation provides some confidence in the validity of the data for the Calico Hills nonwelded unit.

A significant difference exists in values of vertical hydraulic conductivity of the matrix, measured on cores, between the vitric and zeolitic facies of the Calico Hills nonwelded unit. The mean vertical hydraulic conductivity of the matrix of the vitric facies is $4.0 \times 10^{-3}$ m/d, assuming log-normal distribution. The geometric mean of the vertical hydraulic conductivity of the matrix of the zeolitic facies is about $8.0 \times 10^{-6}$ m/d. The marked contrast in vertical hydraulic conductivity of the two facies probably is the result of extensive argillization in the zeolitic facies, which tends to decrease permeability. Values of horizontal hydraulic conductivity are available for only three samples from the zeolitic facies; these have a geometric mean of about $1.0 \times 10^{-4}$ m/d.

## Crater Flat Unit

In about the southern one-half of the central block, the lowermost unit in the unsaturated zone is the Crater Flat unit. This unit consists of the unsaturated welded and underlying nonwelded parts of the Bullfrog Member of the Crater Flat Tuff (table 1). No differentiation is made between the welded and nonwelded components of the Crater Flat unit. The components of the unit are undifferentiated because of the limited extent of the unit in the unsaturated zone beneath the central block, and, therefore, its probable limited effect on the unsaturated flow system. Beneath the central block, thickness of the Crater Flat unit ranges from 0 to about 160 m. Little is known about the unsaturated hydrologic properties of the unit, but it is assumed that the properties are similar to those of the nonwelded and welded counterparts higher in the section.

## Structural Features

The central block of Yucca Mountain is bounded on its west side by a major north-striking normal fault (Solitario Canyon fault, figs. 2 and 3) with greater than 100 m of offset. West of this fault is a chaotic, brecciated and faulted west-dipping zone representing drag on the fault (Scott, 1984).

Although the normal fault has significant dip-slip offset, minor superimposed oblique slip is indicated by oblique slickensides. A zone of imbricate normal faults forms the eastern boundary of the central block (figs. 2 and 3). These faults are west dipping and have vertical offsets of about 2 to 5 m. Northwest-striking strike-slip faults also occur in the area, such as the one forming the northern boundary of the central block, beneath Drill Hole Wash (figs. 2 and 3). These faults probably have less than 200 m of horizontal offset.

These major structural features are not hydrogeologic "units" in the same sense that the stratigraphic units are. However, because the structural features are mappable, have certain measurable hydraulic characteristics, and probably have an effect on flow in the unsaturated zone, they are treated in this report as hydrogeologic units.

Because these major faults and fault zones transect the full thickness of the unsaturated zone, they may be hydrologically significant either as flow barriers or as flow pathways. The unsaturated hydraulic properties of these features have not been measured, but some inferences can be made, based on the physical properties of the welded and nonwelded tuff units, and based on observations of cores. The welded units are relatively brittle. Open faults have been observed in cores even from below the water table (Scott and others, 1983). Fault zones greater than 1.5 m wide and characterized by the presence of breccia have been observed in cores of the Topopah Spring welded unit (Maldonado and Koether, 1983).

Conversely, the nonwelded units generally are more ductile than the welded units and more readily produce a sealing gouge material; thus, they have greater "healing" properties. Fault zones are less common in the Calico Hills nonwelded unit, based on an analysis of cores obtained from a test well and studied by Maldonado and Koether (1983). They also report that some fault zones are characterized by clay gouge. Thus, in general, hydraulic conductivity probably varies greatly along the faults and is greater in welded units than in the nonwelded units.

## CONCEPTS OF UNSATURATED FLOW

The presence of certain hydrogeologic features at Yucca Mountain significantly affects flow in the unsaturated zone at that site. These features include the presence of fractured porous media, layered units with contrasting physical properties, dipping units, and a deep water table resulting in a very thick unsaturated zone. The combination of these features provides a hydrogeologic framework that probably results in certain flow phenomena, namely infiltration into fractured rocks, flow through fractured rocks, retardation of flow by capillary barriers, lateral flow, and vapor flow. Some pertinent aspects of each of these phenomena are discussed below to provide a basis for understanding the specific mechanisms of flow at Yucca Mountain, as described in a later section.

The flow of water downward or laterally through the unsaturated section at Yucca Mountain occurs as infiltration, percolation, and recharge. In this report, "infiltration" is the entry of water into soil or rock below the interface with the atmosphere. "Net infiltration" refers to water that does not remain in shallow storage or is not rapidly returned to the atmosphere via evapotranspiration or shallow lateral flow (interflow) to washes. "Percolation" refers to the flow of water within earth materials, in both the unsaturated and saturated zones. The term "flux" is used to denote the percolation rate. "Recharge" is the entry of water into the saturated zone from the unsaturated zone. In the thick unsaturated zone at Yucca Mountain, the three quantities--infiltration, percolation, and recharge--may have substantially different values.

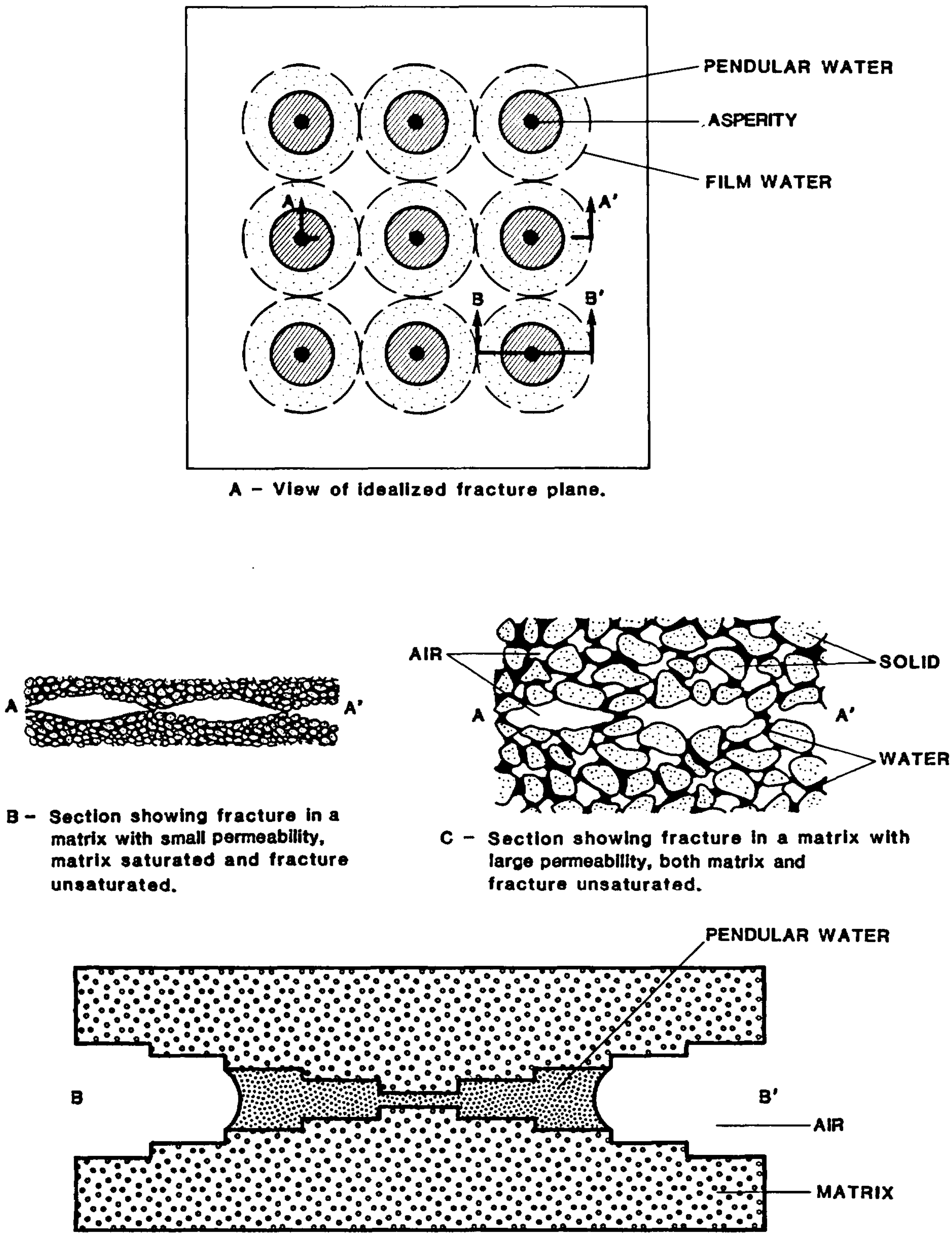
## Flow Through Fractured Rocks

The concept of unsaturated flow through fractured media is a complex subject that has not been studied extensively and remains poorly understood. Nonetheless, an understanding of the conditions under which flow occurs in the matrix and fractures at Yucca Mountain is critical to assessment of the site, because the paths that water takes affects travel times, dissolution rates, transport mechanisms, and potential for sorption of radionuclides.

An understanding of flow in a fractured medium can be developed best by starting with an analysis of flow through a single fracture transecting a porous matrix. Such a system is diagrammatically represented in various ways in figure 5. The plane of the unsaturated fracture can be viewed as containing a series of asperities, or points of contact, surrounded by rings of pendular water (fig. 5A). As described below, the character of flow is determined in large part by the permeability of the matrix, as represented by extreme conditions of small and large permeability (figs. 5B and 5C). The complex natural fracture may be simulated by a discrete model consisting of parallel plates with varying apertures (fig. 5D). Similar cross-sectional configurations would be obtained if the line of section were rotated about the asperity; however, for simplicity of discussion, it is assumed that the cross section in figure 5D remains unchanged along the third dimension.

Theoretical curves relating effective permeability and matric potential (or permeability and saturation) can be useful to illustrate flow characteristics of a fracture and adjoining matrix under varying conditions of matrix permeability. Theoretical drainage curves for two hypothetical cases of a fracture in a matrix with small permeability (as shown in fig. 5B) and a fracture in a matrix with large permeability (as shown in fig. 5C) are shown in figures 6 and 7. These curves were developed using a preliminary general model for flow through unsaturated fractured media. The wetting curves for the matrix (figs. 6 and 7, curves 1a and 1b) are hypothetical and are not based on experimental nor theoretical results.

In the model, flow through a fracture transecting an almost impermeable matrix can occur at any degree of saturation, given a gradient in total water potential. However, when this fracture is bounded by a matrix with small permeability, the significance of fracture flow varies with degree of saturation




A – View of idealized fracture plane.

B – Section showing fracture in a matrix with small permeability, matrix saturated and fracture unsaturated.

C – Section showing fracture in a matrix with large permeability, both matrix and fracture unsaturated.

D – Discrete model.

Figure 5.--Sketches and discrete model of a fracture in a porous matrix.

