Ron
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U.S. GEOLOGICAL SURVEY

Yucca Mountain Project Branch
1261 Town Center Drive, Room 423
Las Vegas, NV 89134

WBS: 1.2.3.3.1.2.4
QA: N/A
September 11, 1996

Susan B. Jones
Assistant Manager for Scientific Programs
Yucca Mountain Site Characterization Office
U.S. Department of Energy
P.O. Box 98608
Las Vegas, NV 89193-8608

PERCHED WATER

Attention: Russell Patterson

Subject: Completion of Level 4 Milestone 3GUS600M: Memo to Technical Project Officer (TPO) - Results of Perched Water Testing

The subject Level 4 Milestone has been completed and is submitted for your information. If you have any questions please call me at 295-5171.

Sincerely,

Robert W. Craig

Robert W. Craig
Technical Project Officer
U.S. Geological Survey
Yucca Mountain Project Branch

Enclosure

cc: w/enclosure:
D. Hoxie, USGS

cc: w/o enclosure:
L. Hayes, M&O/TRW
R. Williams, Jr., USGS
R. Arnold, USGS
D. Gillies, USGS

United States Department of the Interior

U. S. GEOLOGICAL SURVEY
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Denver, Colorado 80225

IN REPLY REFER TO:

WBS 1.2.3.3.1.2.4
Information Only

MEMORANDUM
September 6, 1996

To: R. W. Craig, Chief, Yucca Mountain Project Branch, Las Vegas, NV

From: D. C. Gillies, Chief, Unsaturated Zone and Infiltration Studies Team

Subject: Completion of Level 4 Milestone 3GUS600M (Memo to TPO: Results of Perched Water Testing

As per the milestone "description and completion criteria" (copy attached), please find enclosed three copies of the Memorandum to the Technical Project Officer, "Perched Water Characteristics and Occurrences, Yucca Mountain, Nevada".

cc: w/o enclosures

G. Patterson, YMPB
P. Striffler, YMPB
T. Brady, YMPB
R. Arnold, YMPB
T. Williams, YMPB

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT
PARTICIPANT DELIVERABLE MILESTONE WORK SHEET

Code 3GUS600M
(Project Control Use Only)

Participant U.S. Geological Survey **WBS** 1.2.3.3.1.2.4
(P&S LEVEL)

SA # 0G33124F96 **SA Title** Perched Water Testing in the Exploratory Shaft Facility

Milestone Title MEMO TO TPO: RESULTS OF PERCHED-WATER TESTING

Milestone Level 4

Expected Completion Date 08/30/96

YMSCO Assistant Manager S. Jones **WBS Element Manager** R. Patterson

Description and Completion Criteria

This level 4 milestone will describe the results and interpretation of all observations, tests, and samples for each occurrence of perched water or moist-rock zones in the ESF or in any boreholes drilled in the vicinity of the ESF. Water chemistry and hydraulic characteristics of the perched reservoir will be described. Also included in this report if possible, will be projections of where perched water may occur in or beneath the Main Drift and South Ramp of the ESF.

This report will provide information critical to the understanding of the hydrogeologic conditions causing the accumulation of perched water; whether perched water is a transient or permanent feature; and the implication of a perched reservoir on flux, flow paths, and travel time.

This milestone will be met when the memorandum (plus two information copies) containing the above described information is submitted to the USGS-YMPB TPO. Technical summary may be published subsequent to TPO acceptance and approval.

Code:	assigned by Project Control
Participant:	enter name of YMP participant responsible for milestone
WBS:	enter WBS number from WBS Dictionary at lowest level
Description:	enter description (50 characters)
Expected Completion Date:	enter date the milestone is due at YMPO/NV
WBS Element Manager:	enter name of YMPO person in charge of WBS
Criteria:	enter the deliverable or action that will satisfy the milestone

Submitted By Gary L Patterson **Submittal Date** 1/2/96
Summary Account Manager

Approved By (Same) **Approval Date**
Project Chief

Approved By Daniel C. Gillies **Approval Date** 1-2-96
Team Chief

Approved By Robert W. Craig **Approval Date** 1/17/96 version

AUG 29 1996

PERCHED WATER CHARACTERISTICS AND OCCURRENCES, YUCCA MOUNTAIN, NEVADA

by Pete Striffler, Grady M. O'Brien, Thomas Oliver, and Paul Burger

U.S. GEOLOGICAL SURVEY

Memo to the Technical Project Officer

DRAFT

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY,
NEVADA FIELD OFFICE, under
Interagency Agreement DE-AI08-92NV10874

Denver, Colorado
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary
U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Figures

Tables

CONVERSION FACTORS

Multiply	By	To obtain
meters	3.281	feet
feet	0.3048	meters
square meters	1×10^{-6}	square kilometers
square kilometer	0.3861	square mile
cubic meters	0.001	liters
liters	0.2642	gallons
liters per second	15.853	gallons per minute
liters per second	86.4	cubic meters per day
liters per second	543.44	barrels per day
millidarcies	9.869×10^{-16}	square meters
millidarcies	1.062×10^{-14}	square feet
centipoise	0.001	pascal seconds
meter squared per day	10.765	feet squared per day
pound per square inch	6.895	kilopascal
pound per square inch^{-1}	1.450×10^{-4}	pascal^{-1}
kilograms per cubic meter	3.613×10^{-5}	pounds per square inch
kilogram	2.205	pounds

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5\ °C + 32.$$

Abstract

Perched water in the fractured tuff at Yucca Mountain, Nevada has important hydrologic implications for the travel times and flow paths of water moving through the unsaturated zone. Perched-water zones indicate a slowing of vertical water movement through the unsaturated zone that could cause water to flow horizontally along the perching layer and possibly affect the construction of a high-level nuclear-waste repository.

The incidence of perched water in five boreholes (USW UZ-1, USW UZ-14, USW SD-7, USW NRG-7A, and USW SD-9) in the general vicinity of Yucca Mountain was evaluated. The geologic and hydrologic character of these zones was examined using fracture, lithologic, and hydrologic logs. When available, chemistry and hydraulic test data were used to further determine the nature of the perched-water zones.

The perched water in all of the boreholes was detected at depths of 383 to 492 meters, at least 100 meters above the water table. The perched-water zones were generally in fractured rock units with an impermeable matrix overlying less fractured rock units with a more permeable matrix. In two of the boreholes, USW UZ-14 and USW SD-9, a televiewer log showed water entering the boreholes through discrete fractures. This indicates that the relative fracture frequency and fracture permeability have a strong influence on the accumulation of perched water. Two boreholes, USW UZ-14 and USW SD-7, are located near faults which may be acting as structural dams, allowing water to accumulate in significant amounts.

Pumping tests of the perched water were performed at UZ-14 and SD-7 to determine hydraulic conductivity, and to attempt to quantify the size of the bodies of water. Several feet of residual drawdown after the tests at SD-7 verify that the aquifer is a discreet perched water body, whereas UZ-14 recovered completely and indicates a more extensive water body. The quick rate of recovery at SD-7, relative to pumping tests performed at UZ-14, indicate that the hydraulic conductivity of the SD-7 aquifer is much higher.

Chemical analyses of the perched waters show similarities with regional ground water; chemical composition is similar but relative concentrations differ. Perched water comparisons with pore water chemistry indicate that the water held in the matrix has little influence on perched water, and that the perched water probably moves quickly through fractures.

Although the perched water detected is significantly deeper than the proposed underground Exploratory Studies Facility (ESF) tunnels, the geologic conditions are favorable for the formation of perched-water zones at depths that will be reached by the excavation. To some extent, perched water probably exists near the base of the Topopah Spring Tuff virtually everywhere in the vicinity of the ESF.

Introduction

Yucca Mountain, Nevada is the site under consideration by the U.S. Department of Energy (DOE) as the Nation's first mined geologic repository for storing commercial high-level radioactive wastes. The U.S. Geological Survey (USGS) has been investigating Yucca Mountain and the surrounding region to allow DOE to assess the suitability of the site as a repository.

Using current conceptual designs, the radioactive wastes would be placed within the thick deposits of unsaturated volcanic tuff beneath Yucca Mountain. Investigations are underway to evaluate the hydrologic conditions, processes, and properties of the unsaturated zone at this site. Perched water in the unsaturated fractured tuff at Yucca Mountain has important hydrologic implications for the travel time and flow paths of water in the unsaturated zone. Perched-water zones may indicate a slowing of vertical water movement through the unsaturated zone and could cause water to flow horizontally along the perching layer. The occurrence of perched water in the tuffs surrounding the repository could affect the suitability and design of the site as a high-level radioactive waste repository.

The primary goals of the Perched-Water Study are to detect perched water, estimate the hydraulic properties of perched-water zones, and determine their implications on water flux, flow paths, and travel times. The purpose of this paper is to present preliminary information on the perched water detected to date, including known perched water occurrences and perched water chemistry. Preliminary lithologic and fracture logs were used together with pumping test data to infer the hydraulic properties of the perched-water zones, and to evaluate the significance and extent of the perched water bodies.

General Site Description

A generalized map showing the location of Yucca Mountain is shown in figure 1. Yucca Mountain is located in the driest region of the United States. Precipitation in the Yucca Mountain vicinity ranges from 110 mm/yr to 270 mm/yr, increasing to the northwest (Hudson, U.S. Geological Survey, written commun., 1996). Precipitation is greater at higher altitudes than at lower altitudes. Spatially averaged annual precipitation at Yucca Mountain is estimated to be 161 mm, however most of the water is lost to evapotranspiration; an aerially averaged 11.6 mm/yr infiltrates into the subsurface, (Hudson, U.S. Geological Survey, written commun., 1996).

No perennial streams occur in the area; intense thunderstorms cause short-lived flash floods. In the winter, infrequent snowfall occurs throughout much of the area, but the snow melts or evaporates quickly except in the higher ranges. The altitude of Yucca Mountain (about 1,460 m) generally is too low for snow to persist for more that a few days.

The only reliable sources of surface water are springs, but because of the aridity of the region, most of the water discharged by the springs travels only a short distance before evaporating or infiltrating into the ground. During heavy rains, however, transient floods do occasionally occur in arroyos.

Stratigraphy and Lithology

Yucca Mountain is composed primarily of ashflow and ashfall tuffs that form north-trending fault block ridges. The tuff units thicken to the north end of Yucca Mountain, indicating that the probable source area is the Timber Mountain-Oasis Caldera Complex (Diehl and Chornack, 1990). The exception is the bedded tuffs at the base of the Calico Hills Tuff, whose source area appears to be to the east-northeast of Yucca Mountain (Diehl and Chornack, 1990).

The generalized stratigraphy of the unsaturated zone of Yucca Mountain is shown in Table 1 including the proposed nomenclature of Buesch and others (1996) based on composition and physical characteristics. At Yucca Mountain, the repository would be constructed in the Topopah Spring Tuff of the Paintbrush Group. Of the four formations of the Paintbrush Group, the Topopah Spring Tuff is the lowermost, thickest, and most extensive in the Yucca Mountain area. The Topopah Spring Tuff consists of a multiple-flow, compound cooling unit, and most of it is moderately to densely welded devitrified tuff (Sawyer and others, 1994). Lying below the Paintbrush Tuff are the tuffaceous beds of the Calico Hills Tuff and older tuffs (Table 1).

