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HYDROGEOLOGY OF THE UNSATURATED ZONE,
YUCCA MOUNTAIN, NEVADA

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Abstract

The unsaturated volcanic tuff beneath Yucca Mountain, Nevada, is being evaluated by the U.S. Department of Energy as a host rock for a potential mined geologic repository for high-level radioactive waste. Assessment of site suitability needs an efficient and focused investigative program. A conceptual hydrogeologic model that simulates the flow of fluids through the unsaturated zone at Yucca Mountain was developed to guide the program and to provide a basis for preliminary assessment of site suitability. The study was made as part of the Nevada Nuclear Waste Storage Investigations Project of the U.S. Department of Energy.

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 10°. The central block of Yucca Mountain, the primary area being evaluated for a potential repository, is bounded by major steeply dipping faults or fault zones. The central block is less faulted than the other blocks, but is transected by a few normal faults.

Thickness of the unsaturated zone is about 1,640 to 2,460 feet (500 to 750 meters). Based on physical properties, the rocks in the unsaturated zone are grouped for the purpose of this paper into five informal hydrogeologic units. From top to bottom these units are: 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 unit cubic meter, mean matrix porosities of 12 to 23 percent, matrix hydraulic conductivities with geometric means ranging from 6.5 x 10^{-6} to 9.8 x 10^{-6} foot per day (2 x 10^{-6} to 3 x 10^{-6} meter per day), and bulk hydraulic conductivities of 0.33 to 33 feet per day (0.1 to 10 meters per day). The nonwelded units have a mean fracture density of 1 to 3 fractures per unit cubic meter, mean matrix porosities of 31 to 46 percent, and saturated hydraulic conductivities with geometric means ranging from 2.6 x 10^{-5} to 2.9 x 10^{-2} foot per day (8 x 10^{-6} to 9 x 10^{-3} meter per day).

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Average annual precipitation at Yucca Mountain is estimated to be 5.9 inches (150 millimeters) per year; less than 0.002 inch (0.5 millimeter) per year becomes recharge to the saturated zone. Surface runoff is infrequent and of short duration, and no perennial streams exist in this area. Precipitation occurs during a few intense storms. Water infiltrates principally into the Tiva Canyon welded unit, but also into alluvial surficial deposits, the Paintbrush nonwelded unit, and the Topopah Spring welded unit, where these deposits or units are exposed at the land surface.

According to the conceptual model of flow in the unsaturated zone, percolation through the matrix principally occurs 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 features, and much of it travels directly to the water table.

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 Project 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 1,640 to 2,460 ft (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 Miocene 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 et al., 1984). In addition, these rocks have a fracture density (Scott et al, 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 tuff that overlies the potential host rock probably forms a natural capillary barrier to retard the entrance of water into the fractured tuff. A similar sequence of nonwelded tuff underlies the potential host rock. This underlying nonwelded tuff locally contains 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