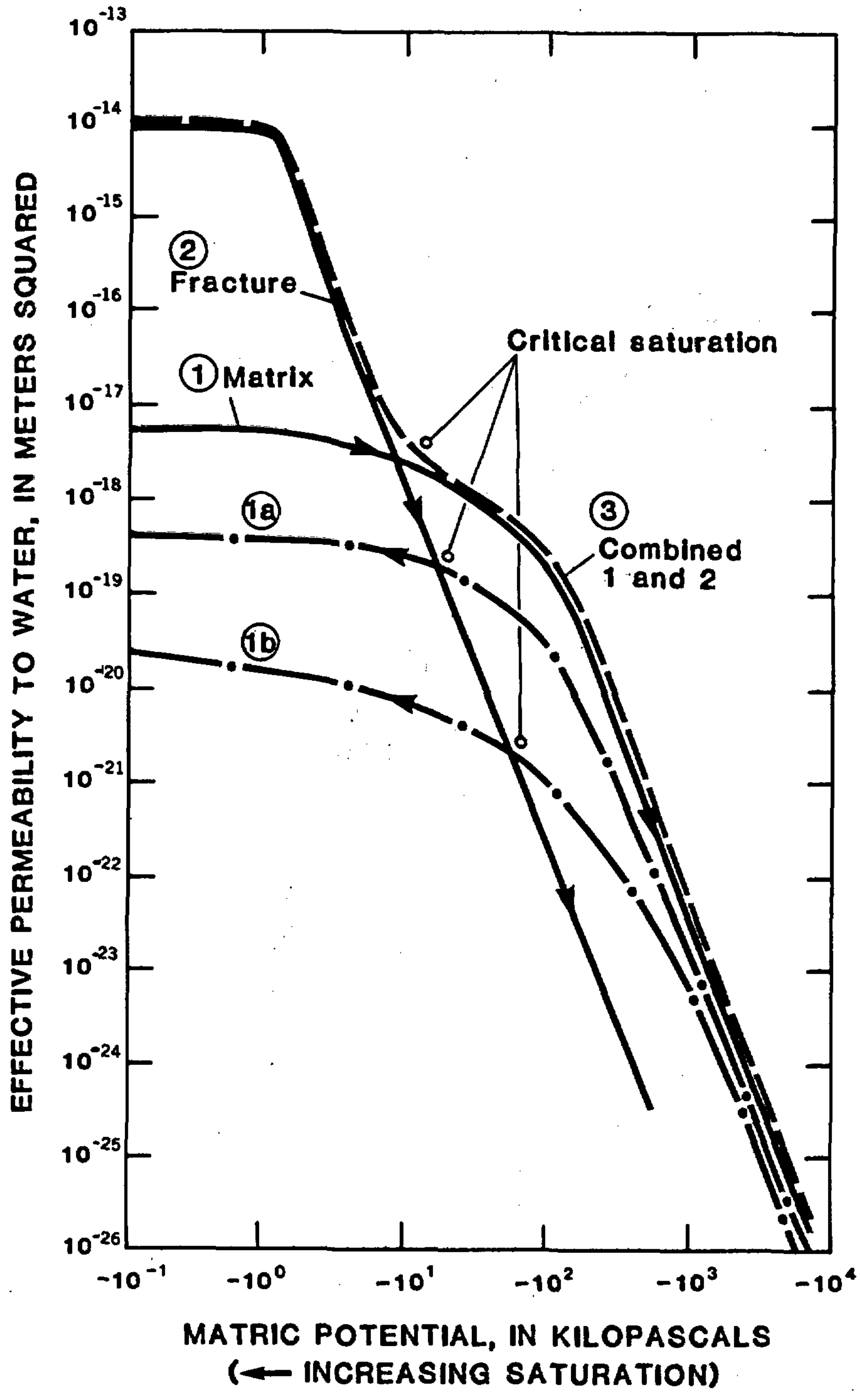



Figure 6.--Hypothetical relationship between effective permeability and matric potential for a double-porosity medium with small matrix permeability. Curves 1a and 1b are wetting curves for the matrix. Downward arrows show drainage curves. Hysteresis in fracture is not shown.

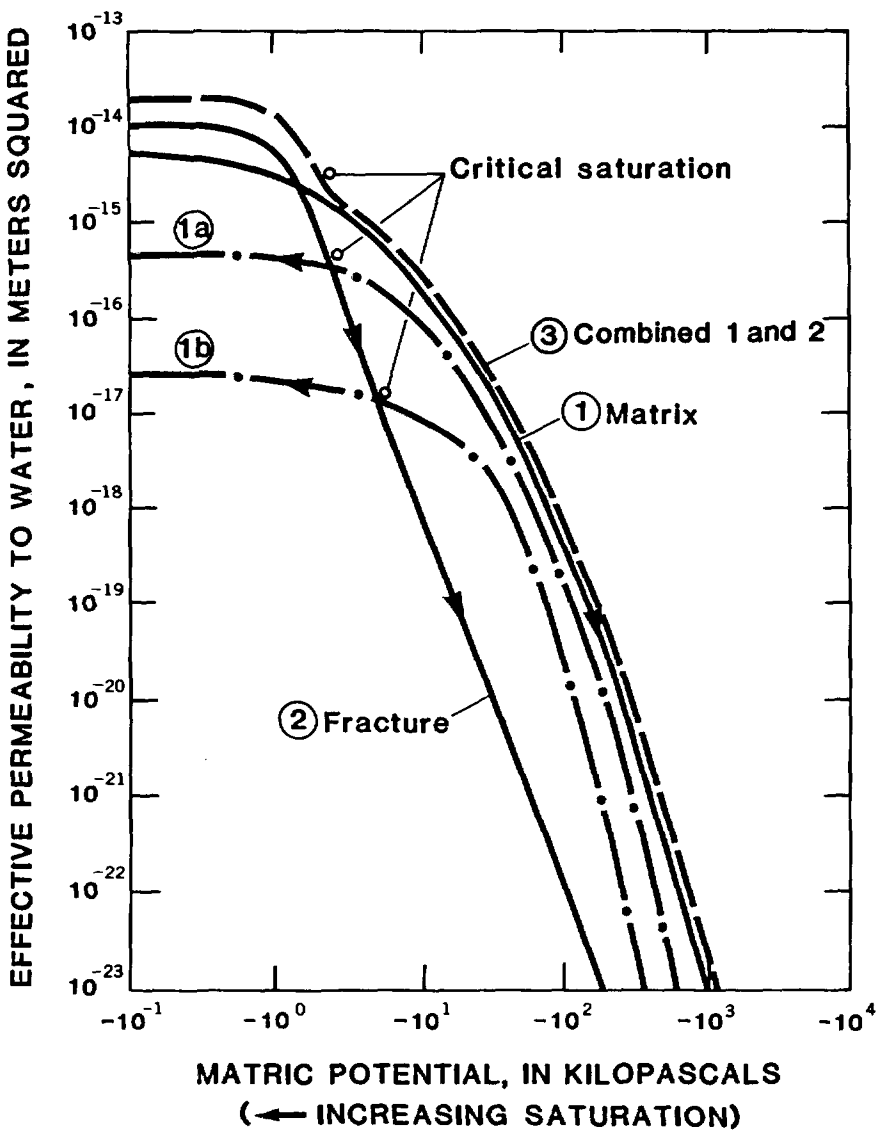



Figure 7.--Hypothetical relationship between effective permeability and matric potential for a double-porosity medium with large matrix permeability. Curves 1a and 1b are wetting curves for the matrix. Downward arrows show drainage curves. Hysteresis in fracture is not shown.

(fig. 6). Considering the drainage curves in this figure (curves 1, 2, and 3), at a small degree of saturation, flow through the fracture is insignificant compared with flow through the matrix, even though the curves are similar for the two components at small degrees of saturation (fig. 6, curves 1 and 2). This difference in flow occurs because the contribution of the fracture to flow is about the same as that of one of the tubular paths in the porous matrix. The quantity of flow in the fracture is insignificant compared to the total flow; therefore, the existence of the fracture does not significantly affect the flow. As saturation increases (assuming that it follows the drainage curve 3) to more than a certain degree (the critical saturation, fig. 6), permeability of the fracture increases much more rapidly than that of the matrix. At complete saturation, the difference in permeability is more than three orders of magnitude. The curve for the combined fracture and matrix (fig. 6, curve 3) closely follows the curve for the matrix until critical saturation is attained, and then closely follows the curve for the fracture after critical saturation is attained.

In figure 7, the theoretical curves are shown for the matrix (curve 1), fracture (curve 2), and combined (curve 3), for the case where the matrix has large permeability. In this case, the point at which fracture flow begins to dominate (the critical saturation) does not occur until the medium is almost completely saturated. The difference in permeability of the fracture and matrix at complete saturation is much less than in the case of the matrix with small permeability.

In the foregoing discussion, it was assumed that the drainage curve accurately represents both wetting and drying conditions. However, the use of moisture-characteristic curves in interpreting conditions under which fracture flow occurs is complicated by the phenomenon of hysteresis in the moisture-content dependent characteristics. Hysteresis occurs in both matrix and, to a lesser extent, fractures. The consequence of this hysteretic phenomenon is that, under transient wetting conditions, fracture flow dominates much earlier than might otherwise be expected.

Matrix hysteresis is the result of air entrapment that occurs in the medium-sized pores during the wetting phase. Because of this entrapment, less water is required to attain a given capillary tension during a wetting phase than during a draining phase. Therefore, the saturation associated with a given tension is less during wetting than during drainage from a fully saturated condition. Furthermore, permeability at a given tension is less during a wetting phase than during a draining phase, because air entrapment during wetting results in a smaller area being available for water flow during this phase. The magnitude of this hysteresis effect depends in part on the rate at which water is introduced into the medium: the effect is greater during rapid rates of wetting, because of the greater percentage of entrapped air that results.

A secondary hysteresis effect occurs when a block of porous material is bounded by fractures in which water is flowing. A very narrow zone of almost complete saturation forms on the faces of the porous block. When this zone surrounds the block, the pressure of the entrapped air increases and results in a resistance to further intrusion of water into the block interior. This secondary effect has been shown to be a significant factor in water flow in unsaturated porous media (Morel-Seytoux, 1969).

The hysteresis phenomonen is illustrated by figures 6 and 7. Curves 1a and 1b are theoretical curves under wetting conditions for a matrix with the same permeability as represented by curve 1, which is for draining conditions. The difference between curves 1a and 1b is the result of differences in the rate of wetting (curve 1a is for slower wetting). The curves show that the dominance of fracture flow starts at a lesser degree of saturation under wetting than under draining conditions, and that the effect is more prominent under rapid wetting conditions. Furthermore, the difference in permeability between matrix and fracture at complete saturation is greater under wetting conditions than under draining conditions. This hysteretic effect is even more significant for a matrix with small permeability.

The moisture capacity of a medium is the rate of change in moisture content with respect to change in pressure head; moisture capacity is dependent on the degree of saturation. In general, if the moisture capacity of the matrix is large compared to that of the fracture, relatively large transient fluxes at the boundary are required to start significant fracture flow. Conversely, if moisture capacity of the matrix is relatively small compared to that of the fracture, a small quantity of water added to the boundary may be sufficient to result in dominance of fracture flow. This relationship is intensified by hysteretic effects, because hysteresis is much more significant in matrices with small moisture capacity. In such rocks, during wetting cycles, only a relatively small quantity of water is required to decrease the tensions sufficiently to divert the flow into the fractures. Because of hysteresis, this quantity is less than that required to attain matrix saturation. In rocks with small matrix moisture capacity and hydraulic conductivity, complete saturation is almost never attained under normal wetting cycles imposed during infiltration.

In modeling a double-porosity medium numerically, a desirable and useful approach is to treat the system as an equivalent porous medium. However, unless the model incorporates the phenomenon of hysteresis, actual fracture flow under transient wetting conditions would occur much earlier than would be predicted by the model. Thus, any model that uses the analogy of an equivalent porous medium needs to include the relationships among all the factors controlling flow to predict flow accurately.

## Capillary Barriers

Capillary barriers occur in unsaturated zones at the contact where a unit containing relatively fine pores or fractures overlies a unit containing relatively coarse pores or fractures. Such capillary barriers probably exist at Yucca Mountain and could serve to retard the rate of percolation.