Hydrology

Hydrologic investigations of the region surrounding the Yucca Mountain site were begun in the late 1950s to evaluate the hydrologic system at the Nevada Test Site. Hydrologic studies for the repository project were started in 1978. Since 1981, boreholes more than 1 mile deep have been drilled into the saturated zone, and tests have been performed to determine parameters as: depth to the water table, total water yield, hydraulic conductivity, transmissivity, and water chemistry. Multiple-well tests are continuing to determine effective porosity and the nature and extent of the contribution of fractures to permeability.

When the advantages of locating the proposed repository in the unsaturated zone became apparent, the emphasis of the studies shifted from the saturated zone to the unsaturated zone. Beginning in 1983, boreholes deeper that 300 meters were drilled into the unsaturated zone, and these holes have been used to monitor the ambient water saturation, water potential, and water and gas flux in the rocks above, below, and in the proposed repository horizon.

The data from rock samples show a wide variation in hydrologic properties among the various hydrogeologic units in the unsaturated zone, however unsaturated-zone flow in and around Yucca Mountain can be characterized generally by primarily matrix flow in the nonwelded rock units and fracture flow in the moderately to densely welded rock units (Montazer and Wilson, 1984, p. 12). The moderate to densely welded rock units have more fractures than the nonwelded rock units. The behavior of the flow system is further complicated by the presence of several major faults and fault zones that potentially have a strong influence on water movement (Montazer and Wilson, 1984, p. 20).

A generalized cross section and conceptual model of flow (fig. 2) show primarily vertical flow in the welded rock units and both horizontal and vertical flow in the less welded rock units. The model shows some lateral movement of water along the nonwelded/welded contacts as well as flow in faults and perching at fault contacts.

The hydrologic conditions at the site are critical to the long-term performance of the repository because hydrologic conditions may affect the performance of the waste package. In addition, the movement of ground water is the principal mechanism for transporting radionuclides to the accessible environment. Hydrologic conditions must also be considered for the preclosure period because they may affect the construction and operation of the repository and the safety of workers. At Yucca Mountain, the unsaturated zone is thick enough (500 to 700 m thick, depending on local topography) to allow the construction of a repository about 200 to 400 meters above the top of the water table. The occurrence of perched water could pose unexpected safety and construction hazards.

Geochemistry

The geochemical environment of the host rock may affect the long-term performance of the repository by affecting the waste package and by retarding the transport of radionuclides (Serne, 1990). The ground water sampled from boreholes that penetrate the host rock and the adjacent units near the proposed repository is of the sodium bicarbonate type, with low total dissolved solids; 100 to 400 milligrams per liter (Benson and McKinley, 1985). Dominant cations are sodium, calcium, potassium, and magnesium. Sodium is most abundant, accounting for 65 to 95 percent of the cations present (Benson and McKinley, 1985). Measurements of the oxidation-reduction potential and the dissolved-oxygen content indicate that most of the waters are oxidizing.

The characteristics of the ash-flow tuffs at Yucca Mountain, especially those of the nonwelded tuffs lying above and below the potential repository horizon, would allow several types of radionuclide retardation. For example, the chemical conditions are such that some of the key radionuclides (the actinides) are more likely to precipitate than to remain in solution in any available liquid water (Thompson, 1988). Another retardation mechanism is matrix diffusion which may occur in fractured rocks with a low matrix permeability. The radionuclides that are carried by flow in a fracture will diffuse into the matrix and back into the fracture, thus requiring a longer time for travel than does the water traveling through the fracture. In addition, minerals with a high sorption capacity (zeolite and clays) are present along potential paths of ground-water flow below the repository and in the saturated zone (Burns and others, 1990).

Perched Water Formation

Perched water can be defined as a saturated zone not directly associated with the static water table (Freeze and Cherry, 1979). The perched-water zone geometry can vary with time and moisture fluctuations, and could allow large amounts of water to be mobilized. Perched water, if extensive, could interfere with the construction and operation of the ESF at Yucca Mountain by affecting the rate of recharge to the saturated zone and changing the flow paths of the hydrologic system.

Perched water may indicate that recharge rates through the unsaturated zone are locally at least as great as the hydraulic conductivity of the confining layer. Perched water can accumulate where there are hydraulic conductivity differences between abutting rock units (Fetter, 1988). A generalized section across Yucca Mountain (fig. 3) shows some likely scenarios for the accumulation of perched water: (1) shows perched water where the relatively permeable nonwelded rock units overlie partially to densely welded tuffs that have a much smaller matrix permeability if the latter are locally relatively unfractured.

(2) Perched water in fracture-flow environments can be found where a highly fractured unit overlies a relatively unfractured unit. Cecil and others (1991) found perched-water zones where highly fractured basalts were underlain by sedimentary interbeds with poor vertical conductivity. Similar occurrences were found in interflow baked zones and where a highly fractured basalt was underlain by an unfractured basalt. Reductions in vertical conductivity can be found where the fractures become filled either with sediment or by chemical precipitation (Cecil and others, 1991). The near- surface fractures at the ESF have had some infilling by calcareous and siliceous materials. During the construction of the starter tunnel of the ESF, several subhorizontal "foliation planes" were encountered; a significant number of fractures terminated against these planes, and some were constrained between two planes (Beason, U.S. Bureau of Reclamation, written commun., 1996). These planes could represent a break in vertical fracture conductivity and might cause perching.

(3) Permeability contrasts could occur potentially at stratigraphic contacts as well as where rock units of different permeability are faulted against each other where movement of water is toward the fault.

(4) Thordarson (1965) found vertical conductivity differences between two units of the Rainier Mesa Tuff on the Nevada Test Site. Perched-water zones were detected near the top of a zeolitic tuff where the fractures were poorly connected and the matrix had a low permeability, greatly reducing the effective conductivity relative to the overlying units. The water was trapped in isolated fractures, and flow only occurred when the individual fractures were secondarily connected. In this case, the fractures were connected to each other naturally by faulting and artificially by drilling and tunneling.

Isolated, water-filled fractures are unimportant in that these do not represent large water bodies nor do they indicate significant geologic control of flow paths in the unsaturated zone. Only if this effect were widespread would it be treated as a significant perched-water zone. Faults filled with sediment, minerals, or other debris could be more important. The capacity of fault zones to collect and transmit water is an important issue because a fault could provide a relatively fast flow pathway. A fault can also connect many fractures that would otherwise be isolated and concentrate flow along a single conduit. Faults in very low permeability rocks can also serve to collect and transmit the water while the surrounding matrix remains unsaturated. Faults may also act as structural barriers to flow, collecting water from fracture or matrix flow in a relatively permeable rock unit and damming it against an impermeable unit displaced by the fault. In this case the capacity for the fault to collect water is greater than the capacity of the fault to transmit water, and an accumulation of perched water results.

(5) Perched water can accumulate as the result of capillary effects. The capillary barrier to downward flow, or field capacity, was defined by Case (1981) as the degree of saturation the rock matrix can sustain by capillary forces against gravity. Capillary forces have a significant effect on the rock's ability to transmit water downward through the matrix.

If flow occurs primarily through the matrix, capillary barrier effects would be expected to occur where densely welded tuffs overlay nonwelded tuffs such as at the contact between the Tiva Canyon welded unit and the Paintbrush Tuff nonwelded units. In this case, the nonwelded matrix takes all of the flow from the densely welded unit and acts as a capillary barrier.

If conditions were sufficient to initiate fracture flow, capillary barrier effects would be expected to occur between the nonwelded units and the relatively large apertures of the fractures in the underlying welded units such as at the contact between the Paintbrush Tuff nonwelded unit and the Topopah Spring Tuff welded unit. Wang and Narasimhan (1986) demonstrated that fracture flow will not be initiated until the matrix is fully saturated even for large, long-duration pulses. They also showed that damping by the matrix in both the Tiva Canyon welded unit and Paintbrush Tuff nonwelded unit would prevent fracture flow in the Topopah Spring Tuff. Using laboratory measurements, Flint and others (1993) found that the unsaturated permeability of the Paintbrush Tuff nonwelded unit was higher than the saturated permeability of the overlying Tiva Canyon welded unit. The difference in permeabilities was not sufficient for the nonwelded unit to act as a capillary barrier to flow.

Flint and others (1993) also theorized that the vitric caprock (Tptrn, Table 1) and the basal vitrophyre (Tptpv, Table 1) of the Topopah Spring Tuff could act to restrict flow due to their low conductivities. However, lateral flow within a highly permeable layer above the caprock was hypothesized (Flint and others, 1993) to preclude the presence of perched water. One-dimensional modeling of the system showed no perching at the basal vitrophyre, but fluxes were assumed to be so small that these layers could transmit them without perching.

Nitao and others (1992) showed that it is possible to initiate fracture flow without fully saturating the matrix. Fracture flow can begin before complete matrix saturation if the fracture can transmit water at rates greater than those at which can be imbibed by the matrix. This situation can arise if the fractures are sufficiently wide, an ample supply of water exists, and if fluid exchange with the matrix is inhibited either by inherently small matrix permeability, entrapped air, or fracture coatings. Environmental tracers associated with atmospheric testing of nuclear weapons have been detected in the nonwelded tuffs underlying the outcropping fractured, welded tuffs (Yang and others, 1996) indicating that the matrix imbibition of water moving along fractures has not been of a magnitude sufficient to prevent penetration of recharge through the fractures.

To use a fracture-flow model for the welded rock units, it is assumed that infiltration combined with the noncapillary effects of the fractures are sufficient to overcome the capillary effects of the matrix. In both cases of capillary barrier effects, the perched water would be a zone of increased saturation, lacking, however, sufficient positive pressure to actually produce water into a borehole or tunnel.

Borehole perched-water descriptions

Geologic and hydrologic data from surface-based boreholes were used to determine similarities and to evaluate the possibility of predicting perched water occurrence. The geologic and hydrologic information for USW UZ-14, USW NRG-7A, USW SD-7, and USW SD-9 has been taken from field logs, logbooks, and composite core logs (Mapa, M&O/SAIC, written commun., 1996). The information for USW UZ-1 was taken from published reports (Whitfield and others, 1990, and Whitfield, 1985).

USW UZ-1

Borehole USW UZ-1 is located in Drill Hole Wash northwest of Jackass Flats (fig. 1). The borehole was drilled to a depth of 387 m and was stopped when a possible perched-water zone was reached (Whitfield and others, 1990). The perched-water zone was reached in or just below the Topopah Spring Tuff (no geologic samples were taken below 370 m). Chemical testing showed that the water was heavily contaminated with water used to drill USW G-1, a borehole less than 300 m to the southeast (Whitfield and others, 1990, p. 6). During the drilling of USW G-1, approximately 8,700,000 liters of drilling fluid were lost into the rock (Whitfield, 1985).