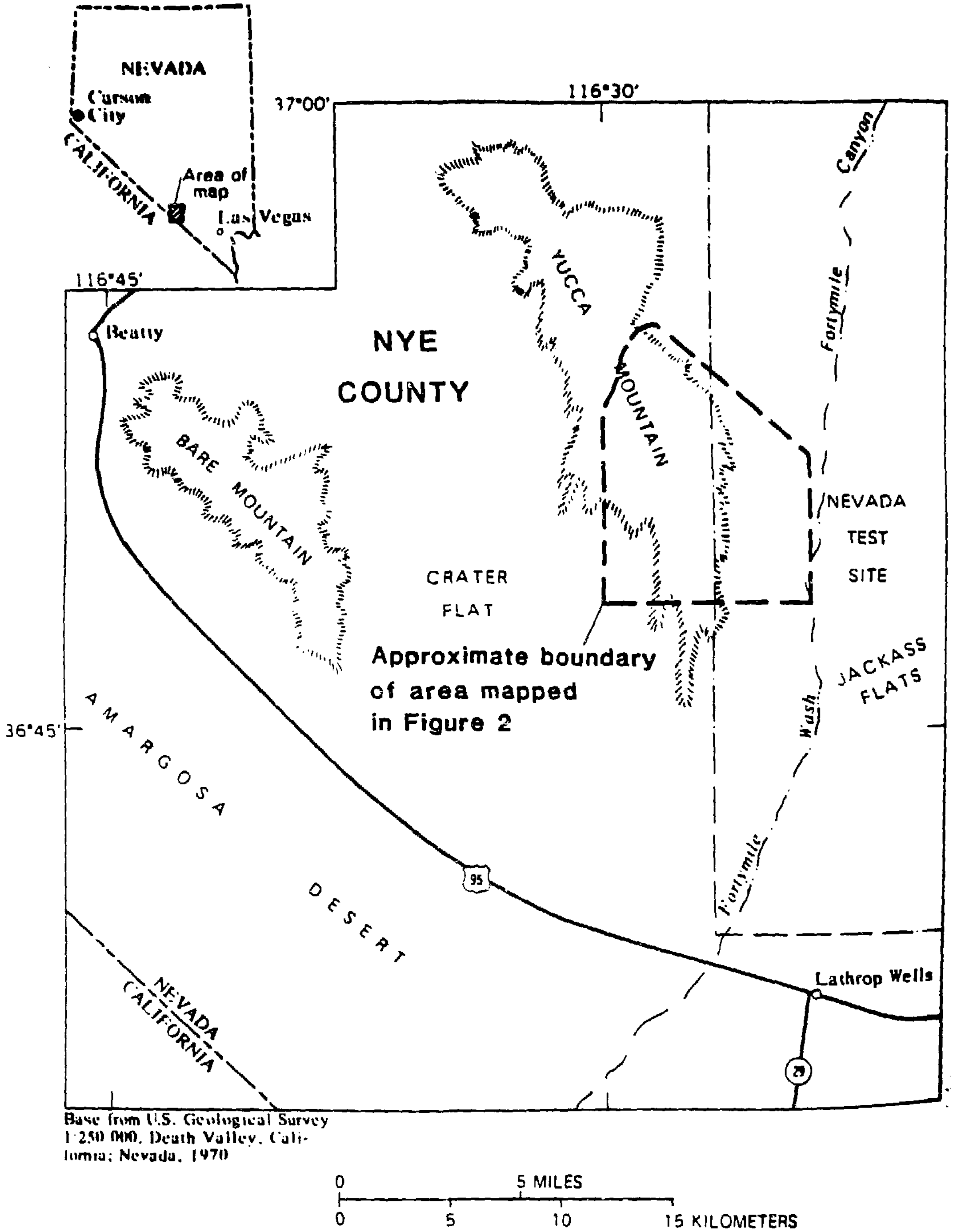
The purpose of this paper is to describe the hydrogeologic setting of the unsaturated zone at Yucca Mountain and to examine some conceptual hypotheses of flow of fluids through this hydrogeologic system. Scott et al. (1983) presented an initial conceptual hydrogeologic model for the unsaturated zone 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. Much of this report is from a more detailed description given by Montazer and Wilson (1984).

Extensive geologic information but relatively few hydrologic data 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 in this report 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. However, the framework presented in this paper provides sufficient flexibility for future adjustments of the boundary conditions and, thereby, modification of the model.

General 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 65 mi (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.

Yucca Mountain is in the Great Basin physiographic province. The maximum altitude of the central block is 4,950 ft (1,509 m). Along the highest ridge within the central block (Yucca Crest, fig. 2), altitudes generally are between 4,806 and 4,840 ft (1,465 and 1,475 m). The crest is about 1,510 ft (460 m) above Jackass Flats (fig. 1) to the east, and about 590 ft (180 m) above Solitario Canyon to the west. Topography of the mountain is rugged. The mountain consists of a series of north-trending fault-block ridges underlain 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.