The principle of a capillary barrier is illustrated by two tubes of different diameters that are in contact with each other (fig. 8A). Theoretically,

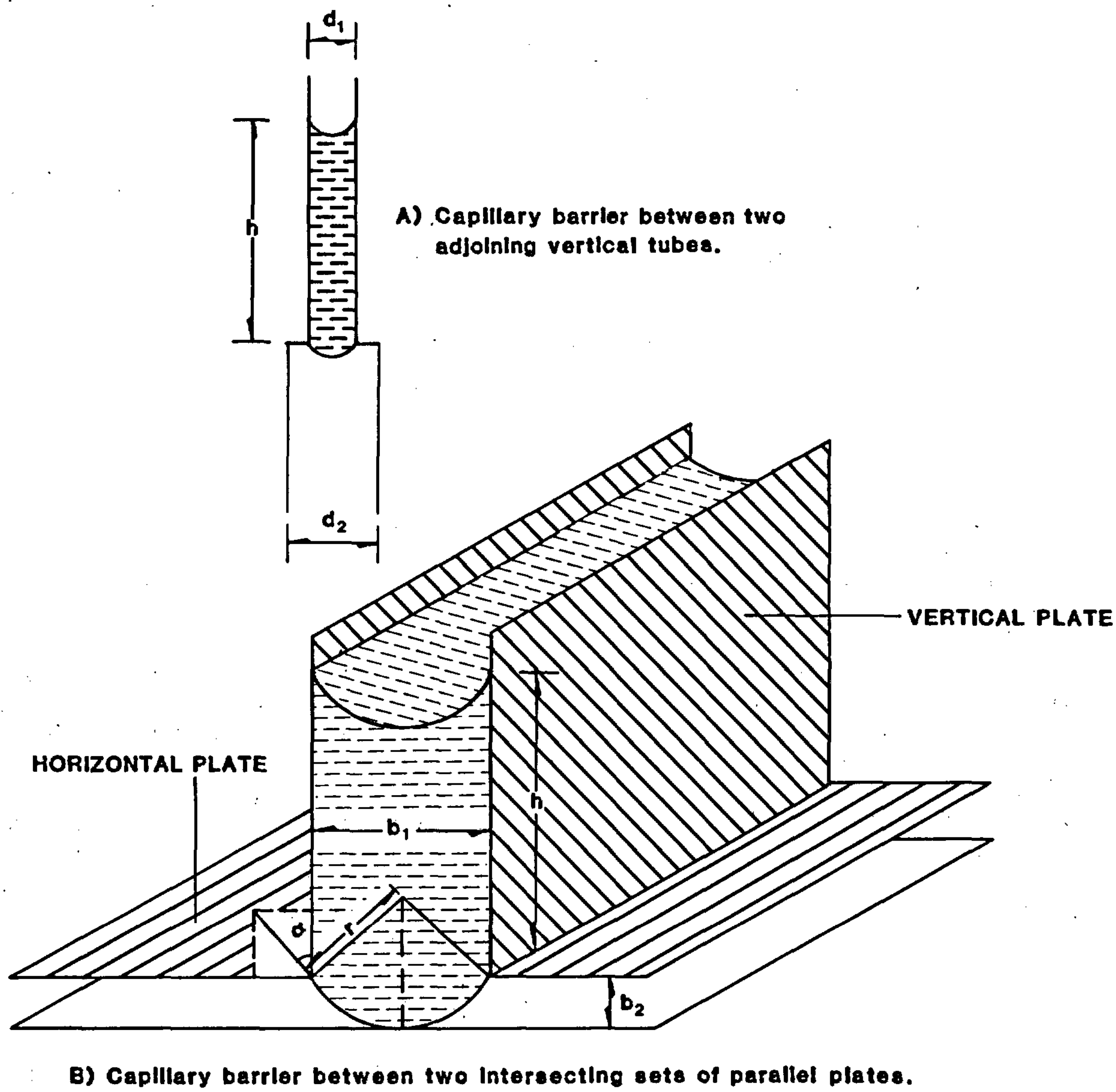



Figure 8.--Sketches illustrating the principle of a capillary barrier (h, capillary rise; α, contact angle between water and the plate wall: b, width of the plate; d, diameter of the tube; r, radius of curvature).

water cannot flow from the smaller tube into the larger tube until the height of the water column exceeds the critical height, which is equivalent to the difference in the capillary rise of the tubes.

Capillary rise in a single tube is given by (Marshal and Holmes, 1979):

$$h = \frac{2\sigma \text{ Cos } \alpha}{\gamma d_1} ; \tag{1}$$

where h is the capillary rise (L);
$\sigma$ is the interfacial tension between water and the tube wall ($FL^{-1}$);
$\alpha$ is the contact angle between water and the tube;
$\gamma$ is the unit weight of water ($FL^{-3}$); and
d is the diameter of the tube (L).

Therefore, the critical height in the two tubes is:

$$h_c = h_1 - h_2 = \frac{2\sigma}{\gamma} \left( \frac{\cos\alpha_1}{d_1} - \frac{\cos\alpha_2}{d_2} \right) \tag{2}$$

where $h_c$ is the critical height (L);
subscript 1 refers to the smaller tube; and
subscript 2 refers to the larger tube.
In equation 2, the critical height increases as $d_2$ increases relative to $d_1$.

Another simple example of a capillary barrier is when a vertical fracture intersects a horizontal fracture, simplified in figure 8B by two intersecting pairs of parallel plates. In this case, two limiting conditions exist that are controlled by the relative sizes of the apertures, $b_1$ and $b_2$. The curvature of the lower meniscus in the vertical fracture is convex downward. The radius of curvature of the meniscus, r, decreases with the height of water column. The contact angle, $\alpha$, between the water and the plates is assumed to be zero. Therefore, the minimum radius of curvature that can be attained by the lower meniscus is one-half the width of the vertical fracture, or $b_1/2$ (Montazer, 1982, equation 3.2.17). This maximum curvature is attained at a height, h, equal to the capillary rise in the fracture:

$$h_c = \frac{2\sigma}{b_1 \gamma} , \tag{3}$$

where $\sigma$ is the interfacial tension between water and the plate material.

If the width of the horizontal plate, $b_2$, is greater than one-half the width of the vertical plate, $b_1/2$, water will not flow until $h_c$ is exceeded in the vertical plate. However, if $b_2$ is smaller than $b_1/2$, the height, h, that is required to initiate flow into the horizontal fracture is obtained from simple geometrical relationships (fig. 8B):

$$h = \frac{2\sigma}{\gamma(\frac{1}{2}\, b_1 \text{ Tan } \alpha + b_2)} \tag{4}$$

where $\sigma$, $\gamma$, $b_1$, $b_2$, and $\alpha$ are as defined before.

In nature, only under rare circumstances do sufficiently marked contrasts in the sizes of pores or apertures occur on a large enough scale so that a truly effective capillary barrier is formed. Generally, a gradation exists between materials with small openings and materials with large openings. Under these conditions, if a capillary barrier develops, it serves to retard, rather than prevent, flow from one unit to another.

The effectiveness of natural capillary barriers depends on the contrast in pore sizes, the state of flux, and the moisture-content distribution of the adjoining units. A common example of a natural capillary barrier is where a fine-grained layer overlies a coarse-grained layer, as illustrated diagrammatically in figure 9. In this example, the fine-grained layer is nearly completely saturated, whereas the coarse-grained layer has a water content much less than the saturation limit. Moisture-characteristic curves relating matric potential and permeability are shown in figure 10 for the two

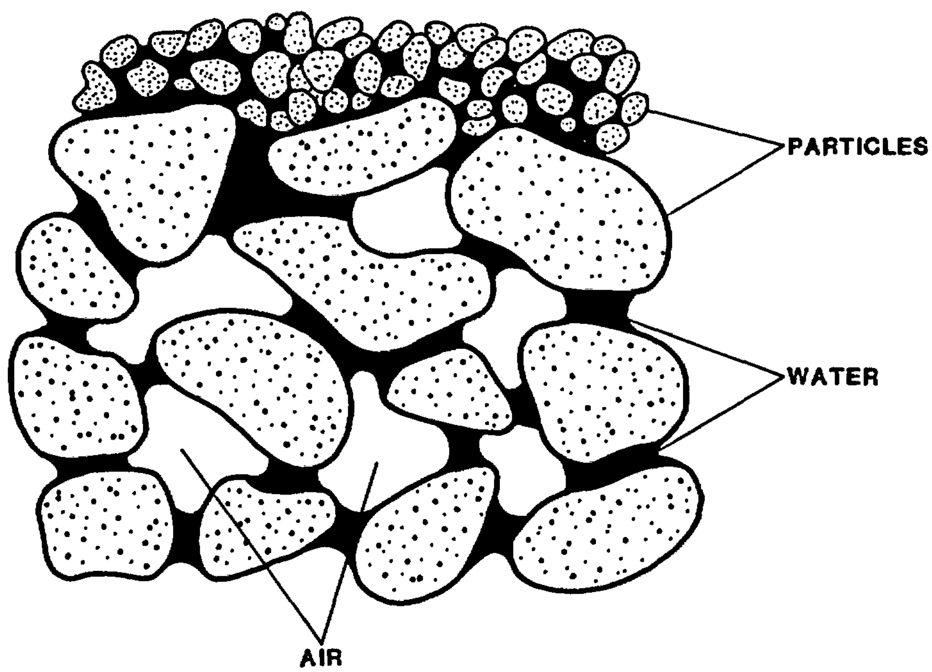



Figure 9.--Sketch of a fine-grained layer overlying a coarse-grained layer, illustrating a natural capillary barrier.

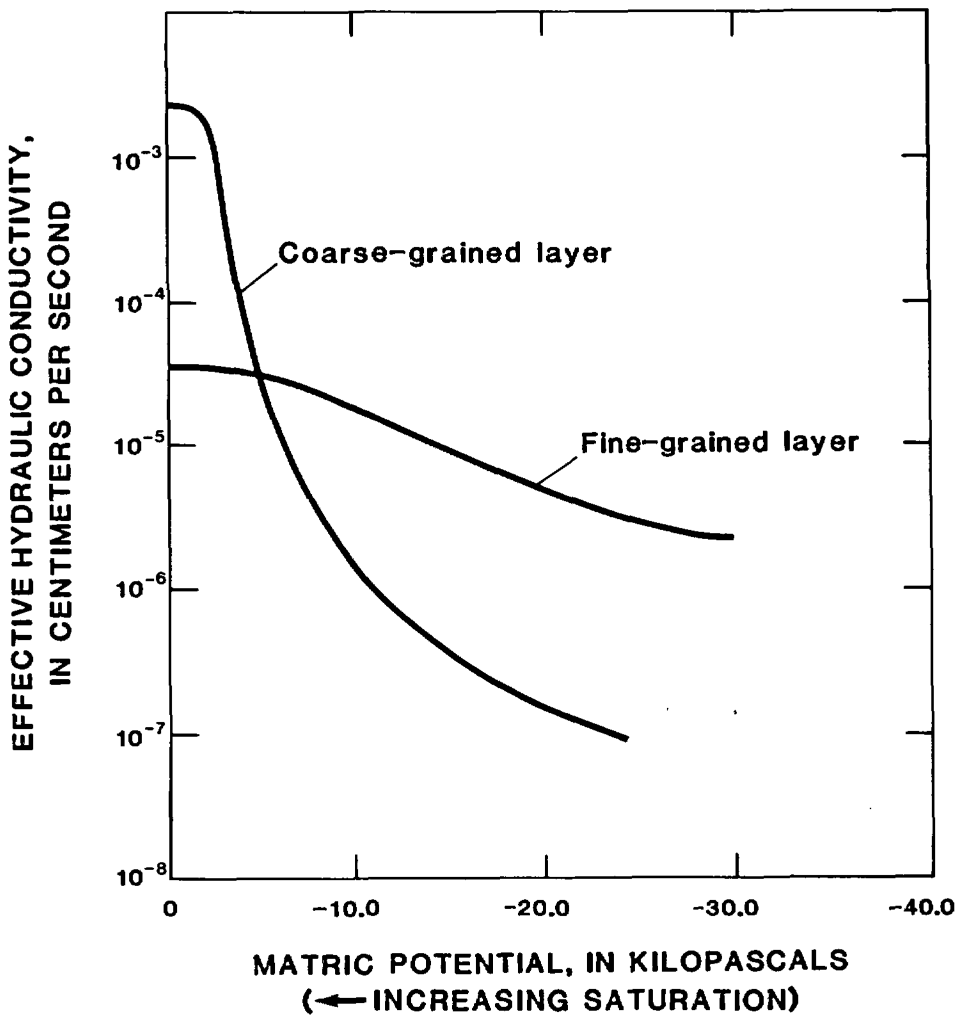



Figure 10.--Hypothetical relationship between effective hydraulic conductivity and matric potential for a fine-grained layer overlying a coarse-grained layer.

hypothetical layers shown in figure 9. At matric potentials less than about -5 kPa, the permeability of the coarse-grained layer is less than that of the fine-grained layer. At a matric potential of about -10 kPa, the difference in permeability is about 1 order of magnitude; at -20 kPa, the difference is about 2 orders of magnitude. The rate of downward flow of water through the two layers is controlled by the layer with less permeability. Thus, at a large matric potential (>-5 kPa), the rate of flow is controlled by the upper, fine-grained layer. At lesser matric potentials, the flow rate is controlled by the underlying coarse-grained layer, and the flow rate is less than the rate at greater matric potentials.

The effectiveness of a capillary barrier is increased if the two layers in contact have markedly contrasting grain-size properties. Under these conditions, the moisture-characteristic curves may not intersect (fig. 11). As the matric potential increases, the contrasts in permeability and moisture content increase, thereby further increasing the effectiveness of the capillary barrier. Capillary barriers also occur in fractured media when contrasting sizes of openings are in contact. Such a situation occurs when fractures with different aperture sizes intersect, and when a porous medium (such as a nonwelded tuff) overlies a fractured medium (such as a welded tuff), where the pores of the upper unit are smaller than the fracture apertures of the lower unit.