[Figure 4. USW UZ-1 Stratigraphy and fracture frequency (from Whitfield and others, 1990).]

The perched water at USW UZ-1 was reached at a depth of 382 m, about 190 m above the predicted potentiometric surface (Luckey, U.S. Geological Survey, written commun., 1994). The simplified fracture and stratigraphic log (fig. 4) shows that the perched-water lies in a zone of less fracturing than the overlying rock. This could indicate that the water is moving relatively quickly through the more highly fractured rock and is being slowed by the less fractured underlying rock, resulting in a perched-water zone.

USW UZ-14

Borehole USW UZ-14 is located about 30 m northwest of USW UZ-1 in Drill Hole Wash. The borehole was drilled to a depth of 678 m. Perched water was encountered at a depth of about 381 m, near the upper contact of the basal vitrophyre of the Topopah Spring Tuff and about 190 m above the predicted potentiometric surface. An individual fracture produced water intermittently at a depth of about 453 m in the Calico Hills Tuff. When water was encountered, several pump tests were conducted. A drawdown test, run for about 3 days at an average pump rate of about 0.059 liters per second (Luckey, U.S. Geological Survey, written commun., 1994) recovered completely after about 5.6 days. This indicates that the perched-water zone may be an extensive perched-water body.

[Figure 5. USW UZ-14 stratigraphy and fracture frequency.]

The perched-water body in USW UZ-14 occurs near the upper contact of the basal vitrophyre (Tptpv, Table 1), the lowermost unit in a sequence of highly fractured pyroclastic rocks above relatively unfractured tuffs (fig. 5). The matrix permeability of the overlying lower nonlithophysal (Tptpln, Table 1) unit is almost 30 times higher than the matrix permeability of the vitrophyre (Flint and others, 1993). The matrix permeability of the vitrophyre is an order of magnitude lower than the underlying partially welded unit and up to six orders of magnitude lower than the nonwelded Calico Hills Tuff. The difference in matrix permeabilities alone would provide for perching on top of the vitrophyre and not at the base, as is indicated by the occurrence of perched water. For water to perch on top of the vitrophyre, the vitrophyre would have to be relatively unfractured. However, limited data from UE25-UZ#16 (LeCain, U.S. Geological Survey, written commun., 1994) show the air permeability of the vitrophyre is within an order of magnitude of the permeability of the Topopah Spring Tuff lower nonlithophysal zone. The air permeability of the nonwelded Calico Hills Tuff is two orders of magnitude less than the vitrophyre. If a correlation is assumed between air and fracture permeability, the fracture permeability in the nonwelded Calico Hills Tuff may be much lower than that of the vitrophyre. Water might be impeded on its way to the water table by the lack of fracture pathways in the nonwelded Calico Hills Tuff, and the perched water encountered at a depth of 381 m in the Topopah Spring Tuff may simply represent the upper part of the perched water body whose base is within the Calico Hills Tuff.

Another possible explanation for the formation of the perched water (Fridrich, U.S. Geological Survey, written commun., 1996), is a hypothesis that invokes the presence of a lateral barrier to flow that effectively ponds the perched water in the vicinity of UZ-1 and UZ-14. In this hypothesis, the lateral barrier may be formed by a northeast trending fault that is a splay off the Solitario Canyon Fault. This fault has been interpreted to be a growth fault, thus by definition it has greater offset and may be more laterally extensive at depth than at the surface. The structural trap that allows the perched water to accumulate is created by the juxtaposition of a more permeable layer (Tptpln or upper Tptpv, Table 1) west of the fault against a less permeable layer (the lower Tptpv or Tpbt1, Table 1) east of the fault. This fault may intercept the water flowing downdip along the crystal-poor vitric zone (Tptpv, Table 1) or zeolitic alteration boundary, and may not have sufficient transmissivity to allow the water to drain as rapidly as it accumulates. This combination could explain the presence of the thick perched-water reservoir at UZ-14 and UZ-1.

USW NRG-7A

Borehole USW NRG-7A is located in Drill Hole Wash. The borehole was drilled to a depth of 461 m into the top of the Calico Hills Tuff (fig. 6). Perched water was encountered between 458 m and total depth, just below the top of the bedded tuff (Tpbt1, Table 1). The water level in the borehole then rose about 30 m to stand at a depth of 428 m, or about 3.5 m above the base of the lower nonlithophysal zone (Tptpln, Table 1). The perched water was encountered about 90.1 m above the predicted potentiometric level for this borehole (Ervin and others, 1994, Plate 1). No televiewer logs of the borehole were run to determine the exact nature and location of the water influx. Based on information from other boreholes, it is probable that water entered the borehole prior to the initial detection during drilling.

[Figure 6. USW NRG7/7A stratigraphy and fracture frequency.]

Again, perched water was encountered near the contact of a series of highly fractured welded tuffs overlying relatively unfractured, nonwelded tuffs. This is similar to USW UZ-1 and USW UZ-14 where perched water may be entrapped in fractures while slowly imbibing into the matrix of the less fractured, underlying rock unit.

USW SD-9

Borehole USW SD-9 is located adjacent to Drill Hole Wash (fig. 1). The borehole was drilled to a depth of 663 m. Water was first noted at 449 m and a televiewer log showed water seeping through a fracture into the hole at a depth of 413 m, about 3 m above the base of the lower nonlithophysal zone (Tptpln, Table 1) and about 157 m above the predicted potentiometric level for SD-9 (Ervin and others, Plate 1). The contact between the welded Topopah Spring Tuff and the nonwelded Calico Hills Tuff is at a depth of about 446 m (fig. 7). The perched-water zone is in fractured welded tuff (Topopah Spring Tuff) underlain by less-fractured nonwelded tuff (Calico Hills Tuff). No pump tests have been run on this perched-water zone, and the extent of the perched-water body is uncertain.

[Figure 7. USW SD-9 stratigraphy and fracture frequency.]

USW SD-7

Borehole USW SD-7 is located on the east slope of Yucca Mountain (fig. 1). The borehole was completed at a total depth of 815 m. Water was first observed during coring at a depth of 488 m, in the bedded tuffs (Tacbt, Table 1) at the base of the Calico Hills Tuff. This level is 4.5 meters above the top of the Prow Pass Member, and about 143 m above the regional water-table (fig. 8). The perched water level subsequently rose 8 meters to a drilling depth of 480 m. The bedded tuff zone is stratigraphically complex, with argillically altered pumice in all layers, predominantly horizontal fractures (noted in core samples during drilling), and a well sorted volcanic sandstone layer with some lamination below 487 m (Wilcoxen, SAIC, written commun., 1995).

[Figure 8. USW SD-7 stratigraphy and fracture frequency.]

The occurrence of perched water at this depth may be directly related to the bedding layers in the Bedded Tuff (Tacbt, Table 1). The matrix permeability of the nonwelded vitric horizon is greater than that of the zeolitized horizon beneath it and the permeability differences alone may be sufficient to cause perched water. Lateral flow may contribute to form a significant body of water, and the horizontally fractured sandstone layer may also accommodate flow, and could be a water bearing stratum.

Similar to UZ-14, a structural dam may be present. Water flowing laterally along fractured bedding layers from west to east may encounter a fault to the east of SD-7. The permeable bedding layers abut the non to partially welded Prow Pass Member at the fault offset. Presumably, the fault does not have sufficient transmissivity to allow the water to drain as rapidly as it accumulates, forming the perched water body.

Hydraulic Tests at USW SD-7

Drilling operations were suspended to perform hydraulic testing during March, 1995. Following completion of testing in March, 1995, the borehole was cored an additional 9.1 m. A second series of hydraulic tests were completed during August, 1995. The single-hole hydraulic tests were conducted to obtain water-quality, transmissivity, and reservoir volume estimates of the perched water-body. The borehole was drilled to a total depth of 815 m following the conclusion of hydraulic testing in August, 1995.

Hydraulic Tests during March, 1995

Several hydraulic tests were conducted in borehole USW SD-7 during March, 1995. Prior to starting a long-term hydraulic test, the borehole was developed during pumping cycles that were several hours long, because it was necessary to remove drilling materials that may have artificially limited the permeability of the water-producing intervals. After repeatable drawdown curves were obtained, a longer-term hydraulic test was conducted. A 30-hour hydraulic test at a mean discharge rate of 0.21 l/s was conducted from March 20-21, 1995. Transmissivity was determined from drawdown data using two analytical solutions and the mean transmissivity was 8 m^2/day (O'Brien, in preparation). Recovery data were not analyzable due to borehole-storage effects dominating the response.

The hydraulic tests provided verification that the water body was perched and of limited extent. Residual drawdown of about 2.3 m resulted from the pumping during March (O'Brien, in preparation). The apparent permanent lowering of the water level indicates that the reservoir is of limited extent and not hydraulically connected to the regional water-table. Water levels appeared to slowly recover after the completion of the March tests, but they never returned to pre-pumping levels.

Hydraulic Tests during August, 1995

Following deepening of the borehole to a depth of 497 m, hydraulic testing resumed in borehole USW SD-7. Available drawdown during pumping was increased as a result of the increased depth of the borehole. The borehole was pumped and developed until repeatable drawdown curves were obtained. A 64.6-hour hydraulic test at a mean discharge rate of 0.16 l/s was completed. The response to pumping was similar to the March, 1995 testing with the exception of the water level being lowered below the interval that was apparently producing water. After about 60 hours of pumping the water level in the borehole reached a depth of 488 m and the time-rate of drawdown increased. The sudden change in the drawdown curve indicated that this interval contained the primary water producing fracture(s) or layer of porous rock matrix (O'Brien, in preparation). Analysis of the drawdown data resulted in a mean transmissivity estimate of 4 m^2/day.

Similar to the March tests, most of the recovery occurred during the first 20 minutes after the termination of pumping. Slow recovery, at the rate of about 1 m per 6 days, continued until water-level monitoring was terminated. Long-term recovery could not be monitored due to the perched zone in the borehole being cased to allow the drilling operations to resume. Determination of transmissivity from the recovery data was considered unreliable, and therefore not provided (O'Brien, in preparation). Residual drawdown due to pumping during August was about 2.9 m.

Reservoir Volume

Using the results of the March and August, 1995 hydraulic tests the reservoir volume intersected by borehole USW SD-7 was estimated. The volume of the water body was estimated to be 97,000 l prior to pumping (O'Brien, in preparation). This reservoir-volume estimate does not include any water that might be down dip or otherwise hydraulically inaccessible to the borehole.

Pumping Tests at USW UZ-14

Perched water was encountered in UZ-14 at a depth of about 381 m, near the upper contact of the basal vitrophyre of the Topopah Spring Tuff, and about 190 m above the predicted potentiometric surface. Approximately 9.8 m of water-filled borehole was available for the tests. Following a period of borehole development several drawdown/recovery tests were conducted. Pump test #3 was run for approximately 9.3 hours with an average output of 0.118 liters/sec. Maximum drawdown was about 6.1 m (Thamir, in preparation). The water level was still recovering when pump test #4 was started. Pump test #4 was run for 66.75 hours at an average pump rate of 0.059 liters/sec. Maximum drawdown was 3.5 m, and the water level recovered completely within 72 hours.