Approximate boundary of area mapped in Figure 2

Base from U.S. Geological Survey 1:250 000, Death Valley, California; Nevada, 1970

Figure 1.--Location of Yucca Mountain

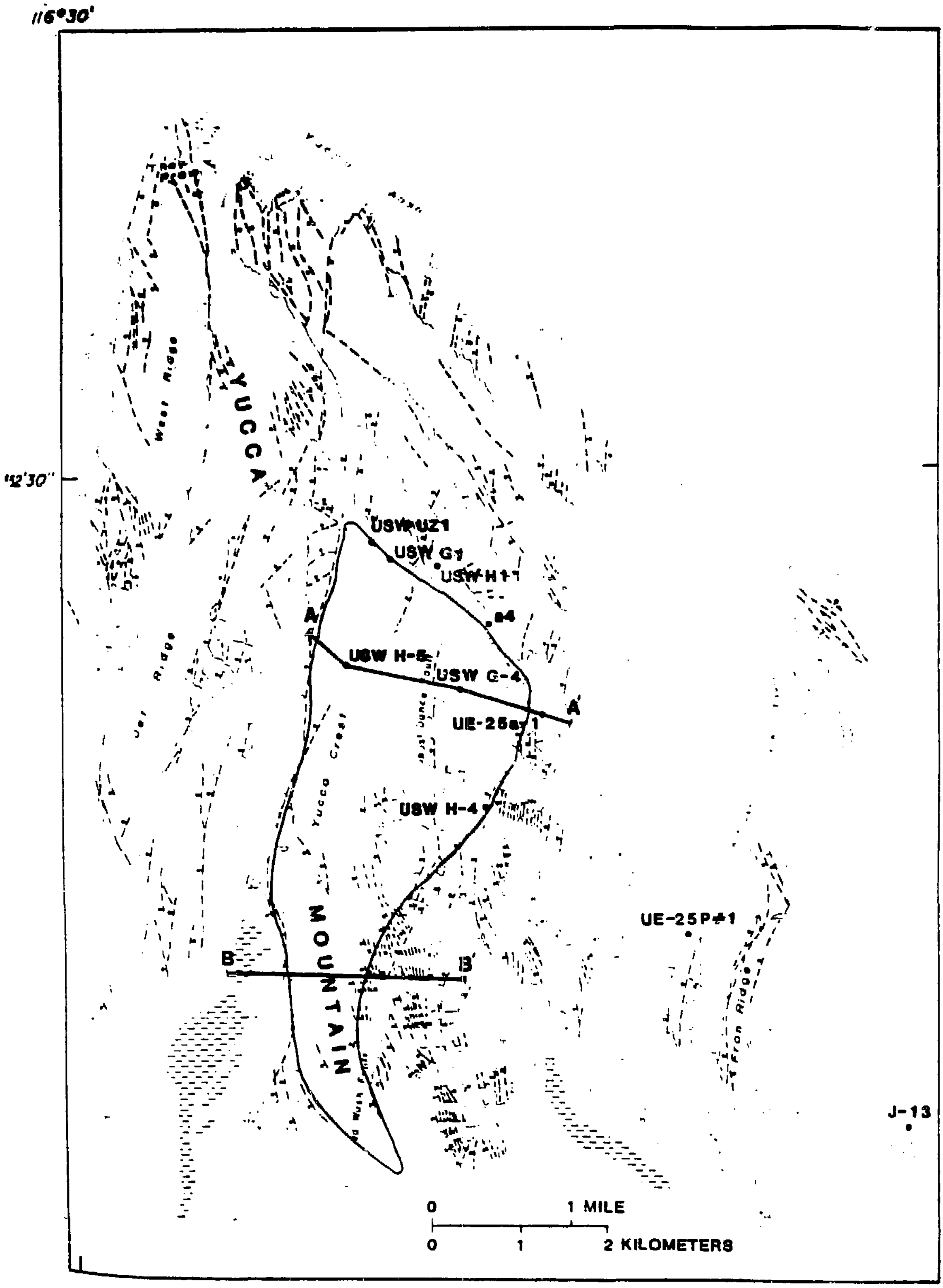


Figure 2.--Generalized geologic map of the Yucca Mountain central block and vicinity (modified from Montazer and Wilson 1984; Scott and Castellanos, 1984).