The capillary-barrier phenomenon has been studied by various investigators. Palmquist and Johnson (1962) conducted a laboratory experiment in a multilayered system. Their experiment showed that the existence of a fine-grained layer above a coarse-grained layer substantially retards flow into the coarse-grained layer. The result was greater moisture retention in the fine-grained layer, in the presence of the coarse-grained layer, than in a uniform fine-grained soil. Hillel and Talpaz (1977) investigated the phenomenon by numerical modeling. Their study indicated that, when a thin layer of clay overlies a sand layer, a substantial change in moisture profile occurs. They showed that volumetric moisture content in the sand layer could be as much as 20 percent less near the contact.

A complex and transient situation can occur when a porous medium is bounded above and below by a double-porosity medium, as illustrated hypothetically by welded and nonwelded tuff units in figure 12. In the nonwelded unit of this example, the pore diameters are smaller than the fractures and larger than the matrix pores of the overlying and underlying welded units. At relatively slow fluxes, flow occurs principally in the matrices of the three units; a capillary barrier to downward flow occurs only at the upper boundary of the nonwelded unit (matrix-to-matrix), because a fine-grained matrix overlies a coarse-grained matrix. At fluxes sufficiently rapid to cause significant fracture flow in the welded units, a capillary barrier between matrix and fractures occurs only at the lower boundary of the nonwelded unit. In this case, the matrix of the nonwelded unit is relatively finer-grained than the fractures in the underlying unit. Nonetheless, some fracture flow can occur in the lower welded unit.

## Infiltration into Fractured Rocks

Infiltration of rainfall, surface runoff, or snowmelt into rocks at the land surface is the process that introduces water downward into the unsaturated zone. If the exposed rocks consist of relatively permeable fractures

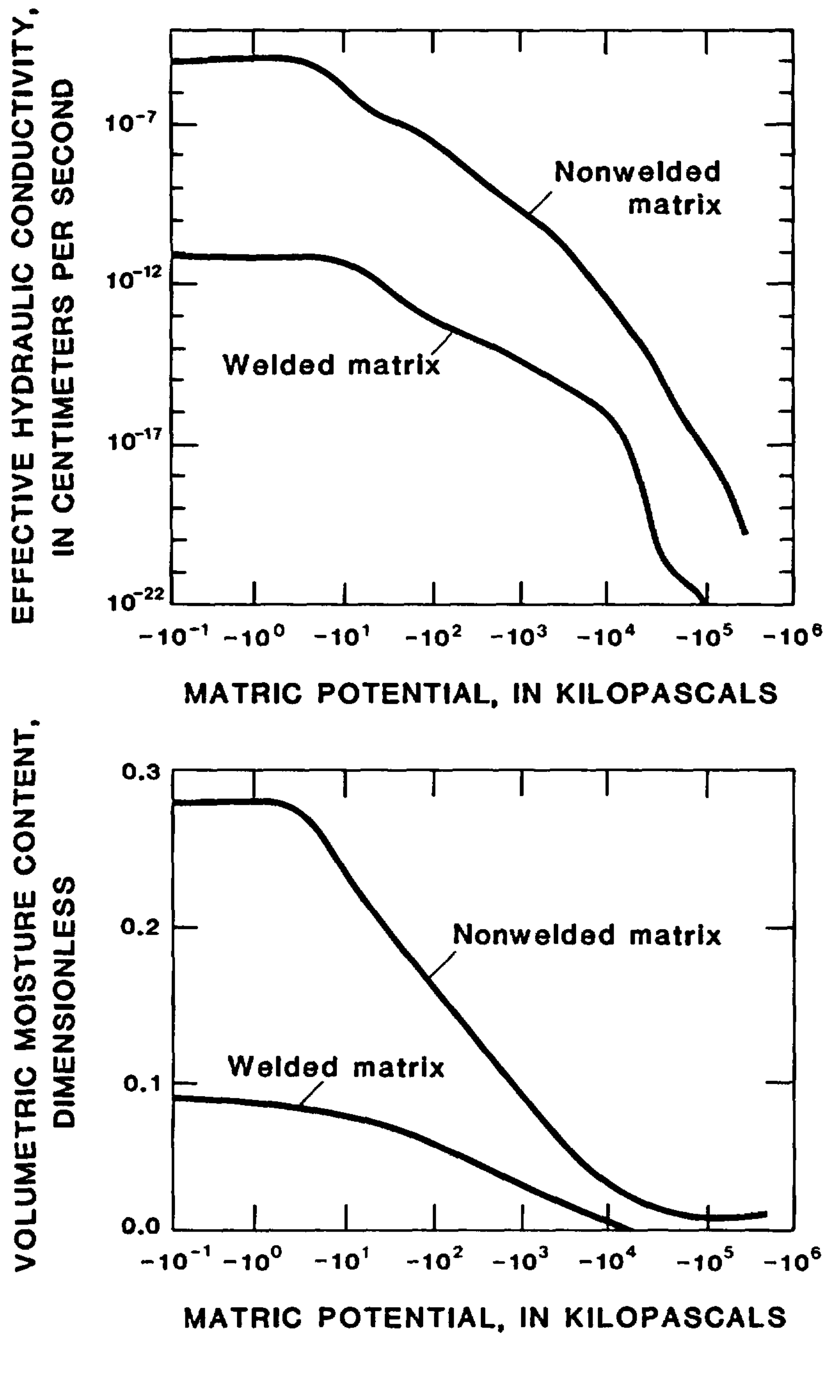



Figure 11.--Hypothetical relationships among hydraulic properties for two layers with markedly contrasting grain sizes.

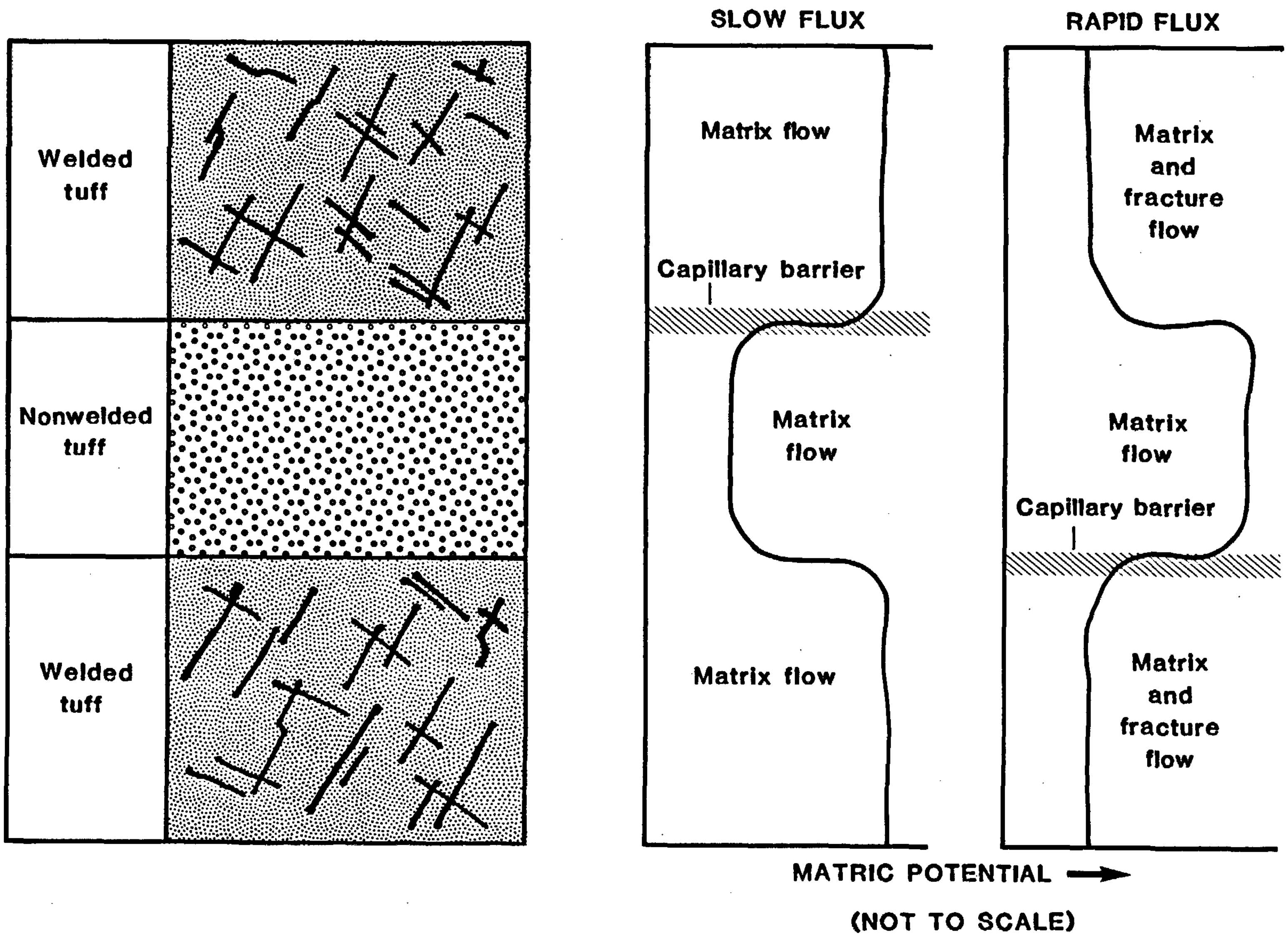



Figure 12.--Distribution of matric potential with depth and positions of capillary barriers, under slow and rapid fluxes, in a section of a porous medium bounded by double-porosity media.

and a relatively impermeable matrix, initial flow is likely to be in the fractures. During infiltration, the depth that water flows in fractures is affected by a variety of factors, including: (1) The initial state of saturation of the rock mass; (2) the properties of the matrix, principally matrix moisture capacity and permeability; and (3) the intensity of the infiltration. The concepts of fracture flow described above may be applied to understand infiltration phenomena and mechanisms and rates of percolation in the unsaturated zone at Yucca Mountain.

As infiltrating water moves along fracture walls, it becomes absorbed by the matrix. Tensions (also referred to as matric suction, equivalent to absolute value of matric potential) in the matrix near the fracture walls are decreased, whereas tensions in the rock-mass interior remain substantial and saturations remain unaffected. This condition allows fracture flow to continue to greater depths. Rapid infiltration rates, small matrix permeability, and small matrix moisture capacity enhance deep fracture flow. For example, Montazer (1982) observed water moving in fractures to depths of several tens of meters in metamorphic rocks within a few days after rapid snowmelt, without pervasive saturation of the matrix. Thordarson (1965) reported relatively short travel times (0.8 to 6 years) for water flow through unsaturated fractures in the tunnels that intersect the zeolitized nonwelded tuff in Rainier Mesa, about 45 km northeast of Yucca Mountain. However, in this case, the matrix was reported to be completely saturated.

## Lateral Flow

Lateral flow under unsaturated conditions can occur under various circumstances. For example, if layered rock units in the unsaturated zone are dipping, a horizontal component of the potential gradient is induced along the contacts between layers. The magnitude of the lateral component of flow can be substantial if the layers are very anisotropic, resulting in relatively substantial permeability along bedding planes compared to vertical permeability.

The potential for lateral flow has been demonstrated by numerical modeling (Johnson and others, 1983). Results show that, when a dipping fine-grained layer overlies a coarse-grained layer, the moisture accumulation in the fine-grained layer allows flow to occur laterally downslope along the contact. Similarly, when a dipping coarse-grained layer overlies a fine-grained layer, lateral flow occurs if the percolation rate into the upper layer is greater than can be transmitted by the lower layer at the prevailing moisture content or ambient hydraulic conductivity. Preliminary numerical modeling of hydrologic conditions at Yucca Mountain (G. Bodvarsson and J. Rulon, Lawrence Berkeley Laboratory, written commun., 1984) confirms the feasibility of lateral flow under such conditions.

## Vapor Movement

Vapor movement in the unsaturated zone occurs by both diffusive and convective processes. Diffusion of water vapor results from temperature and vapor-density gradients, and convective flow of vapor-saturated air is principally the result of temperature and pneumatic-potential gradients. Large temperature differences normally exist in thick unsaturated zones, and, if overall matric potential is small, free convective movement of vapor may dominate over diffusive flow. Near the land surface, where substantial matric-potential gradients exist because of evaporation, diffusive movement of vapor overwhelms other mechanisms. However, when substantial barometric fluctuations create substantial pneumatic-potential gradients, forced convective movement of vapor may occur near the land surface.