Because the water level recovered completely following the pump tests, the perched water aquifer was considered infinite for test analysis purposes. Transmissivities were calculated using Jacob's approximation (Freeze and Cherry, 1979, p. 347, modified). Transmissivity for test #3 was calculated to be 0.55 m^2/day, and 0.62 m^2/day for test #4 (Thamir, in preparation), with a mean value of 0.59 m^2/day for the two tests.

Analytical solutions that can be used to determine hydraulic conductivity and transmissivity require simplifying assumptions which are rarely met when testing in flow regimes with discreet fractures. Assumptions that are potentially violated include radial flow, laminar flow, infinite reservoir, homogenous, and isotropic media. In discreet fracture flow regimes the majority of the permeability and flow is from a unique zone, with little contribution from the rock matrix. The analytical solutions provide reasonable estimates of average permeability in porous-media flow conditions even if the assumptions are not strictly met. However, in this situation, with predominate fracture flow, violation of the assumptions most likely produces errors in the calculation of hydraulic conductivity and transmissivity. Nonetheless, these solutions provide the best estimates of aquifer properties.

A Conceptual Model of Perched-Water Flow at USW SD-7

As previously discussed, the occurrence of perched water at USW SD-7 could be due to a hydraulic conductivity contrast between layers, presence of a fractured layer overlying an unfractured layer, or another similar scenario. A north-south trending fault, that forms a low permeability boundary, could be preventing the water from draining down dip, as illustrated in Figure 9.

The physical orientation of the perched-water system can only be hypothesized based on the available information. There is evidence that a discrete fracture zone exists and it is likely that it follows the dip of bedding (~6° east). Although there could be a network of interconnected fractures at random or high angle orientations, for simplicity a single zone of sub-horizontal fractures following bedding is considered (fig. 9). Fractures are probably the single most important feature necessary to allow significant saturated flow at Yucca Mountain. Boreholes that do not intersect significant fractures will probably not produce significant volummes of water. Most occurrences of perched water at Yucca Mountain were not in sufficient quantities to allow pumping. This does not necessarily mean that the perched reservoir was smaller than that intersected by borehole USW SD-7, it could merely be due to the borehole not intersecting a producing zone of the system.

Matrix permeability that is much less than fracture permeability would result in matrix flow being a minor part of the flow system during pumping. Hydraulic-test data from borehole USW SD-7 indicated that the flow was probably from discrete fractures or a small interval in the borehole. If the rock matrix was contributing significant water to the borehole the time-rate of drawdown would probably not have increased as dramatically when the water level was lowered below the producing interval.

The initial occurrence of water in borehole USW SD-7 indicated that the perched-water system was under confined conditions, because the water rose above the level at which it was encountered. However, given the dip of the bedding and the limited height of the water column, the system is probably in contact with the atmosphere and under water-table conditions at some distance from the borehole (figure 9). Early-time pumping would appear to be under confined conditions, with a rapidly expanding cone-of-depression. A decrease in water level in the borehole would be quickly transmitted to the edges of the reservoir. As the drawdown reached the reservoir boundary, where water-table conditions exist, an unconfined response would dominate the drawdown data. An actual dewatering of the fracture zone would occur at the interface between the saturated and unsaturated portions of the fractured zone.

As the reservoir volume was depleted, the driving hydraulic head on the system would be reduced, which would lead to lower rates of inflow to the borehole. Therefore, the apparent transmissivity would decrease with increased depletion of the reservoir due to pumping. This is a possible explanation for the decreasing transmissivity estimates in subsequent tests. A perched-water system is effectively altered following dewatering due to pumping, so different systems were tested during March and August, 1995 in borehole USW SD-7 (O'Brien, in preparation). Transmissivity estimates are probably only reliable for the conditions at the time of testing and differences should be expected if significant dewatering has occurred.

After termination of pumping, the fracture zone near the borehole quickly refilled with water and reached equilibrium within several minutes. A relatively small amount of the total recovery occurred after the initial surge of water into the borehole. This slow recovery could be a delayed-yield type of response, where water was draining from the interval dewatered during pumping. The drainage would result in rising water levels after the fracture network had reached its initial equilibrium level. However, depth-to-water measurements between the March and August hydraulic tests indicated that the water level was continuing to slowly rise (O'Brien, in preparation). If drainage from the dewatered portion of the reservoir was contributing to the recovery, its influence would be expected to only last for a few days.

Long-term recovery of the water levels may be indicating that there are perched-water reservoirs adjacent to the reservoir intersected in borehole USW SD-7. The reservoirs are probably separated by low permeability boundaries (figure 10). The water level in the block intersected by borehole USW SD-7 was artificially lowered due to pumping, which created a hydraulic head difference between the adjacent blocks and induced flow into the USW SD-7 block. Over a long period of time, the perched water level in these blocks would equilibrate to the same level. This model implies that there is potentially a much larger reservoir that is compartmentalized by low-permeability boundaries. The possibility of compartmentalization of fractured aquifers in southern Nevada has been previously suggested by I.J. Winograd and others (Young, 1938).

This conceptual model of the perched-water flow system is one of many possible models that can reasonably explain the responses observed in borehole USW SD-7. Other occurrences of perched water at Yucca Mountain potentially fit this model. Boreholes that did not produce significant amounts of water that would allow pumping probably did not intersect a significant fracture. Occurrence of perched water at generally the same stratigraphic level also leads to the possibility that some perched-water bodies are separated by low permeability boundaries.

Water Chemistry

The chemical composition of perched water provides information on the transport and interaction of the recharge water within the unsaturated zone while the isotopic content can provide insight on the source and residence time of the perched water. Using either plastic or stainless-steel bailers, perched water samples were collected from boreholes USW NRG-7A, USW SD-7, USW SD-9, USW UZ-1, and USW UZ-14. In addition, a series of hydrochemical samples were collected during the pumping tests at boreholes SD-7 and UZ-14. After collection, the perched water samples were stored in an ice-cooler and then transferred at the end of each day to the Sample Management Facility for long term storage in a cold room. Determinations of pH, specific conductance, and alkalinity were conducted in the field laboratory shortly after collection. During the pumping tests, the water quality parameters were monitored every half hour to hour. For comparison, water composition data from the saturated zone at wells USW G-2 and USW H-1 as well as pore water extracted from core collected at USW UZ-14 are presented.

As can be seen from Table 2, the perched water samples from USW UZ-14 are relative in composition to pore water extracted from core from the lower nonlithophisal unit of the Topopah Spring Tuff (Tptpln, Table 1) with sodium and calcium the major cations and bicarbonate and chloride the predominant anions. The remaining perched water compositions are similar to the saturated zone water samples from G-2 and H-1 and relative to the pore water composition from the Calico Hills Tuff (Tac, Table 1) at UZ-14 with the predominate ions being sodium and bicarbonate. However, while the relative major ion compositions of perched water are similar to the pore water, the absolute concentrations are significantly different. This is most evident with the hydrologically conservative chloride concentrations. Perched-water samples collected from UZ-14 all have chloride concentrations between 6 and 15 mg/L while the average chloride concentration of pore water extracted from UZ-14 cores within the perched-water reservoir is about 87.5 mg/L, indicating nonequilibrium conditions between the perched water and pore water. Evaporation of water from core could cause chloride concentrations in extracted water to appear higher than in situ conditions, however evaporation is minimal in properly packaged core (Striffler and Peters, 1993), and would not account for the differences shown above. If matrix pore water had contributed significantly to the perched-water reservoir, the chloride concentration of perched water should be similar to that of the pore water, which is not observed (Yang, U.S. Geological Survey, written commun., 1996). The smaller concentration of chloride in perched water indicates little interaction of fluid with rock, and that the perched water probably was derived from water flowing rapidly through fractures. These data are strong evidence that fracture flow is the principle source of perched-water reservoirs at Yucca Mountain.

Table 3 presents carbon isotope data from the perched water samples. The ^{14}C values range from 66.9% to 27.2% modern which translates into uncorrected ^{14}C ages of about 3,500 years to about 11,000 years. Water ^{14}C ages, however, are influenced by the dissolution of calcite as the recharge water flows through the unsaturated zone. The $\delta^{13}C$ data provides a good indication of dissolution since $\delta^{13}C$ for calcite range from -3 to -9‰ while biogenic $\delta^{13}C$ values range from -18 to -23‰. With the exception of NRG-7A, $\delta^{13}C$ for the perched water samples range from -9.2 to -14.4‰. The relative heavy $\delta^{13}C$ values in the perched water indicate the presence of calcite in the perched water. Since the calcite ages at Yucca Mountain have been dated in excess of 20,000 years, dissolution of this calcite would make the perched water samples appear older than they actually are. The lighter $\delta^{13}C$ value at NRG-7A, however, would indicate a liquid-gas interaction occurred after calcite dissolution and the sample at NRG-7A is actually older than it appears. Accounting for calcite dissolution and liquid-gas interactions, the implied residence time for the perched water samples is from about 4,000-7,000 years. An exact correction cannot be applied because the variability of the calcite ^{14}C ages and the seasonal and annual variability of CO_2 $\delta^{13}C$ values in the soil. (Yang and others, 1996)

The remainder of Table 3 presents the stable isotope and tritium data. All of the perched water samples contain background tritium concentrations. If any post-bomb water infiltrated the perched-water reservoir through rapid fracture flow, the volume was so small as to be undetectable. The stable isotope values in the perched water range from -87.4 to -102‰ for δD and from -12.8 to -13.8‰ for $\delta^{18}O$. Water from the last ice age (about 10,000 years ago), however, have stable isotope values ranging from about -115 to -120‰ for δD and -15 to -20‰ for $\delta^{18}O$. If perched waters contained water from the last ice age, the stable isotopes values should be lighter than water in the saturated-zone, a fact that is not observed. Since the perched waters are, in fact, slightly heavier than saturated zone samples, this is consistent with a residence time of about 7,000 years.

Occurrences of Perched Water in the Vicinity of the ESF

Perched water has been identified in five boreholes in the vicinity of the ESF. Boreholes in this area that did not encounter perched water were not drilled to a depth sufficient to intercept the geologic units where perched water has been identified. To some extent, perched water probably exists near the base of the Topopah Spring Tuff virtually everywhere in the vicinity of the ESF.

The presence of perched water in the vicinity of the potential repository has several implications. The very occurrence of perched water implies that at some time in the past, the percolation rate through the unsaturated zone has exceeded the saturated hydraulic conductivity of the perching layer. The presence of perched water implies that there may be preferential pathways for percolation through the unsaturated zone. Depending on the hydraulic conductivity and length of the flow path, preferential pathways could 1) either increase or decrease the predicted travel time from the surface to the saturated zone, 2) divert percolation away from the potential repository, or 3) transmit water from the repository horizon to the water table (Patterson, U.S. Geological Survey, written commun., 1996).