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

CONTACT

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

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

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 5.9 in/yr (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 tuff 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 (including the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members), tuffaceous beds of Calico Hills, and Crater Flat Tuff (including the Prow Pass and Bullfrog Members). 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 tuff. 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.

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 330 ft (100 m) of vertical separation (Scott et al., 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 tuff than in nonwelded tuff (Scott et al., 1983).

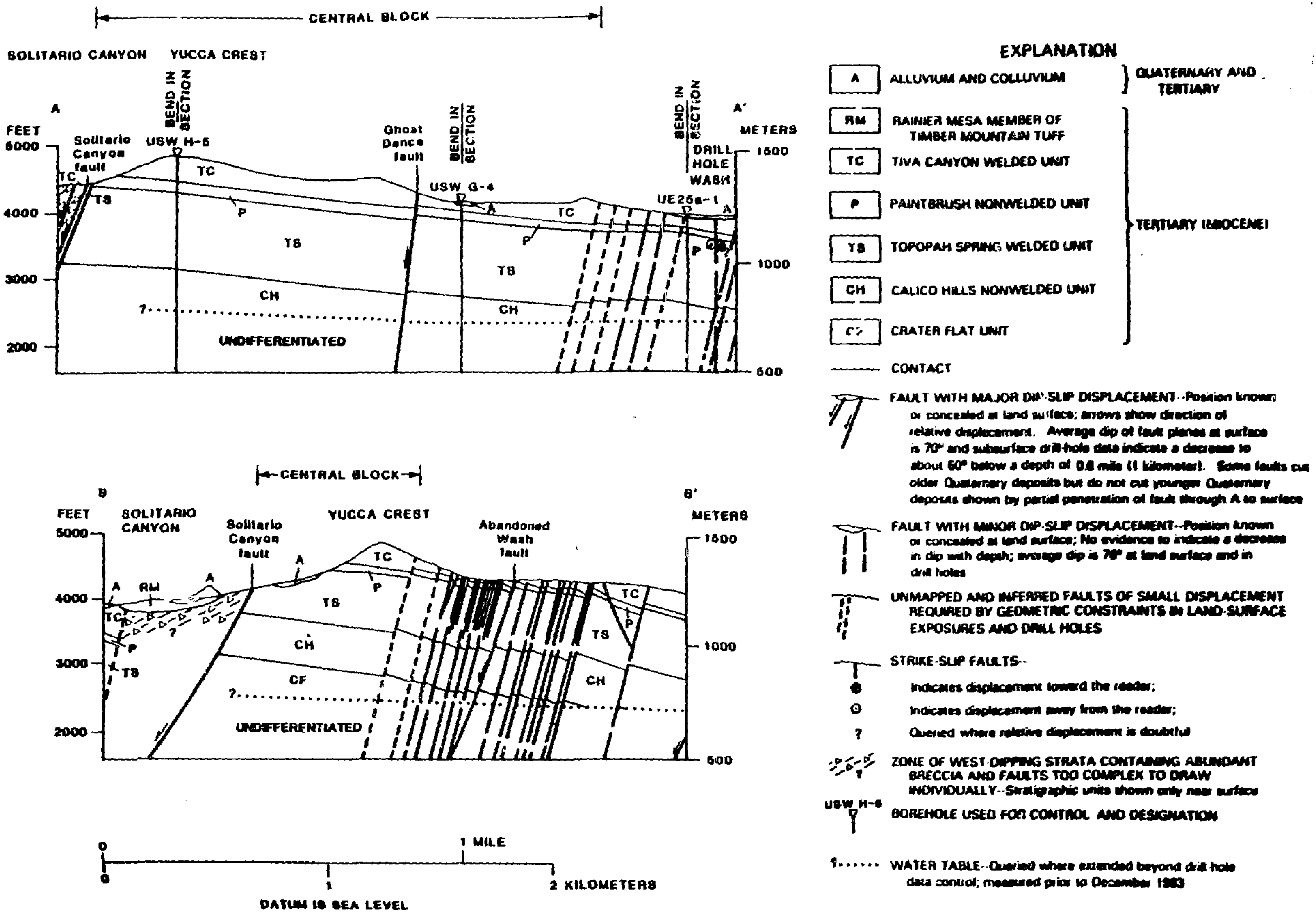


Figure 3.--Hydrogeologic sections across Yucca Mountain (modified from Montazer and Wilson, 1984; Scott and Bonk, 1984)

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 long, 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 thick unsaturated zone occurs beneath Yucca Mountain. The water table ranges in depth from about 2,395 to 2,560 ft (730 to 780 m) (Robison, 1984). This depth range, combined with the rugged topography of the mountain, gives a range of unsaturated-zone thickness of about 1,640 to 2,460 ft (500 to 750 m).

Hydrogeology

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 et al. (1983) and as that used informally within the NNWSI Project. Hydrogeologic units consisting of vitrophyres and moderately to densely welded devitrified tuff alternate with hydrogeologic units consisting of nonwelded to partially welded tuff and bedded tuff. 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.

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). 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 (0.33 to 33 ft/d, or 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 (6.5×10^{-6} to 9.8×10^{-6} ft/d, or 2×10^{-6} to 8×10^{-6} m/d) are substantially less than hydraulic conductivities of the vitric facies and bedded layers of the nonwelded units (.013 to 0.03 ft/d, or 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.