Convective transport of vapor is likely to occur where thick fractured-rock units occur in the unsaturated zone, such as at Yucca Mountain. Several factors enhance this likelihood: (1) A substantial thickness assures a well developed thermal gradient; (2) the fractured nature of the rocks facilitates movement of vapor-saturated air; and (3) the small negative water potential decreases the likelihood of liquid water occurring in the fractures, thereby providing more opportunity for movement of vapor-saturated air.

Movement of vapor-saturated air by convection develops when this air moving downward in the unsaturated zone is subjected to higher temperatures with depth. Density of vapor-saturated air at these depths is less than at shallower depths, and a convective force develops that tends to move the vapor-saturated air upward along fractures. At shallow depths the air cools, has a greater density, and tends to move downward.

Within the small-permeability matrix, an equilibrium probably always exists between the vapor phase and the liquid absorbed between the grains. However, because of convective flow, this equilibrium may not exist between the vapor and liquid phases in the fractures. Therefore, some vapor diffusion probably occurs between the matrix and fractures. This probable diffusion occurs from the matrix to the fractures in deep zones and from fractures to the matrix in shallow zones. This inversion occurs because at shallow depths the vapor density in the fractures is greater than that in the matrix. Therefore, two flow paths may exist for vapor in a double porosity medium. One is along the convection path of the vapor-saturated air in the fracture network, and the other is partly along the upward component of this convection path and partly along the downward flow path within the matrix. Knowledge of the occurrence of such phenomena helps to understand the movement of environmental isotopes in the unsaturated zone.

The foregoing discussion of vapor flow is a very simplified description of a complex phenomenon. More elaborate treatment of the subject is beyond the scope of this report and would be very speculative without sufficient field and experimental data. The concept of vapor transport is discussed here principally to introduce the possibility of the occurrence of this phenomenon at Yucca Mountain and to stimulate further research in this area.

## Capillary Fringe

The concept of capillary fringe in a thick heterogeneous unsaturated zone is ambiguous. The commonly used definition of the capillary fringe was presented by Meinzer (1923), as quoted by Lohman and others (1972, p. 3):

> "Capillary fringe is the zone immediately above the water table in which all or some of the interstices are filled with water that is under less than atmospheric pressure and that is continuous with water below the water table."

Application of this definition to Yucca Mountain could result in the conclusion that the "capillary fringe" extends to near the land surface, because relatively substantial matrix saturations exist almost continuously throughout the thickness of the Topopah Spring welded unit. The phrase "immediately above the water table" in this definition is also ambiguous because it could mean a few meters or a hundred meters. Freeze and Cherry (1979) use the term "tension-saturated" zone to describe the capillary fringe, but they also use a definition similar to Meinzer's (1923). If the capillary-fringe concept were to be applied to the fractures in the welded tuff at Yucca Mountain, the extent of the fringe above the water table in the fractures probably could be no more than a few centimeters; whereas, the extent of the fringe above the water table in the matrix could be up to several tens of meters.

Beneath the eastern and northern parts of Yucca Mountain, where the water table occurs in the Calico Hills nonwelded unit, the capillary fringe in the matrix may extend several tens of meters above the water table or all the way to the contact of this unit with the overlying Topopah Spring welded unit. In the western and southern parts of the mountain, where the water table occurs in the Crater Flat unit, the capillary fringe in the fractures probably is no more than a few meters; whereas, in the matrix, the capillary fringe may be continuous to the upper contact of the Calico Hills nonwelded unit.

Another complicating factor is that the thickness of the capillary fringe is both spatially and temporally variable, because of the variable spatial and temporal distributions of flux. Therefore, because of all these ambiguities, the term "capillary fringe" is not used in this report. Instead, actual saturation profiles are used to describe various moisture regimes at Yucca Mountain.

# CONCEPTUAL MODEL FOR YUCCA MOUNTAIN

The manner in which flow probably occurs in the unsaturated zone at Yucca Mountain is described below, based on: (1) Knowledge of the hydrogeologic framework; (2) application of the principles of unsaturated flow, including those described above; and (3) interpretation of some preliminary data from ongoing field and laboratory investigations.

## Unsaturated-Zone Flux

### Precipitation, Infiltration, and Recharge

The ultimate source of water in the unsaturated zone at Yucca Mountain is precipitation on the mountain. In fact, the quantity of annual precipitation is used as a basis for some techniques to estimate infiltration and recharge. Measurements of precipitation at Yucca Mountain were initiated too recently to obtain reliable direct estimates of average annual precipitation at the mountain. However, estimates can be made based on the regional distribution of precipitation or on relationships established between altitude and precipitation. From a regional map of precipitation presented by Winograd and Thordarson (1975, fig. 3), precipitation at Yucca Mountain is estimated to be about 100 to 150 mm/yr. Quiring (1983) established local relationships between altitude and precipitation for 1964-81 at the Nevada Test Site. Quiring's (1983) data included limited data outside the Test Site and data from 13 stations within the Test Site that range in altitude from 914 to 1,524 m. From a map showing precipitation-to-altitude ratios (Quiring, 1983, fig. 11), precipitation for the approximate range of altitudes at Yucca Mountain (about 1,220 to 1,465 m) is estimated to be 138 to 166 mm/yr. For purposes of discussion and analysis in this report, an average value of 150 mm/yr is assumed for Yucca Mountain. Quiring's (1983) data indicate that about 73 percent of this quantity falls during the cool season (October-April).

At Yucca Mountain, infiltration rate is both spatially and temporally variable. Spatial variations of infiltration are mostly dependent on the variations in properties of the surficial units and topography. Yucca Mountain is underlain mostly by alluvial and colluvial deposits and by fractured welded tuffs, principally the Tiva Canyon welded unit. The area underlain by outcrops of nonwelded units is relatively small. Alluvial and colluvial deposits fill the valleys and washes that form the main channels for surface runoff. Because the Tiva Canyon welded unit crops out throughout most of the central block, this unit has the most exposure to the precipitation on the mountain.

Direct measurements of infiltration and recharge have not been made at Yucca Mountain. Estimates of recharge have been made by using various indirect methods; these methods can be applied to estimate net infiltration. However, the spatial and temporal relationships between infiltration and recharge are complex, because of the hydrogeologic variability of Yucca Mountain. Some water that infiltrates returns to surface runoff by interflow, and another part is stored in the soils and rocks and returns to the atmosphere by evapotranspiration. The interflow probably is of short duration and occurs only during intense storms. This conclusion is inferred from the lack of evidence for springs or seeps along the washes. A small quantity that is not evapotranspired or discharged as interflow percolates deep into the unsaturated zone and becomes net infiltration. The quantity of net infiltration that percolates through different paths is quite variable; therefore, the average recharge does not represent percolation rates through specific flow paths. Nonetheless, it may be assumed that, beneath the entire mountain, the present net infiltration into the unsaturated zone is an indication of expected future recharge into the saturated zone. Estimates of present recharge can be used as an index to past net infiltration.

Various approaches were taken to obtain preliminary estimates of net infiltration and recharge at Yucca Mountain. These approaches include techniques that provide regional values for recharge, generally based on water-budget studies, and analyses of geothermal-heat flux.

Estimates of recharge in the region surrounding Yucca Mountain have been reported by other workers. Recharge to the carbonate aquifer underlying much of the Nevada Test Site and vicinity was estimated to be 3 percent of the precipitation falling on upland outcrop areas of the regional carbonate aquifer (Winograd and Thordarson, 1975). Applying this percentage to probable precipitation at Yucca Mountain (150 mm/yr) gives a recharge rate of about 4.5 mm/yr. Waddell and others (1984), using data from Winograd (1981), estimated a flux of about 0.5 mm/yr through alluvium in Yucca Flat, about 40 km northeast of Yucca Mountain. Case and others (1984) determined a typical value of pore velocity of about 3.3 mm/yr (for conditions of saturation) in Frenchman Flat, about 40 km east of Yucca Mountain. This is equivalent to a flux of 1 mm/yr if an effective porosity of 30 percent is assumed for the soil. None of these studies provides a reliable basis for estimating recharge at Yucca Mountain itself, where, as at all sites, the actual value depends on site-specific microclimates, soil conditions, vegetative cover, topography, and hydrogeologic setting of the unsaturated zone.

Techniques for estimating recharge for ground-water basins were developed by Eakin and others (1951) and Malmberg and Eakin (1962). The method uses regional relationships that were established among recharge, altitude zone, and precipitation. Rush (1970) applied the technique to estimate recharge to ground-water basins in southern Nevada. Czarnecki (1984) used Rush's (1970) results and estimated recharge to be about 0.5 mm/yr in a precipitation zone that includes Yucca Mountain as well as parts of Jackass Flats and Crater Flat.

The maximum recharge estimated by Rush (1970) for Crater Flat and Jackass Flats is 3 percent of precipitation, which occurs on a small area north of Yucca Mountain with altitudes between 1,524 and 1,829 m. This percentage represents 4.5 mm/yr (3 percent of 150 mm/yr) and is considered as the upper bound for the recharge rate that may be occurring in certain parts of the saturated zone beneath Yucca Mountain.

Another method that is used indirectly to estimate recharge is an analysis of geothermal-heat flux. In this method, percolation rate is estimated by separating the conductive and convective components of the heat flux (Sass and others, 1980). Sass and Lachenbruch (1982) estimated a vertical water flux of 1 to 10 mm/yr in the combined saturated and unsaturated zones of Yucca Mountain, using geothermal data from various boreholes. If this flux represents the vertical-downward percolation rate within the upper part of the saturated zone, then theoretically, the flux value would be equivalent to the recharge rate. However geothermal flux in the saturated zone is complicated by the horizontal water flux, which varies with different hydrogeologic conditions. In addition, borehole-completion methods and conditions could affect the results (Sass and others, 1980; Sass and Lachenbruch, 1982). The complexity is illustrated by an analysis by Sass and others (1980) of heat-flow data from borehole UE-25a#1, which showed a negative (upward) water flux of more than 150 mm/yr in the saturated zone.

Similarity of the estimates of recharge made from geothermal heat-flux methods and those from regional water-budget studies are not necessarily to be expected. In the regional water-budget method, the basic assumption is that ground-water discharge is in equilibrium with net infiltration within a given basin (Watson and others, 1976). For a system with a thick unsaturated zone, such as Yucca Mountain, this balance may not exist. An imbalance could result because the travel time that may be required for the infiltrated water to reach the water table could be several thousand years, and, according to the current conceptual model, this travel time could vary substantially from place to place within the unsaturated zone. Therefore, the water-budget method provides a correlation among the modern mean values of precipitation, discharge values that could be the combined result of various paleoclimatic and modern climatic conditions, and altitude. Thus, discharge values represent the average net infiltration that has occurred during a long span of geologic time.

The geothermal heat-flux method provides estimates of recharge that could be the result of paleoclimatic infiltration. The variability of estimated vertical flux values and directions (150 mm/yr upward to 10 mm/yr downward) of Sass and others (1980) and Sass and Lachenbruch (1982) probably reflects the large variability of vertical flux in the upper parts of the saturated zone at Yucca Mountain. This flux could be the result of infiltration events that occurred during a long span of geologic time that included times when climates were wetter than the modern climate. A range of recharge rates of 0.5 to 4.5 mm/yr (estimated by the water-budget method) for Yucca Mountain probably is conservative, because values in this range represent long-term average values and not necessarily the quantity of recharge that occurs as a result of modern arid climatic conditions. The net infiltration (and resultant recharge) due to modern climatic conditions probably will be much less.

## Percolation

Estimates of percolation rates, or fluxes, in individual units provide an indication of the flux in a specific part of the unsaturated zone. However, because of the potential for capillary barriers and lateral flow, percolation rates at any point do not necessarily reflect net infiltration or recharge. Percolation rates in parts of the unsaturated zone were estimated from analyses of the geothermal heat flux and from effective permeability and hydraulic gradient.

By considering the geothermal gradient only from the unsaturated zone, the same data and method of analysis used by Sass and Lachenbruch (1982) resulted in a calculated large negative (upward) flux of vapor-saturated air in the Topopah Spring welded unit. When this flux was corrected for the densities and thermal properties of vapor-saturated air, an equivalent negative (upward) water flux of about 1.5 mm/yr was obtained.