Perched water bodies of large volume could indicate that structural or stratigraphic traps are present that allow percolation to accumulate. The mechanical stability of these trapping mechanisms becomes an important issue if perched water is discovered above or updip from the potential repository. Perched water in close proximity to the waste-emplacement drifts is an additional potential source of water that may become mobilized as vapor as a result of waste-generated heat, a fact that needs to be considered when attempting to analyze the impact of that mobilized water on repository performance.

Summary and Conclusions

The stratigraphic location of the perched water encountered in four of the boreholes discussed above is similar. In each case, perched water was encountered near the top of the crystal-poor vitric zone (Tptpv. Table 1) of the Topopah Spring Tuff. Although the bottom of the perched-water body generally is unknown, the water typically is perched in a zone of relatively higher permeability overlying a zone of relatively lower permeability. The active permeability may be fracture permeability, matrix permeability, or both, and the perched water may be a result of water flowing through zones with high fracture frequency overlying zones with low fracture frequency. Figures 4, 5, 6, 7, and 8 show fracture frequency plots (Mapa, M&O/SAIC, written commun., 1996) for the boreholes with the locations of the tops of the perched water within each borehole. In each borehole the perched-water body lies within a zone of relatively high fracture permeability. In each case, the water is perched upon less-intensely fractured nonwelded tuff underlying the crystal-poor vitric zone.

There also seems to be evidence of faults or fault splays acting as structural barriers to flow; at SD-7 the Abandoned Wash Fault is in proximity to act as a barrier, and at UZ-14 a possible fault splay from the Solitario Canyon Fault is proposed (Fridrich, U.S. Geological Survey, written commun., 1996). Mobilized water in fractures may be reaching relatively impermeable rock layers offset by the faulting and becoming trapped. Depending on amount of offset and the permeability of the fault zone, this mechanism could account for substantial bodies of perched water. In both UZ-14 and SD-7 perched water was encountered at a depth consistent with the above hypothesis. Faulting may form an impermeable boundary which can effectively accumulate mobilized water, assuming that net inflow exceeds the capacity of the barrier to transmit water.

A perched-water body was tested at borehole USW SD-7. The water level was approximately 150 m above the regional water-table near the base of the Calico Hills Tuff. Pumping tests indicate that water was entering the hole from a discreet interval at a borehole depth of about 488 m. A mean transmissivity of 6 m^2/day was obtained from two drawdown tests. The most reliable estimates of the reservoir volume were on the order of 8×10^5 liters with an area of about 0.01 km^2.

The perched water body detected in borehole USW UZ-14 near the base of the Topopah Spring Tuff, nearly 200 m above the regional water table, was tested to determine aquifer properties. The water level recovered nearly completely following each pump test, implying that aquifer boundaries were not reached. Using infinite aquifer analysis methods a mean transmissivity value of 0.59 m^2/day was estimated.

The relative major ion concentrations of perched water are similar to pore water, however the absolute concentrations are significantly different. If matrix water had contributed significantly to the perched water reservoir, chemical concentrations of the perched water should be similar to the pore water, which is not observed. The dissimilar concentrations suggest little interaction of fluid with rock, and that the perched water probably was derived from water flowing through fractures. Chemistry data present strong evidence that fracture flow is the principle source of perched water reservoirs at Yucca Mountain. The perched water samples all contain background tritium concentrations, indicating that the perched water sampled had accumulated prior to the atmospheric testing of nuclear weapons. If any post-bomb water has mixed with the perched water, the volume of such water must have been too small to influence tritium concentrations.

The presence of perched water at Yucca Mountain may have influences on the construction and operation of the ESF. Perched water could increase the potential for water to come into extended contact with waste canisters. Large amounts of water could also interfere with scientific and construction activities in the ESF.

The occurrences of perched water at Yucca Mountain that have been studied have been stratigraphically deeper than any of the currently planned ESF excavations. Perched water could be encountered, however, if ESF construction activities are expanded to include test alcoves which penetrate the Calico Hills Tuff or vitrophyre units; units where perched water is likely. The understanding of this risk should be considered before construction begins.

Careful analysis of the geologic, structural, stratigraphic, and hydrologic characteristics of a perched-water zone could provide important information concerning fluid movement through the unsaturated zone. Perched water has strong implications concerning the controls on flow of water moving to the saturated zone at Yucca Mountain.

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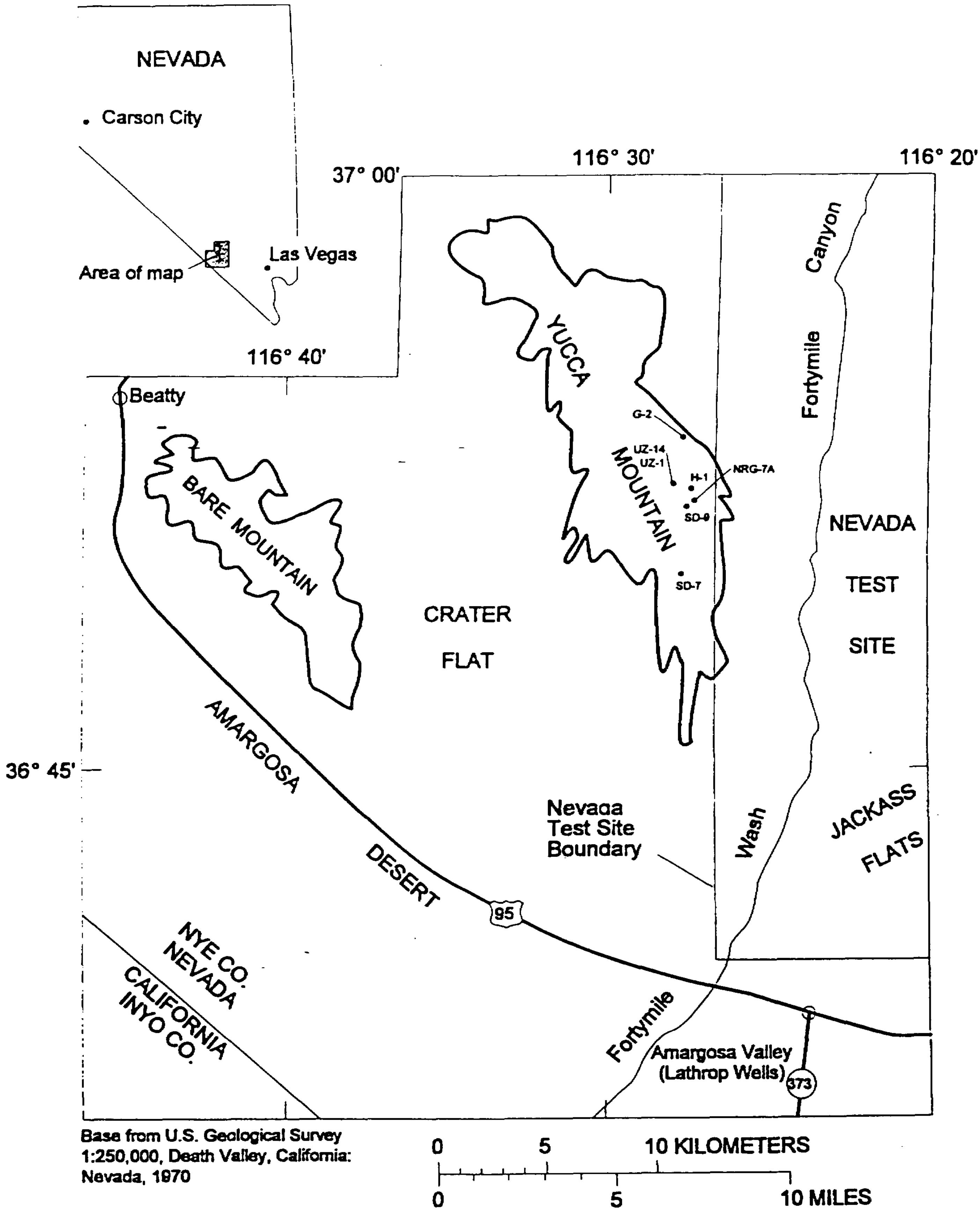


Figure 1. Location of study area and geographic features.

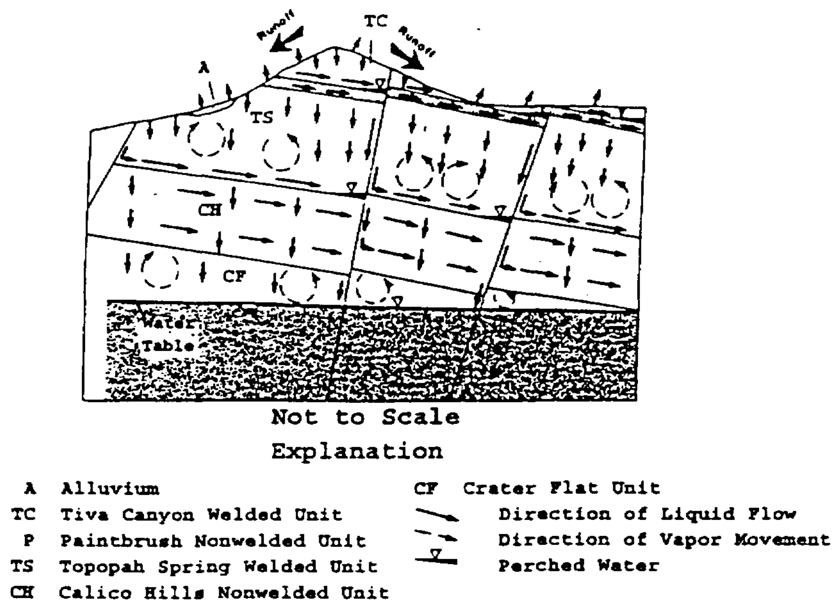
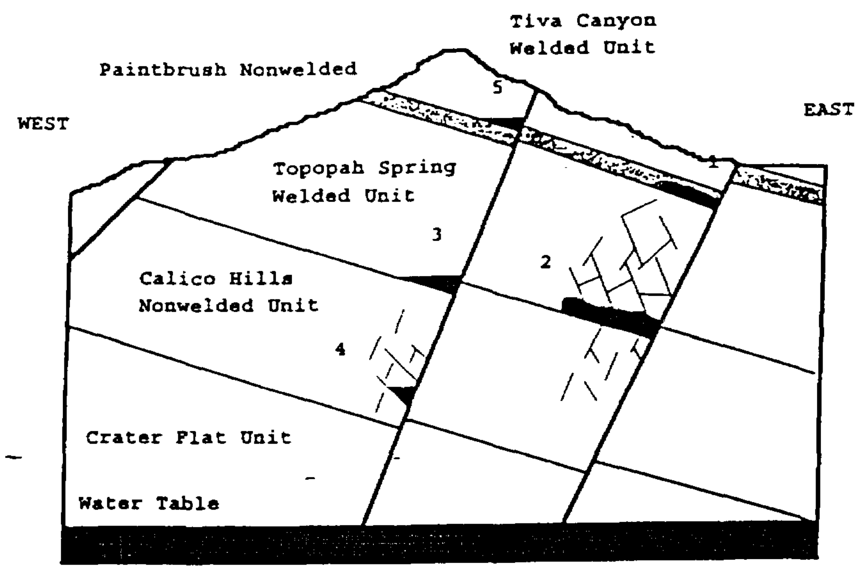


Figure 2. Generalized section across Yucca Mountain showing flow regime under baseline conditions (from Montazer and Wilson, 1984).