Table 1.--Summary of hydrologic properties of hydrogeologic units (modified from Montazer and Wilson, 1984)

(MD, moderately to densely welded; NP, nonwelded to partially welded; (V), vitric; (D), devitrified; B, bedded; fractures/m³, fractures per cubic meter; fractures/yd³, fractures per cubic yard; Std. dev., standard deviation; m/d, meters per day

Stratigraphic unit		Tuff lithology	Hydrogeologic unit	Approximate range of thickness[1], in feet (meters)	Fracture density[2], in fractures/yd³ (fractures/m³)	Generalized permeability[3]		Matrix properties (from analyses of core)[4]											
								Porosity (percent)			Saturation (percent)			Water content by weight (percent)			Hydraulic conductivity, in ft/d (m/d)		
																	Saturated		Effective
						Matrix	Fracture	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]
Alluvium		----	Alluvium	0-98 (0-30)	----	Generally substantial	----	--	--	----	--	--	--	--	----	----	--	------	---------
Paintbrush Tuff	Tiva Canyon Member	MD	Tiva Canyon welded unit	0-492 (0-150)	8-16 (10-20)	Negligible	Substantial	12	12	7.6	6	67	23	6	5.1	6.5	11	6.6×10^{-6} (2×10^{-6})	
	Yucca Mountain Member Pah Canyon Member	NP, B	Paintbrush nonwelded unit	65-328 (20-100)	1 (1)	Moderate	Small?	14	46	11	9	61	15	9	19	11	5	3×10^{-2} (9×10^{-3})	9.8×10^{-4} ([5]3×10^{-4})
	Topopah Spring Member	MD	Topopah Spring welded unit	951-1180 (290-360)	6-30 (8-40)	Negligible	Substantial	56	14	5.5	44	65	19	29	5.5	2.8	27	9.8×10^{-6} (3×10^{-6})	5.2×10^{-7} ([6]1.6×10^{-7})
Tuffaceous beds of Calico Hills		NP, B (V)	Calico Hills nonwelded unit Water table Saturated zone	328-1312 (100-400)	2-3 (2-3)	(V) Substantial	Small?	5 (V)	37	8	1 (V)	90	--	-- (V)	----	----	4 (V)	1.3×10^{-1} (4×10^{-2})	(V) 5×10^{-4} ([6]1.5×10^{-4})
Crater Flat Tuff	Prow Pass Member	(D) (in part zeolitic)				(D) Small to negligible		(D) 34	31	7.5	(D) 25	91	6	26	16	5	(D) 22	2.6×10^{-5} (8×10^{-6})	(D) 5.2×10^{-8} ([6]1.6×10^{-8})
	Bullfrog Member	MD, NP, B (undifferentiated)	Crater Flat unit	656 (0-200)	6-19 (8-25)	Variable	Variable	42	23	6.4	21	90	4.7	--	----	----	19	5×10^{-6}	--------