The long-term geothermal data from borehole USW UZ-1, which was the first vertical borehole at Yucca Mountain drilled with air, also show a negative (upward) flux of about 1 to 2 mm/yr in the Topopah Spring welded unit. These values were obtained by application of the method described by Bredehoeft and Papadopulos (1965) to temperature data from USW UZ-1 obtained 90 days after permanent emplacement of the thermocouples in that borehole. In using this method, appropriate values for properties of vapor-saturated air were used instead of values for properties of water.

In the unsaturated zone at Yucca Mountain, thermal flux is complicated by movement in both liquid and vapor phases, by heterogeneity of the hydrogeologic system, and by possible lateral flow. Both upward vapor movement in the fractures and downward liquid flow in the matrix may occur. In this case, water flux estimated from geothermal heat flow represents only the net flux and not the flux either in the fractures alone or in the matrix alone. However, the negative water fluxes estimated from the geothermal data indicate that an upward component of vapor flux probably exists in the fractures of Topopah Spring welded unit. Anomalies in geothermal gradients can also be due to variations in thermal conductivity of the material. Until more comprehensive studies are conducted to determine the cause of these anomalies, the fluxes estimated from this method are considered preliminary.

Percolation rates in the unsaturated zone also were estimated by applying effective permeability and hydraulic gradient in Darcy's equation. Weeks and Wilson (1984) used this method to estimate a matrix flux of about 0.003 to 0.2 mm/yr in parts of the unsaturated zone penetrated by borehole USW H-1. Effective permeabilities were estimated from mercury porosimetry data, and the in-situ potential gradients were extrapolated from water-content measurements and moisture-characteristic curves of core samples. Based on this information, and on a recognition of the substantial thickness of some of the hydrogeologic units at Yucca Mountain, Weeks and Wilson (1984) assumed that a quasi-steady-state condition and a unit hydraulic gradient exist in those parts of the section unaffected by boundary conditions. This situation may occur tens to hundreds of meters below land surface and in the central parts of some of the thick unsaturated hydrogeologic units. This assumption may be reasonable for certain sections of the Yucca Mountain unsaturated zone, but the heterogeneity of the hydrogeologic system and the potential for lateral flow in various hydrogeologic units probably result in a complex distribution of the matric potential and hydraulic gradient.

Borehole USW H-1 was cored using air foam (air, detergent, and water) as the drilling fluid (Rush and others, 1983). The unsaturated-zone borehole USW UZ-1, about 600 m northwest of USW H-1, was drilled using air as the drilling fluid. Water contents were measured for the drill cuttings of USW UZ-1. Water contents reported for the cores from USW H-1 might be expected to be more than, and those for USW UZ-1 might be expected to be less than the natural-state water contents. However, a similarity exists between the water-content measurements from the two boreholes, which indicates that neither drilling method significantly altered the natural water contents. However, a discrepancy exists between the in-situ potential measurements in borehole USW UZ-1 and the matric potentials reported for borehole USW H-1. Values of the potentials measured in-situ in USW UZ-1 are one to two orders of magnitude smaller (which means larger tensions). This discrepancy currently is being evaluated.

Montazer and others (U.S. Geological Survey, written commun., 1984) used the in-situ potential gradient measured in USW UZ-1 and effective permeabilities of the core from an adjacent borehole (USW G-1) to calculate the flux. Their preliminary analysis showed that, in the matrix of the Topopah Spring welded unit, downward flux ranges from $1 \times 10^{-7}$ to $1 \times 10^{-4}$ mm/yr, substantially less than values estimated by Weeks and Wilson (1984). The discrepancy in the flux estimates also is the result of comparing in-situ measurements in USW UZ-1 with extrapolated values based on core analysis used by Weeks and Wilson (1984).

Preliminary analysis of data from borehole USW UZ-1 indicates both upward and downward water fluxes occur in the Paintbrush nonwelded unit. Estimates of flux range from 10 to 30 mm/yr, both in upward and downward directions when only vertical flow is considered.

Weeks and Wilson (1984) present a value of relative permeability of 0.003, corresponding to a saturation value of 51 percent, for one sample from the Paintbrush nonwelded unit. Using this relative permeability value and the geometric mean of the saturated hydraulic conductivity ($9 \times 10^{-3}$ m/d, table 1) for this unit, a downward vertical flux of about 100 mm/yr is obtained if a hydraulic gradient of unity is assumed. However, in calculating flow across a layered system, it is more appropriate to use harmonic mean of the hydraulic conductivities (Bear, 1972 p. 153). The harmonic mean of five values of hydraulic conductivity for the Paintbrush nonwelded unit is $1.1 \times 10^{-5}$ m/d. The reason for the smaller harmonic mean, compared to the arithmetic and geometric means, is the existence of a vitric and argillic(?) layer (R. W. Spengler and D. C. Muller, U.S. Geological Survey, written commun., 1984) with very small permeability near the upper contact of the Paintbrush nonwelded unit. Using the harmonic mean of the saturated hydraulic conductivity and the relative permeability of 0.003, a vertical flux of 0.012 mm/yr is obtained. The mean saturation value for the Paintbrush nonwelded unit is 61 percent (table 1). When this saturation value is used in the empirical equation of Weeks and Wilson (1984), derived for the one sample from this unit, a relative permeability of 0.03 is obtained. Using this value and the harmonic mean of the saturated hydraulic conductivity, the calculated vertical flux is about 0.12 mm/yr. However, the layer with very small permeability possibly is discontinuous, which could result in a greater downward vertical flux in this unit. In this case, the calculated vertical flux is about 98.6 mm/yr, based on a geometric mean of the saturated hydraulic conductivity of $9 \times 10^{-3}$ m/d and a relative permeability of 0.03 corresponding to a mean saturation of 61 percent.

Preliminary modeling of the conditions in the section penetrated by borehole USW UZ-1 shows that a large lateral component of flow needs to be incorporated in order to explain the distribution of the matric potentials measured in the Paintbrush nonwelded unit in USW UZ-1 (G. Bodvarsson, Lawrence Berkeley Laboratory, written commun., 1984). Therefore, estimates of percolation rates assuming only vertical flow in this unit may not be reliable.

As discussed previously, the overall lateral hydraulic conductivity of the Paintbrush nonwelded unit is much greater than the vertical hydraulic conductivity of this unit. This difference results in a large potential for lateral flux. In an analysis of flow parallel to layers in layered material, the arithmetic mean of the hydraulic conductivities needs to be used instead of the harmonic mean (Bear, 1972, p. 151). The arithmetic mean of the saturated hydraulic conductivity of this unit is about 0.08 m/d. Using a relative permeability of 0.03, corresponding to 61 percent mean saturation, an effective hydraulic conductivity of $2.4 \times 10^{-3}$ m/d is obtained. Assuming uniform lateral distribution of matric potential and a dip of 7°, the flux that could be transmitted laterally in this unit is about 108 mm/yr. Assuming an average thickness of 85 m, the potential lateral volumetric flow rate in this unit is about 9.1 $m^3$/yr per unit distance along the strike of this unit. The equivalent volumetric flow rate of the net infiltration rate of 4.5 mm/yr over a span of 1,000 m, the widest section of the central block, is 4.5 $m^3$/yr per unit distance along the strike of this unit. Therefore, the potential lateral flow capacity of the Paintbrush nonwelded unit is about twice the estimated upper bound of the volumetric infiltration rate, if all the infiltrated water were to be transmitted laterally through this unit. The actual value of lateral flow probably is much less.

This analysis is based on an over-simplification of conditions, and comprehensive numerical modeling is needed to estimate the actual lateral-flow potential. The principal limitation of this analysis is that the conclusions are based on the distribution of the saturated hydraulic conductivities. A more appropriate approach would be to use the distribution of individual values of effective hydraulic conductivity; these can be applied as they become available to calculate lateral fluxes.

Similar analyses were made to estimate fluxes in the Calico Hills nonwelded unit. Using the effective hydraulic conductivities of this unit (table 1) and assuming a unit hydraulic gradient in the vertical direction, a vertical matrix flux of 55 mm/yr was estimated for the vitric facies, and 0.006 mm/yr was estimated for the zeolitic facies of this unit. However, the vitric facies is underlain by the zeolitic facies throughout the central block; therefore, the downward flux through the unit would be limited by the slower flux rate through the zeolitic facies. Fracturing in the zeolitic facies of this unit is discontinuous, and even if fracture flow were to occur, most of the travel path would be in the matrix. Lateral flow could occur in the vitric facies and in the few thin-bedded layers of vitric tuff that exist in the zeolitic facies.

## Summary of Flux

In the foregoing discussion, various approaches were used to provide information about infiltration, percolation, and recharge at Yucca Mountain. The uncertainty in the individual results is relatively large; however, analysis of the combination of the results provides some guidance for estimating bounds on the percolation rates in various sections of the unsaturated zone of Yucca Mountain, and bounds on recharge and net infiltration beneath the mountain as a whole.

From analyses of the relationships among precipitation, recharge, and altitude, recharge to the saturated zone is conservatively estimated to be 0.5 to 4.5 mm/yr. This range of values probably can be assumed to represent the range of net infiltration, but this assumption may not be valid if the travel time through the recharging paths (structural features, for example) is longer than the duration of major phases of climatic cycles. Results of analyses of the hydraulic properties show that: (1) From 0.1 to 98.6 mm/yr of vertical flux may be occurring in the Paintbrush nonwelded unit, but the magnitude of vertical flux depends on the effectiveness of the capillary barrier at the lower contact of this unit; (2) the capacity to transmit lateral flux in the Paintbrush nonwelded unit is more than 100 mm/yr, and the potential lateral volumetric flow rate is about twice the maximum estimated volumetric infiltration rate; (3) from $10^{-7}$ to 0.2 mm/yr of flux could be occurring in the matrix of the Topopah Spring welded unit, but flux in the fractures is unknown;

(4) flux in the Calico Hills nonwelded unit is variable but probably is limited to 0.006 mm/yr in the downward dirction; and (5) results of analyses of the geothermal heat-flux data show that about 1.0 to 2.0 mm/yr of upward net flux occurs in the Topopah Spring welded unit, possibly as a result of upward-moving vapor-saturated air, but the results are uncertain because of possible alternative interpretations of the data. These analyses indicate that the distribution of the vertical percolation is nonuniform in the unsaturated zone at Yucca Mountain. In the Paintbrush nonwelded unit, percolation rates probably are rapid and occur both vertically and laterally; but in the Topopah Spring welded unit, rates probably are extremely slow or even negative.

## Flow-System Boundaries

Boundaries of the unsaturated flow system at Yucca Mountain consist of: (1) An upper boundary, the land surface: (2) a lower boundary, the water table; and (3) vertical boundaries, defined by vertical planes arbitrarily placed near the margins of the mountain block under consideration. The geometries of the upper and lower boundaries are reasonably well defined by topographic maps and potentiometric-surface maps (Robison, 1984). The directions of flux at the boundaries can be inferred from assumed or known unsaturated-zone conditions, as illustrated in the simplified east-west section across Yucca Mountain in figure 13.

As shown in figure 13, flux directions are variable along the western and eastern vertical boundaries. In the welded units, these boundaries are assumed to be no-flow boundaries, because the dominant direction of flow probably is vertical. Within the nonwelded units, these vertical boundaries are either sinks or sources, because of the lateral flow that probably occurs within these units. The Paintbrush nonwelded unit is assumed to be a sink at both western and eastern boundaries. On the western side of the block, this unit is exposed to the atmosphere and, therefore, evaporation from this surface results in discharge. On the eastern side, the flow is eastward (downdip) and thus also discharges from the block. In the Calico Hills nonwelded unit, the western vertical boundary is a source, assuming that conditions similar to those described for Yucca Mountain also exist farther west. On the eastern side of the block, the vertical boundary intersecting this unit is a sink, because lateral flow in this unit results in discharge from the block across the boundary.

In the conceptual model, the magnitude of flux across the upper and lower boundaries (net infiltration and recharge rate) is assumed to be 4.5 mm/yr for the mountain as a whole. The precipitation that occurs at Yucca Mountain (about 150 mm/yr) can fall in just a few storms a year, each lasting a few days (H. W. Church, Sandia National Laboratories, written commun., 1983). Therefore, it is assumed that infiltration occurs during a few brief and moderately intense storms during the year. For the remainder of the year, the upper boundary is assumed to be an evapotranspiration boundary (a sink). Deep percolation and recharge probably occur more or less at a steady rate.