Explanation

1. Perched water in a permeable layer overlying an impermeable layer
2. Perched water in a fractured unit overlying a relatively unfractured unit
3. Fault-controlled perched water
4. Perched water collected in a fault from isolated fractures or brought from above into a nonwelded unit by a fault
5. Perched water held by capillary effects in a nonwelded unit

Figure 3. Generalized cross section showing possible perched-water zones.

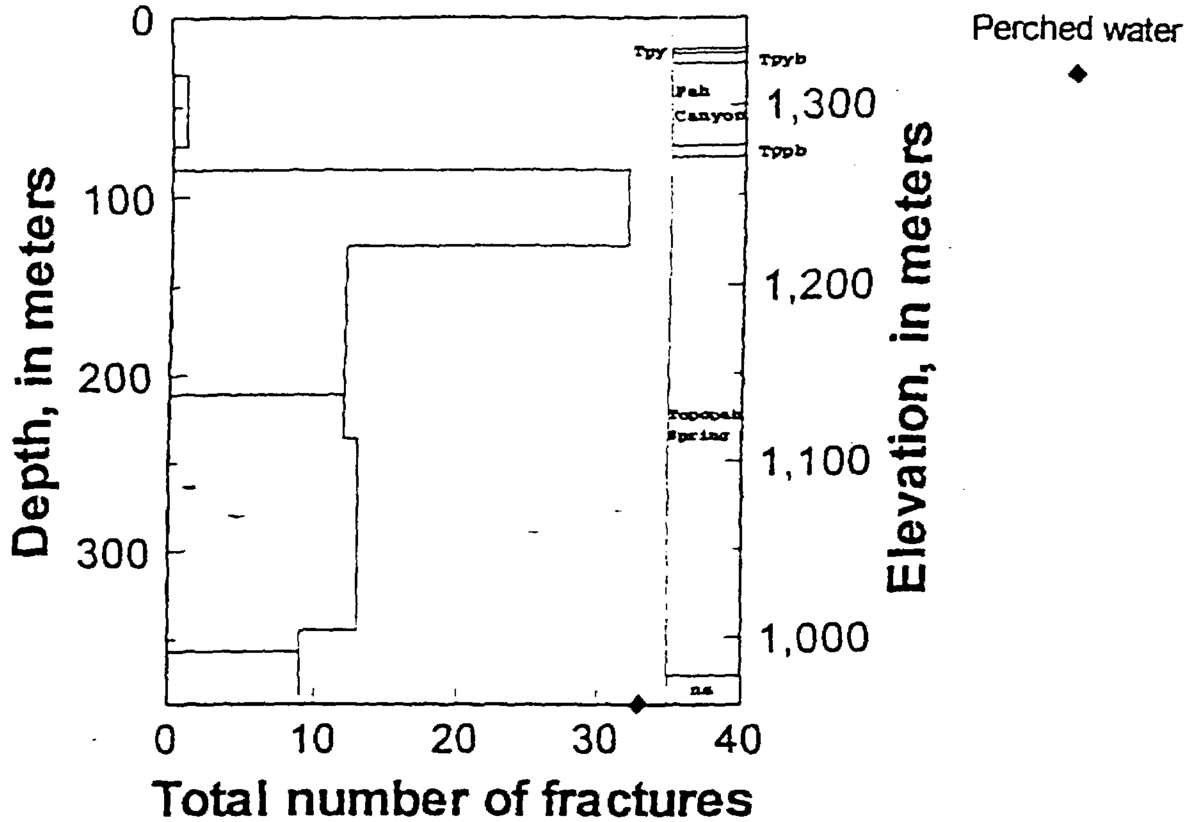


Figure 4. USW UZ-1 Stratigraphy and fracture frequency (from Whitfield et al., 1990)

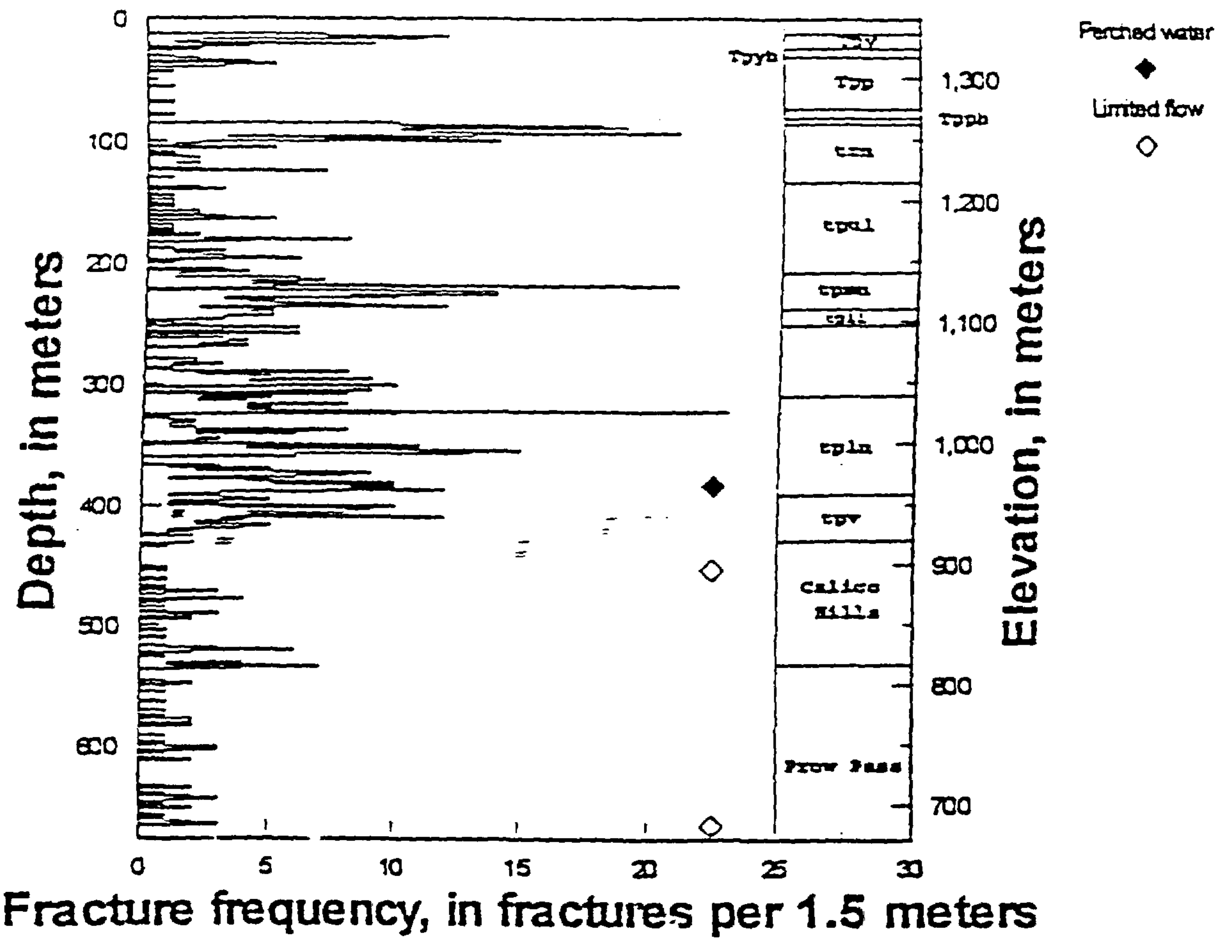


Figure 5. USW UZ-14 Stratigraphy and fracture frequency. (Mapa, M&O/SAIC, written commun., 1996)

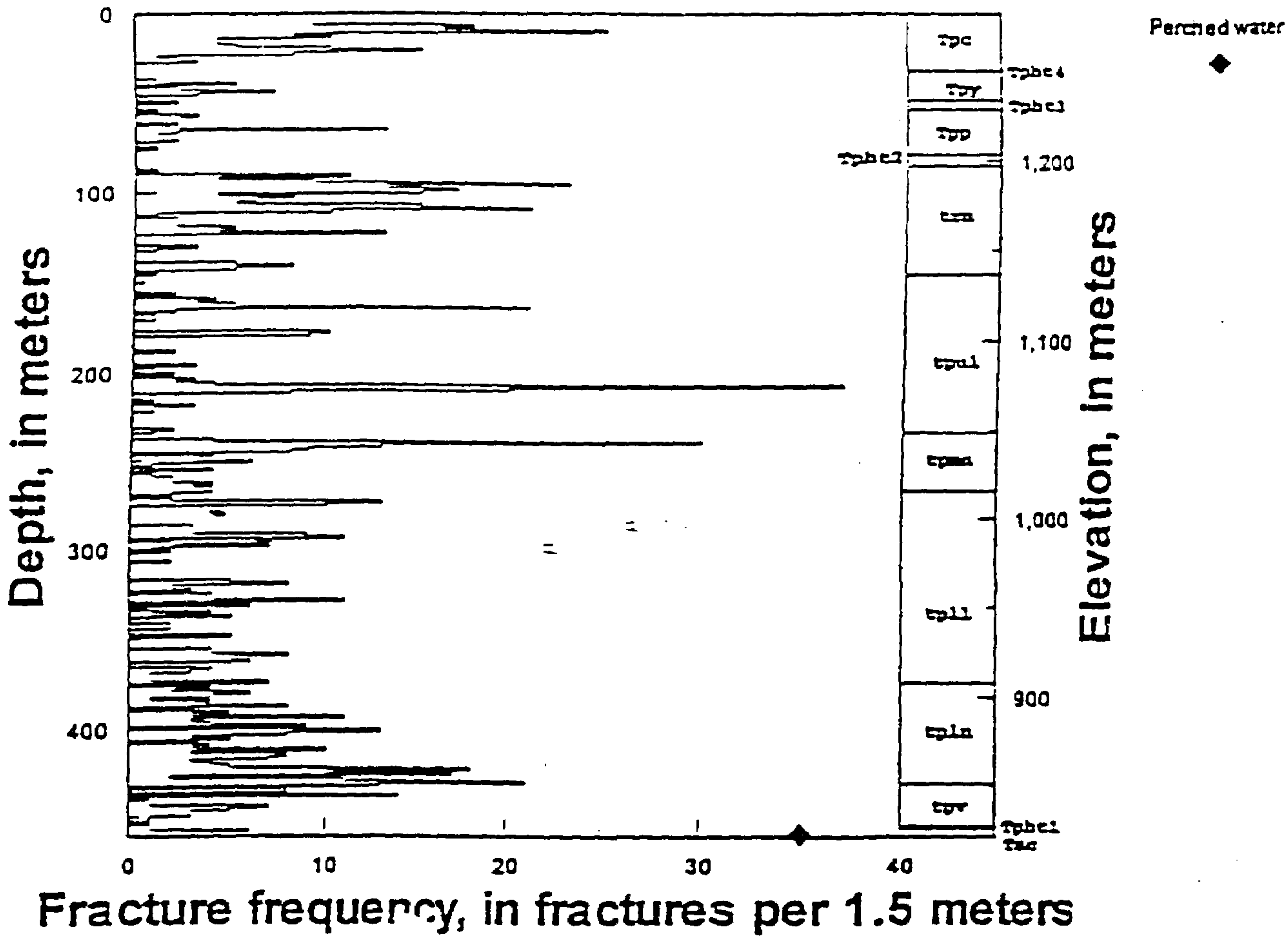


Figure 6. USW NRG-7A Stratigraphy and fracture frequency. (Mapa, M&O/SAIC, written commun., 1996)