[1] Thickness from geologic sections of Scott and Bonk (1984).

[2] Scott et al. (1983).

[3] Inferred from physical properties.

[4] Sources: Anderson (1981); R.R. Peters (Sandia National Laboratories, written commun., 1983); Bush et al. (1983); Thordarson (1983); Weeks and Wilson (1984).

[5] [6] Single values of relative permeability from Weeks and Wilson (1984) (5) and from G.W. Gee (Pacific Northwest Laboratories, written commun., 1983) (6) were applied to the geometric means of saturated hydraulic conductivity.

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.

Conceptual Model of Flow

The manner in which flow probably occurs in the unsaturated zone at Yucca Mountain is described hereafter, 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. A detailed description of the conceptual model of flow is given in Montazer and Wilson (1984).

Average annual precipitation at Yucca Mountain is estimated to be about 5.9 in/yr (150 mm/yr). From analyses of the relationships among precipitation, recharge, and altitude, recharge to the saturated zone is conservatively estimated to be about 0.02 in/yr (0.5 mm/yr). This value probably approximates 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. Estimates of flux distributions are summarized as follows (Montazer and Wilson, 1984): (1) From 0.004 to about 4 in/yr (0.1 to about 100 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 4 in/yr (100 mm/yr), and the potential lateral volumetric flow rate is about twice the maximum estimated volumetric infiltration rate; (3) from 4×10^{-3} to 2×10^{-2} in/yr (0.1 to 0.5 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 2.4×10^{-4} in/yr (0.006 mm/yr) in the downward direction; and (5) results of analyses of the geothermal heat-flux data show that about 1×10^{-3} to 2×10^{-3} in/yr (0.025 to 0.05 mm/yr) of upward 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.

The general concept of flow at Yucca Mountain is illustrated in the section shown in figure 4. Flow through the unsaturated system is initiated by infiltration of precipitation at the land surface. 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 is not lost by evapotranspiration and interflow becomes net infiltration and moves rapidly downward through fractures of the Tiva Canyon welded 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 flow occurs through the matrices 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.

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 feet 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 nonwelded 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 unsaturated lateral flow along the contact between the Tiva Canyon welded and the Paintbrush nonwelded 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 moves 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 welded unit; however, movement 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 be smaller than the downward liquid flux. Probably only a small part of the net infiltration is transmitted through the Topopah Spring welded unit. The excess net infiltration probably flows laterally into the structural features, which, therefore, transmit the major part of the infiltrated water.