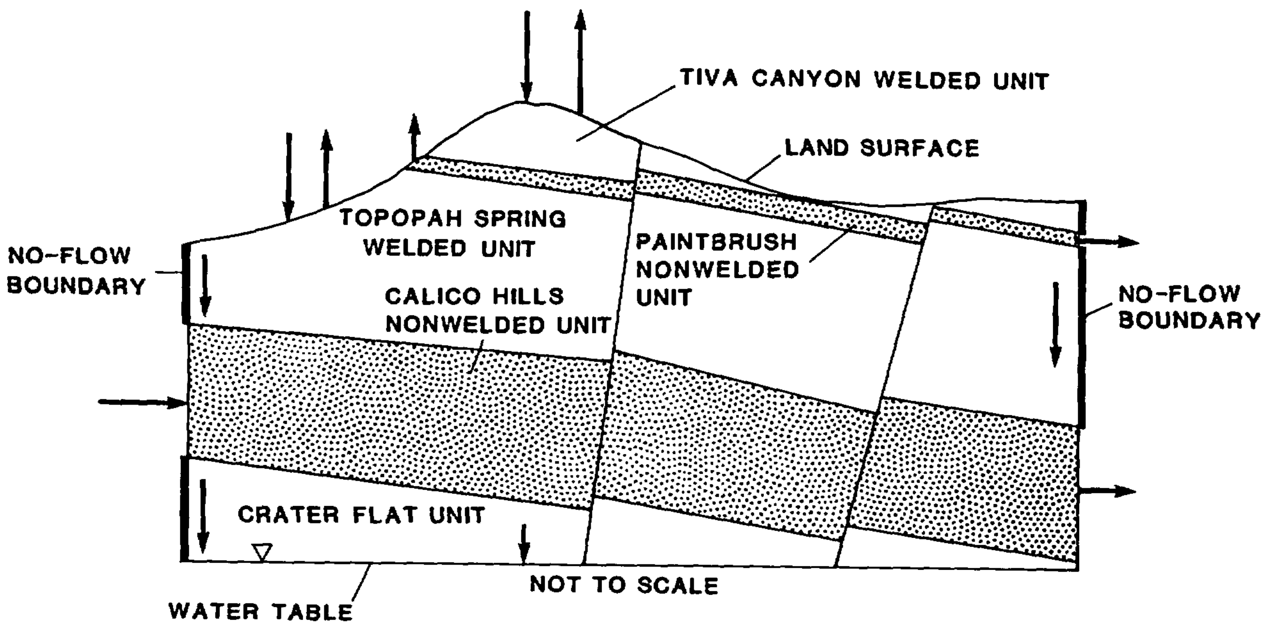


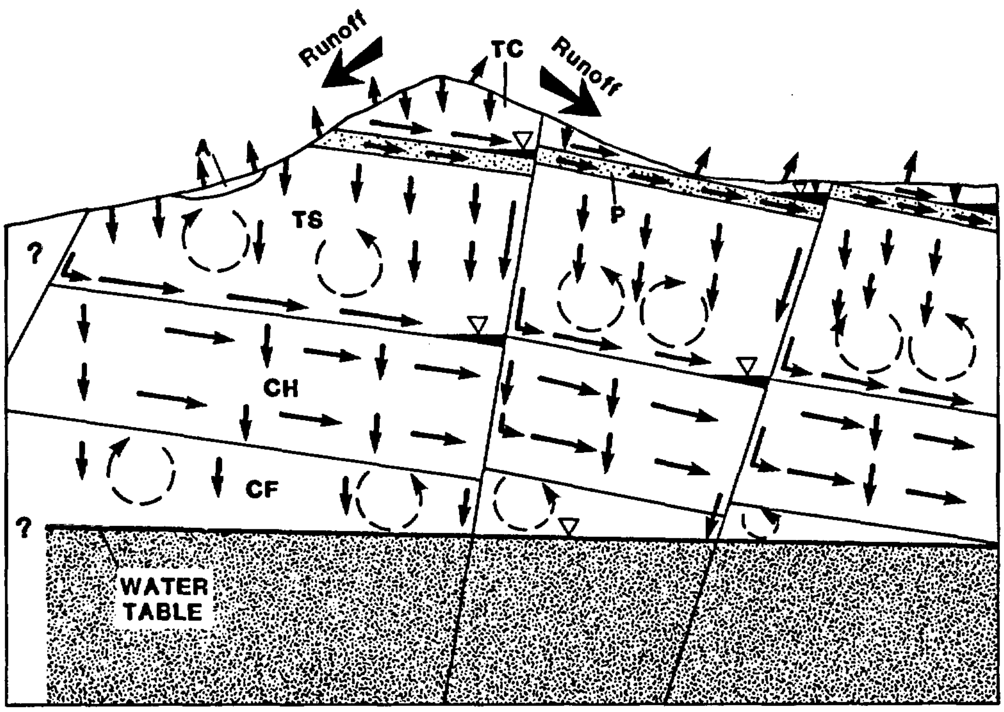

Figure 13.--Generalized section across Yucca Mountain showing positions of flow boundaries and inferred flux directions (arrows) at the boundaries.

## Flow in Hydrogeologic Units

The manner in which flow occurs in the hydrogeologic units is affected by the net infiltration rate as well as by the physical properties of those units. In the following discussion, flow is described assuming a net infiltration rate of 4.5 mm/yr occurring during a few moderately intense storms during the year. The patterns of flow in the various units are illustrated schematically in figure 14, a simplified section across Yucca Mountain.

### Units at the Land Surface

Hydrogeologic units exposed at the land surface at Yucca Mountain and vicinity include alluvium, the Tiva Canyon welded unit, the Paintbrush nonwelded unit, and the Topopah Spring welded unit. Water infiltrating these units either is returned to the atmosphere by evapotranspiration or percolates downward beyond the effects of evapotranspiration.




NOT TO SCALE

EXPLANATION

A ALLUVIUM
TC TIVA CANYON WELDED UNIT
P PAINTBRUSH NONWELDED UNIT
TS TOPOPAH SPRING WELDED UNIT
CH CALICO HILLS NONWELDED UNIT
CF CRATER FLAT UNIT
DIRECTION OF LIQUID FLOW
DIRECTION OF VAPOR MOVEMENT
PERCHED WATER

Figure 14.--Generalized section across Yucca Mountain showing flow regime under baseline conditions. Lengths of solid arrows show relative magnitude of fluxes.

Percolation through the alluvial deposits is slow, as evidenced by experiments conducted in desert alluvial material (Kearl, 1982; E. P. Weeks, U.S. Geological Survey, written commun., 1984). Alluvial and colluvial deposits generally have small effective hydraulic conductivity, large specific retention, and large effective porosity as compared to the fractured rocks. Therefore, a large proportion of the water infiltrated into the alluvial and colluvial material is stored in the first few meters of the soil and is lost to evaporation during dry periods. During periods when relatively long-lasting runoff occurs in the alluvial channels, some of the infiltrated water probably reaches depths not affected by evapotranspiration.

Alluvial and colluvial deposits are underlain either by the Tiva Canyon welded unit, the Paintbrush nonwelded unit, or the Topopah Springs welded unit in the washes east of Yucca Crest. Deposits in Solitario Canyon are underlain by bedrock of varying composition. On the east side of the canyon, the exposed bedrock mostly is composed of the Topopah Spring welded unit.

The contact between alluvium and the Paintbrush nonwelded unit commonly is gradational. The transition is from heterogeneous alluvium to broken and weathered bedrock to intact bedrock. The Paintbrush unit is finer in texture and has smaller hydraulic conductivity than alluvial material. The unit generally is indurated but has small fracture density (table 1).

Flow from alluvial material into the Paintbrush nonwelded unit probably occurs during infiltration. A potential for lateral flow exists, because of layering of the materials in the transition zone. The quantity of water that percolates into the Paintbrush unit is small beneath alluvial deposits because the flux in alluvial deposits is slow (E. P. Weeks, U.S. Geological Survey, written commun., 1984). However, no capillary barrier occurs at this contact to retard the downward flow of water. Where the alluvial cover is absent, direct infiltration into this nonwelded unit can occur.

Percolation of infiltrated water through the exposed fractures of the Tiva Canyon welded unit is relatively rapid, because of the large fracture permeability and small effective porosity of this unit compared to the alluvial material. Therefore, a large proportion of the infiltrated water normally is percolated sufficiently deep within the fractured tuff to be unaffected by the evaporation potential that exists near the surface. Depending on the intensity of the infiltration, percolation downward through the Tiva Canyon welded unit may occur without a significant change in rate. A small proportion of the water percolating through the fractures slowly diffuses into the matrix of the Tiva Canyon welded unit. Downward flow in the matrix is very slow, because of the small effective hydraulic conductivity of the matrix. During dry periods, some of the diffused water flows back into the fractures and probably reaches the land surface by vapor diffusion. The mass of water involved during this process probably is negligible compared to the percolating water.

Infiltration occurs directly into the Paintbrush nonwelded unit at a few outcrops. Because of the relatively small permeability (compared with alluvium) and discontinuous fracturing, direct infiltration into this unit probably is slow. In addition, most outcrops are situated on steep slopes, where the potential for runoff is great. Therefore, only a small quantity of water can infiltrate into this unit directly, and nearly all of it probably is returned to the atmosphere by evaporation (fig. 14).

The Topopah Spring welded unit is exposed on the west side of Yucca Crest, east of Solitario Canyon. Infiltration mechanisms in this unit are similar to those of the Tiva Canyon welded unit. The steep slope results in a smaller ratio of infiltration to runoff than in the Tiva Canyon unit. A small proportion of the infiltrated water returns to the atmosphere, but most of it percolates vertically downward until it reaches the upper contact with Calico Hills nonwelded unit. At this contact, a sequence of events occurs that is similar to that described below for the Paintbrush nonwelded unit. Some lateral spreading may occur within the Topopah Spring welded unit. Because of the large area of vertical exposure and probable active vapor movement within this unit, some water probably is lost to the atmosphere through vapor transport and by evaporation (fig. 14).

## Paintbrush Nonwelded Unit

A marked contrast in material properties exists at the contact between Tiva Canyon welded unit and the underlying Paintbrush nonwelded unit; this contrast significantly affects the flow direction. The densely fractured Tiva Canyon unit, with small matrix porosity and permeability, overlies the very porous, sparsely fractured Paintbrush unit. Flow of water through fractures of the Tiva Canyon unit occurs rapidly until it reaches the contact. At this point, the velocity is significantly decreased because of the greater effective porosity and lesser hydraulic conductivity of the Paintbrush unit. Because of this contrast, air entrapment occurs in the upper part of the Paintbrush unit. This air entrapment further decreases the effective hydraulic conductivity and the effective porosity of the Paintbrush nonwelded unit and results in an overall decrease of flux into this unit during periods of pulsed percolation. As a result, lateral unsaturated flow of water above this contact can occur. Perching of this water may occur above this unit if displacement along faults has created significant permeability contrasts on opposite sides of the fault (fig. 14). Lack of evidence of spring-discharge points along the outcrop of the contact between the Paintbrush nonwelded unit and the Tiva Canyon welded unit indicates lack of an extensive perched groundwater system in these two units. Winograd and Thordarson (1975) also report that perched waters in other areas of Nevada Test Site do not occur in the welded tuff aquifers.

The overall hydraulic conductivity of the Paintbrush nonwelded unit in the direction of dip is 10 to 100 times greater than overall hydraulic conductivity in the direction normal to the bedding plane. This difference is inferred from the occurrence of bedded layers with large hydraulic conductivity that are interbedded with nonwelded zeolitic layers with relatively small hydraulic conductivity (Anderson, 1981; Scott and others, 1983). The combination of dipping beds (about 10° to the east) and differences in directional permeability creates a downdip component of flow. The magnitude of this component depends on the magnitude of the principal hydraulic-conductivity ratio. The magnitude probably is sufficient to decrease the vertical percolation into the underlying Topopah Spring welded unit to almost zero. The water moving laterally flows downdip until structural features are encountered that create perching conditions or provide pathways for vertical flow (fig. 14). (See discussion, "Flow through structural pathways.")