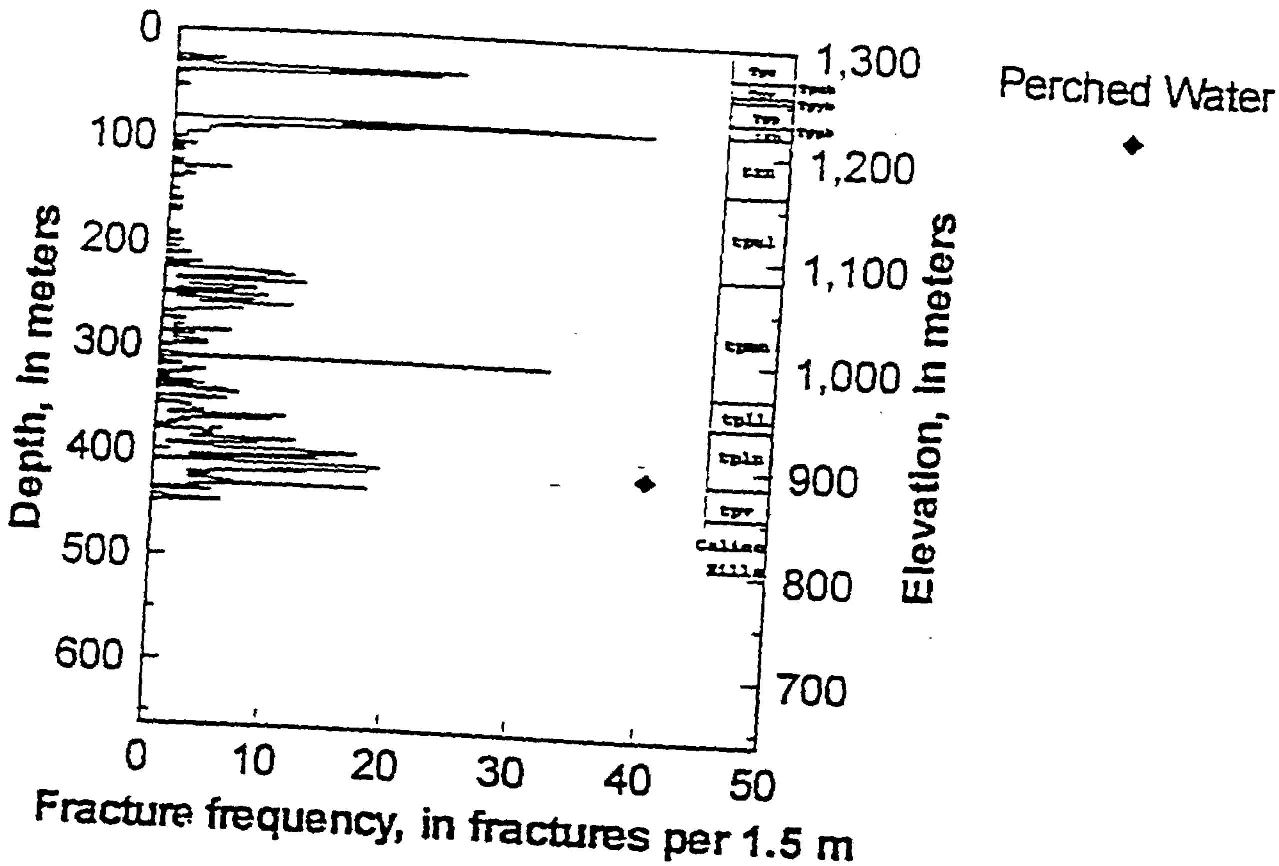


Figure 7. USW SD-9 Stratigraphy and fracture frequency. (Mapa, M&O/SAIC, written commun., 1996)

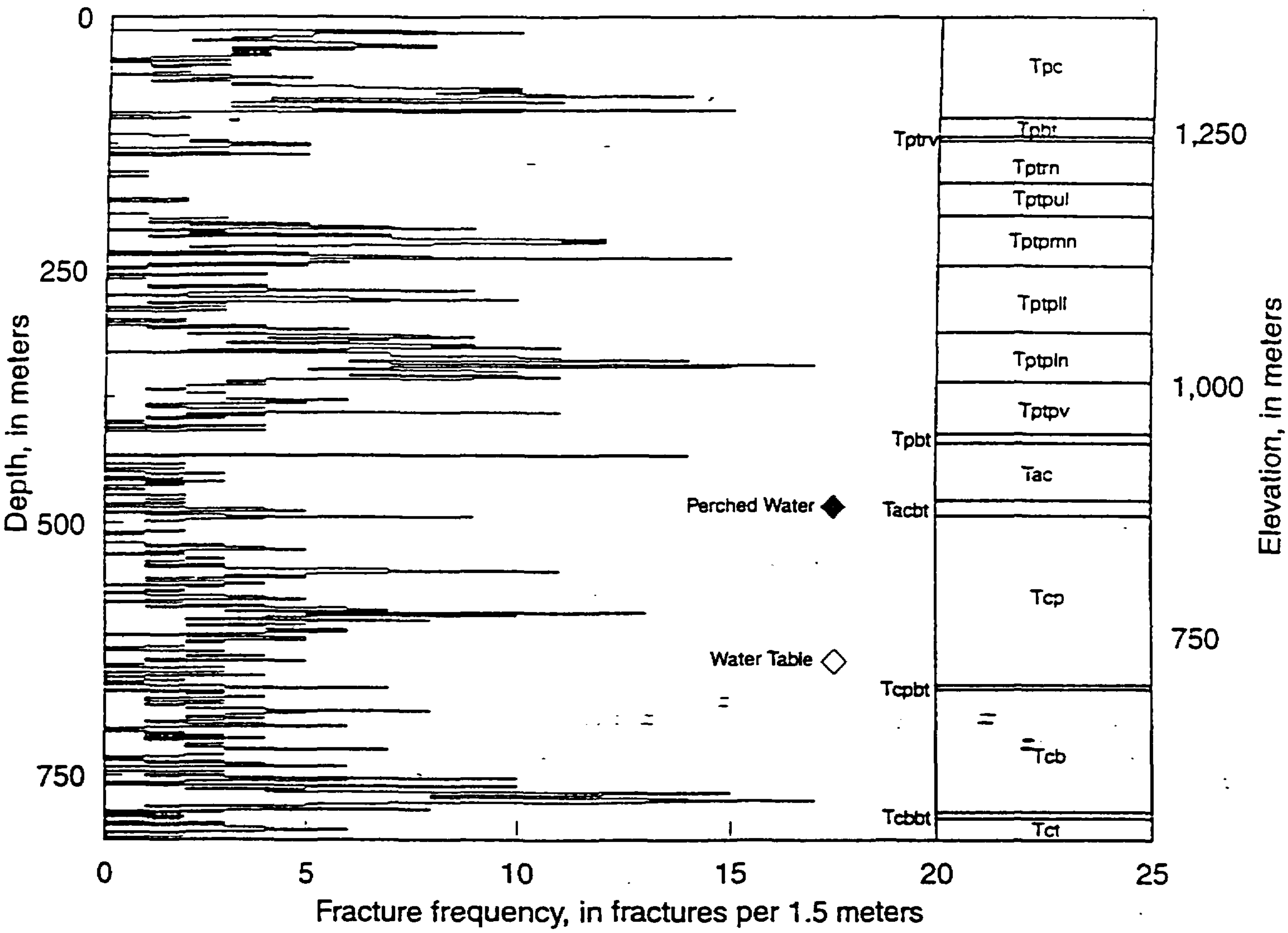
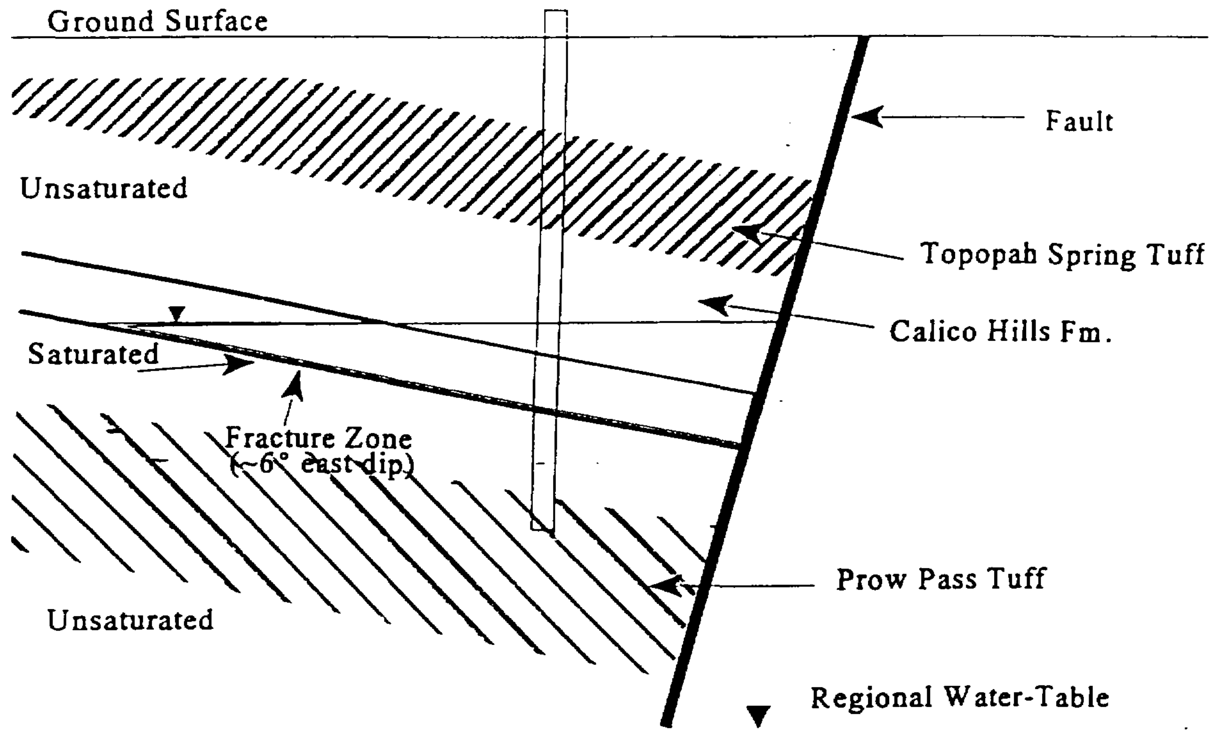


Figure 8. USW SD-7 Stratigraphy and fracture frequency. (Mapa, M&O/SAIC, written commun., 1996)

Borehole USW SD-7



Not to Scale
Stratigraphy is generalized

Figure 9. Idealized conceptual model of perched-water system intersected by borehole USW SD-7.