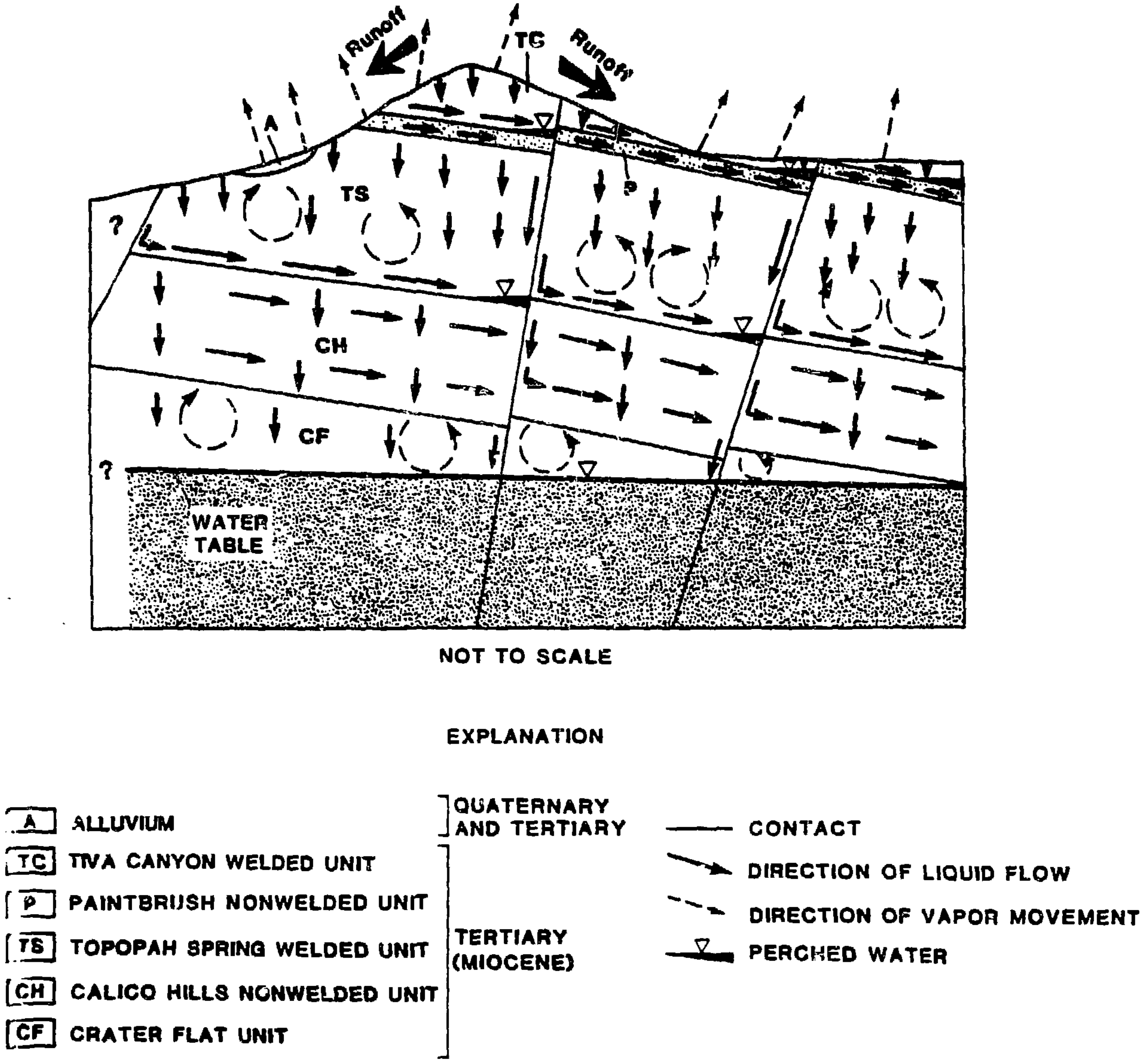


Figure 4.--Generalized section across Yucca Mountain showing conceptualized flow regime. Lengths of solid arrows show relative magnitudes of fluxes (modified from Montazer and Wilson, 1984).

Flow enters the Calico Hills nonwelded unit either from the matrix of the Topopah Spring welded unit or 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 nonwelded unit. This laterally moving water percolates downward into the matrix of the Calico Hills unit. Vertical flux through this unit probably is limited to 2.4×10^{-4} in/yr (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 tuff units 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.

Conclusions

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 types 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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