## Topopah Spring Welded Unit

Some water flows from the matrix of the Paintbrush nonwelded unit into the fractures or matrix of the underlying Topopah Spring welded unit. The matrix of the lower unit has finer pores and much less matrix hydraulic conductivity than the overlying unit (table 1). Under these conditions, no matrix-to-matrix capillary barrier occurs. However, a capillary barrier does exist between the matrix of the Paintbrush nonwelded unit and the open fractures of the Topopah Spring welded unit. Theoretically, if fracture apertures are larger than the largest pore diameters of the overlying unit, no flow into the fractures can occur until the pressure at the base of the pores becomes atmospheric. In fact, however, opening sizes and moisture conditons are such that some sheet flow can occur along the walls of the fracture in quantities that are greater than the flow in the matrix of the welded unit (Montazer, 1982; Evans, 1983). Eventually, the water moving through the fractures of the Topopah Spring welded unit diffuses into the matrix and moves very slowly downward (fig. 14). Most of this water is returned to the upper parts of the unit by vapor diffusion, as indicated by an analysis of thermal-gradient data from borehole USW UZ-1.

## Calico Hills Nonwelded Unit

Flow enters the Calico Hills nonwelded unit either from the matrix of the Topopah Spring welded unit or through structural flowpaths. Because little if any flow occurs in the fractures of the lower part of Topopah Spring unit, these fractures do not contribute to flow into the Calico Hills unit.

The nature of flow at the contact between the Topopah Spring and Calico Hills units depends on whether the vitric or zeolitic facies of the Calico Hills unit is present. The permeability and effective porosity of the vitric facies are much greater than those of the matix of the Topopah Spring unit (table 1), resulting in a capillary barrier where those units are in contact. Conversely, the permeability of the zeolitic facies is about the same as for the matrix of the Topopah Spring unit, resulting in continuity of matrix flux across the contact.

Flux within the Calico Hills nonwelded unit occurs with some lateral component of downdip flux, because of the existence of layers with contrasting hydraulic conductivity in the unit. A large-scale anisotropy probably is caused by intercalation of tuffs with large and small permeability and by compaction. The discontinuous fracture system in the zeolitic facies probably decreases the magnitude of the anisotropy, because fractures tend to create a larger component of vertical permeability.

Water that flows downdip along the top of the Calico Hills nonwelded unit slowly percolates into this unit and slowly diffuses downward. This downdip flow probably persists for longer distances along the upper contact of the zeolitic facies, which has less permeability than the vitric facies. In either case, flux into each facies is more-or-less distributed evenly. Fracture flow occurs near the uppermost layers of the Calico Hills unit, but diffusion into the matrix probably removes the water from the fractures deeper in the unit, and flow becomes limited mostly to within the matrix except along the structural flowpaths. At the upper contact of the unit, an upward component of flux from the matrix of the Calico Hills nonwelded unit into the matrix of the Topopah Spring welded unit may develop, because of differences in the capillary pressures.

### Crater Flat Unit

Beneath the southern part of the block, the Crater Flat unit occurs between the Calico Hills unit and the water table. Included are the welded part and underlying nonwelded part of the Bullfrog Member of the Crater Flat Tuff. Flow patterns and processes that occur higher in the section are repeated in this unit; therefore, it is an extra buffer to water before it enters the saturated zone (fig. 14).

## Flow through Structural Pathways

Relatively larger fluxes occur along the structural flowpaths than within the units they intersect. These structural flowpaths are either hydraulically continuous through the Calico Hills nonwelded unit, or their hydraulic conductivity diminishes as they intersect this unit, because of changes in material properties. The Calico Hills nonwelded unit is more ductile than the overlying Topopah Spring welded unit. This ductility gives the unit sealing properties. In addition, because of the lesser shear strength of this unit compared to that of the Topopah Spring unit, gouge formation along faults and shear zones is more common. These properties probably result in a general smaller fracture conductivity in this nonwelded unit.

In the case where the structural flowpaths are hydraulically continuous across the upper contact of the Calico Hills nonwelded unit, water flows downward without a significant change in its path until it reaches the water table. In the more probable case where the structural flowpaths become hydraulically discontinuous, water either may become perched at the upper contact of the Calico Hills nonwelded unit or water could begin to flow downdip along this boundary or both (fig. 14). Intermediate conditions between the two extreme cases also are possible; that is, the change in continuity of a structural path could be such that it would allow some proportion of water to flow downward and the rest to be perched or flow downdip along the contact. All these cases probably exist at various locations within the mountain.

## SUMMARY AND CONCLUSIONS

The unsaturated zone at Yucca Mountain, is being evaluated by the U.S. Department of Energy to ascertain its suitability for a mined geologic repository for high-level nuclear waste. A conceptual hydrologic model that describes the flow of fluids through the unsaturated zone at Yucca Mountain was developed in order to provide a basis for preliminary performance assessment and to guide further investigations. This model is based on current understanding of the unsaturated flow through a heterogeneous section of layered- and fractured-rock formations. The description of the model is conjectural and the proposed model is not the only reasonable one. For simplicity of expression, the model is described as if it were a true expression of the facts. The model can be modified as more data become available.

Total thickness of the unsaturated zone ranges from about 500 to about 750 m. Tuffaceous rocks in the unsaturated zone beneath Yucca Mountain are grouped in this report into five informal hydrogeologic units, based principally on their degree of welding: (1) Tiva Canyon welded unit; (2) Paintbrush nonwelded unit; (3) Topopah Spring welded unit; (4) Calico Hills nonwelded unit; and (5) Crater Flat unit. Compared to the nonwelded units, the welded units have relatively large mean fracture density (8 to 40 fractures per unit cubic meter), small mean matrix porosities (12 to 23 percent), and large bulk hydraulic conductivities (0.1 to 10 m/d). Mean matrix porosity of the nonwelded units ranges from 31 to 46 percent. Hydraulic conductivities of the welded and the zeolitic facies of the nonwelded units ($2 \times 10^{-6}$ to $8 \times 10^{-6}$ m/d) are substantially less than hydraulic conductivities of the vitric facies and bedded layers of the nonwelded units (0.004 to 0.009 m/d). At Yucca Mountain, the central block, or primary repository area, is bounded on the east and west sides by major north-striking normal faults or fault zones that may be either flow barriers or flow pathways in the unsaturated zone. Other faults with similar hydrologic characteristics occur in the central block; however, faulting within the block is much less than outside the block.

Hydrogeologic features that probably affect flow significantly in the unsaturated zone at Yucca Mountain include the presence of fractured porous media, layered units with contrasting properties, dipping units, bounding major faults, and a deep water table. These features probably result in the occurrence of phenomena such as fracture and matrix flow, retardation of flow by capillary barriers, infiltration into fractured rocks, lateral flow, perched ground-water zones, and vapor movement. All these phenomena are incorporated into the conceptual model.

Average annual precipitation at Yucca Mountain is estimated to be about 150 mm/yr. Average recharge rate beneath Yucca Mountain is estimated to be 0.5 to 4.5 mm/yr. Infiltration rate is both spatially and temporally variable and probably occurs as periodic moderately intense pulses.

Water infiltrates principally into the Tiva Canyon welded unit, but also into the alluvium, Paintbrush nonwelded unit, and Topopah Spring welded unit where they are exposed at the land surface. Water that does not become evapotranspiration and interflow becomes net infiltration and moves rapidly downward through fractures of the Tiva Canyon unit. The combination of dipping beds, permeability layering, and capillary-barrier effects results in significant lateral flow within the Paintbrush nonwelded unit toward the bounding structural features. Most of the infiltrated water is transmitted downward to the water table along structural features. Some matrix-to-matrix flow occurs from the Paintbrush nonwelded unit into the underlying Topopah Spring welded unit, but a capillary barrier retards flow into the fractures of the Topopah Spring welded unit. Percolation rates are variable (0.1 to 98.6 mm/yr) in the Paintbrush nonwelded unit and overlying units but extremely slow ($10^{-7}$ to 0.2 mm/yr) or even negative in the Topopah Spring welded unit, except along completely penetrating, very conductive structural features.

At Yucca Mountain, nonuniform infiltration periodically produces moderately intense fluxes. Under such fluctuations of infiltration intensity, a zone of transient flux develops near the upper part of the unsaturated-zone profile. At depths greater than a few tens to hundreds of meters, this transient flux dampens out and flow reaches a more or less (quasi) steady-state condition. In the shallow transient zone, the phenomena of hysteresis and air entrapment are active. One of the effects of these phenomena is to start fracture flow in the Tiva Canyon welded unit much earlier in the wetting cycle than would be predicted by the drainage curves. Therefore, pulses of infiltration may cause rapid percolation down through the Tiva Canyon welded unit and into the Paintbrush nonwelded unit. Hysteresis effects may occur in the upper part of the Paintbrush unit and result in rejection of downward percolating water much sooner than would be predicted by drainage curves. These effects result in the start of lateral flow along the contact between the Tiva Canyon and the Paintbrush units. Depending on the areal extent of the infiltration pulse, this lateral flow may reach structural features, where development of perched ground water is possible. This temporarily perched ground water drains into the structural flowpaths and much of it travels directly to the water table; some of this water diffuses into the matrix of the Paintbrush nonwelded unit and other units along the path.

Several factors indicate that the net flux in the Topopah Spring welded unit is very small. Fracture flow into the Topopah Spring welded unit is retarded by the capillary barrier that exists between the Paintbrush nonwelded unit and this welded unit. Limited fracture flow may occur near the upper contact of the Topopah Spring unit; however, diffusion into the matrix diminishes the extent of fracture flow in the deeper parts of this unit. Considering the potential for vapor transport under geothermal gradients, the net flux in parts of the Topopah Spring welded unit may even be negative (upward). Of the conservatively estimated 4.5 mm/yr net infiltration, probably only a maximum of 1 mm/yr (equivalent to saturated hydraulic conductivity of the unit) is transmitted through the Topopah Spring unit. The excess net infiltration probably flows laterally into the structural features. The flux along these features could be large because of their relatively small widths. Therefore, the structural features probably transmit the major part of the infiltrated water.

Flow enters the Calico Hills nonwelded unit either from the matrix of the Topopah Spring welded unit and through structural flowpaths. Most structural features probably become hydraulically discontinuous as they cross the Calico Hills nonwelded unit. Some water reaches the water table through these features, but perched water and down-dip flow may occur along the upper contact of the Calico Hills unit. This laterally moving water percolates downward into the matrix of the Calico Hills unit. Vertical flux through this unit is limited to 0.006 mm/yr. Lateral flow probably occurs within this unit, but may not be as significant as the lateral flow within the Paintbrush nonwelded unit.

Structural features transect a variety of welded and nonwelded tuff units. Variations in properties of these tuffs could result in local perching above or within the nonwelded units in the vicinity of these structural features. This perched water may take a variety of pathways: (1) It may move laterally along the upper contact or within the nonwelded unit; (2) it may move downward through the nonwelded unit; or (3) it may move downward along the structural pathway. The result is an uneven distribution of moisture content within the unit in the vicinity of the structural feature. Ultimately, the water flows through the Calico Hills nonwelded unit and reaches the water table, either beneath the central block, or at the structural features immediately east of the block, or farther east where the water table is within the Topopah Spring welded unit.

The authors believe that the conceptual model described in this report is based on an appropriate hydrogeologic framework. Therefore, the degree to which the model accurately describes flow conditions at Yucca Mountain depends in large measure on the appropriateness of the assumptions used and on the boundary flux assigned to the model. Many of the processes incorporated in the model are based on the presumed substantial difference between the relatively slow percolation rate in the Topopah Spring welded unit beneath the block and the relatively large net infiltration entering the system. Several lines of evidence support the slow percolation rate. However, the net infiltration at Yucca Mountain principally is based on an application of regional analyses; thus, the rate is very uncertain. Further definition of this rate is required to assess the accuracy of the flow conditions described by the model.

The model can provide a basis for making preliminary assessments of the hydrologic integrity of a potential repository in the unsaturated zone at Yucca Mountain. Such assessment modeling needs to incorporate the phenomena of fracture flow, lateral flow, capillary barriers, flow through structural features, and hysteretic effects.

The model also can be a guide for further investigations of the hydrology of the unsaturated zone at Yucca Mountain. Such investigations could include evaluations of: (1) Flux in the shallow hydrogeologic units, to identify more directly the net infiltration rate; (2) flux in the major structural features bounding the central block, to assess the significance of such features and similar ones that might exist or develop in the central block; (3) the presence or absence of perched water bodies, to assess their impact on repository construction and integrity; (4) two-phase flux in the Topopah Spring welded unit, to evaluate the potential for upward moving water; and (5) the assumptions made in developing the conceptual model, to assess the appropriateness of the model and to provide a basis for its revision.

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