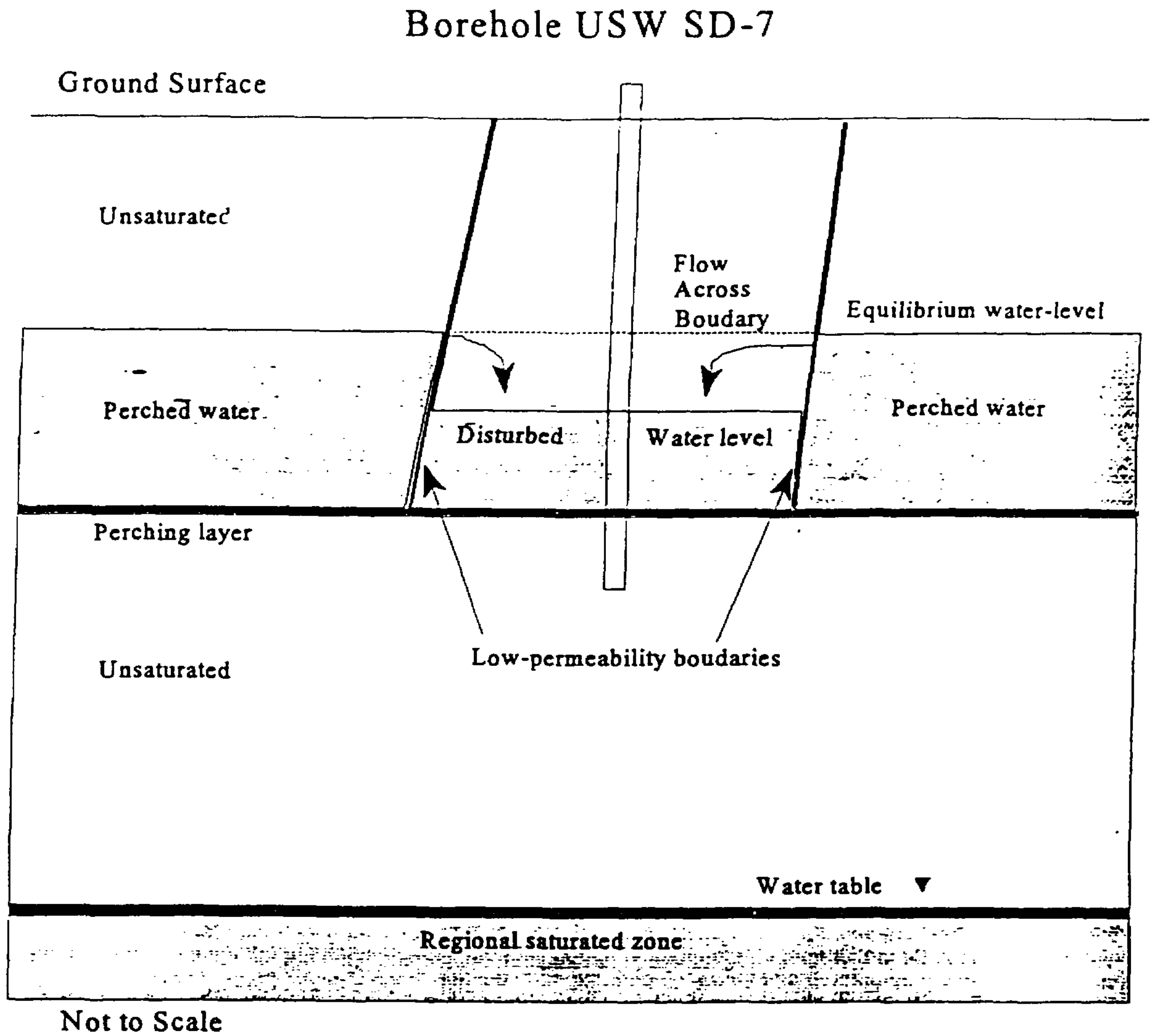


Figure 10. Conceptual model of compartmentalized flow in perched-water system intersected by borehole USW SD-7.

Table 1. Generalized lithostratigraphy of Yucca Mountain unsaturated zone (from Buesch and others, 1996).

Symbol	Stratigraphic Unit
Tpc	Tiva Canyon Tuff
Tpbt	Pre-Tiva Canyon Bedded Tuff
Tpy	Yucca Mountain Tuff
Tpp	Pah Canyon Tuff
Tpt	Topopah Spring Tuff
Tptrv	Vitric Zone - Crystal rich member
Tptrn	Nonlithophysal Zone
Tptpul	Upper Lithophysal Zone
Tptpmn	Middle Nonlithophysal Zone
Tptpll	Lower Lithophysal Zone
Tptpln	Lower Nonlithophysal Zone
Tptpv	Vitric Zone - Crystal poor member
Tpbt	Pre-Topopah Spring Bedded Tuff
Tac	Calico Hills Tuff
Tacbt	Pre-Calico Hills Bedded Tuff
Tcp	Prow Pass Tuff

TABLE 2: Physical and Chemical composition of water samples from various boreholes, Yucca Mountain, NV
(--, data not available; 0, values below detection limit; SC, specific conductance; charge balance, (meq cation-meq anion)/(meq cation+meq anion)*100)

Sample	Date	pH	SC (µS/cm)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO3 (mg/l)	Cl (mg/l)	Br (mg/l)	NO3 (mg/l)	SO4 (mg/l)	Balance (percent)
Perched-water Composition													
NRG-7A	03/07/94	8.7	224	3	0	6.8	42	114	7	0	1	4	-0.3
NRG-7A	03/08/94	8.0	245	4.6	0.1	7.5	42	126	9.4	--	--	6.9	4.1
SD-9	07/06/94	8.6	445	2.9	0.2	9.8	98	217[a]	5.6	0	3.3	27.6	3.6
UZ-14-1	08/02/93	7.6	312	23	1.8	5.6	39	150	7.9	.2	8.6	14.3	0.2
UZ-14-2	08/02/93	7.8	308	24	1.8	3.9	38	148	9.1	.11	2.5	13.8	-1.2
UZ-14	08/03/93	8.1	335	31	2.7	4.4	40	148	8.3	.41	6.9	16.3	5.0
UZ-14	08/05/93	8.3	518	45	4.1	5.8	88	106	15.5	.4	0	223	-2.0
UZ-14	08/17/93	8.1	412	37	3.1	6.3	40	144	7.2	.11	2.7	57.3	0.5
UZ-14	08/19/93	8.0	328	30	2.4	3.3	35	144	7.0	.11	5.4	22.9	0.3
UZ-14	08/25/93	8.0	306	25	2.2	1.7	36	147	6.3	0	4.0	151	0.2
UZ-14	08/27/93	7.8	305	27	2.1	1.8	34	142	6.7	.11	4.5	14.1	0.0
UZ-14	08/31/93	7.8	--	31	2.5	4.1	35	146	7.0	.11	7.1	24.2	0.1
SD-7	03/08/95	--	--	14	0.13	5.3	46	112	4.4	0	33.8	9.1	2.5
SD-7	03/16/95	8.1	239	13	0.13	5.3	45	128	4.1	0	33.8	9.1	-2.9
SD-7	03/17/95	8.2	265	13	0.08	5.5	46	130	4.1	0	22.8	8.6	-0.3
SD-7	03/20/95	8.0	265	13	0.07	5.4	46	127	4.1	0	13.4	8.5	3.3
SD-7	03/21/95	8.2	259	14	0.08	5.5	45	128	4.1	0	13.2	10.3	2.2
UZ-1	07/11/83	8.0	393	23	2.4	10	57	139	12.4	0	28	12	0.0
Saturated-zone Water Composition													
G-2 (649 m)	02/08/95	7.6	251	8.1	0.50	6.3	46	116	6.6	.1	0	13	5.0
G-2 (792 m)	02/08/95	7.4	248	7.9	0.46	5.2	46	114	6.5	.1	0	13	5.0
H-1	10/20/80	7.7	255	4.5	0	2.4	51	122	5.7	0	0	18	0.6
Pore Water Composition													
UZ-14 (383.7 m)	01/14/94	--	--	43	3.7	--	67	170	88	0	16	19	-4.9
UZ-14 (389.4 m)	01/14/94	--	--	62	4.5	--	49	170	87	0	17	45	-7.1
UZ-14 (456.0 m)	04/11/95	8.4	500	2.1	0	--	122	228	28	0	10.8	14.3	4.0
UZ-14 (464.7 m)	04/14/95	7.7	560	1.1	0.1	--	137	232	26.2	0	12.5	22.3	7.3

[a] Includes 10 mg/l as $CO_3^{=}$

TABLE 3: Isotopic composition of perched water samples from various boreholes, Yucca Mountain, NV

Sample Location	Date	Carbon-13 (‰)	Carbon-14 (PMC)	Tritium (pci/l)	Deuterium (‰) SMOW	Oxygen-18 (‰) SMOW
NRG-7A	03/07/94	-16.6	66.9	10.4	-93.9	-12.8
SD-9	07/06/94	-14.4	41.8	0	-97.8	-13.3
UZ-14-1	08/02/93	-10.2	41.7	.3	-98.6	-13.8
UZ-14-2	08/02/93	-10.1	40.6	3.1	-97.5	-13.5
UZ-14	08/03/93	-9.5	36.6	0	-97.1	-13.4
UZ-14	08/05/93	-9.2	66.8	.4	-87.4	-12.1
UZ-14	08/17/93	-9.8	32.3	1.8	-97.8	-13.3
UZ-14	08/19/93	---	28.9	3.1	-97.9	-13.4
UZ-14	08/27/93	-9.6	27.2	0	-97.3	-13.4
UZ-14	08/31/93	-11.3	29.2	0	-97.6	-13.1
SD-7	03/08/95	-10.4	34.4	6.2	-99.8	-13.4
SD-7	03/16/95	-9.4	28.6	---	-99.7	-13.3
SD-7	03/17/95	-9.5	28.4	---	-99.6	-13.3
SD-7	03/20/95	-9.5	27.9	---	-99.6	-13.4
SD-7	03/21/95	-9.5	28.4	---	-99.6	-13.3
UZ-1	07/11/83	-12.1	63.8	3.1	-102.0	-13.0