GEOHYDROLOGY OF ROCKS PENETRATED BY TEST WELL USW H-4, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

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METRIC CONVERSION TABLE

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

Multiply SI units	*By*	*To obtain inch-pound unit*
centimeter	3.937×10^{-1}	inch
degree Celsius (°C)	F = 9/5°C + 32	degree Fahrenheit
kilometer (km)	6.214×10^{-1}	mile
liter (L)	2.642×10^{-1}	gallon
liter per second (L/s)	1.585×10^{1}	gallon per minute
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	1.076×10^{1}	foot squared per day
millimeter (mm)	3.937×10^{-2}	inch

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[1] Approximate.

SYMBOLS LIST

Symbol	Description	Dimension
Q	Flow rate.	Liters per second.
T	Transmissivity.	Meters squared per day.
t'	Time since discharge stopped.	Minutes.
Δs	Drawdown for one log cycle.	Meters.

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ABSTRACT

This report presents the results of hydraulic testing of rocks penetrated by USW H-4, one of several test wells drilled in the southwestern part of the Nevada Test Site, in cooperation with the U.S. Department of Energy, for investigations related to the isolation of high-level radioactive wastes in volcanic tuffs of Tertiary age. All rocks penetrated by the test well to its total depth of 1,219 meters were volcanic.

Static water level was at a depth of 519 meters below land surface. Hydraulic-head measurements made at successively lower depths during drilling in this test hole indicate no noticeable head change. A radioactive-tracer, borehole-flow survey indicated that the two most productive zones in this borehole occurred in the upper part of the Bullfrog Member, depth interval from 721 to 731.5 meters, and in the underlying upper part of the Tram Member, depth interval from 864 to 920 meters, both in the Crater Flat Tuff.

Hydraulic coefficients calculated from pumping-test data indicate that transmissivity ranged from 200 to 790 meters squared per day. The hydraulic conductivity ranged from 0.29 to 1.1 meters per day.

Chemical analysis of water pumped from the saturated part of the borehole (composite sample) indicates that the water is typical of water produced from tuffaceous rocks in southern Nevada. The water is predominantly a sodium bicarbonate type with small concentrations of calcium, magnesium, and sulfate. The apparent age of this composite water sample was determined by a carbon-14 date to be 17,200 years before present.

INTRODUCTION

The U.S. Geological Survey has been conducting investigations at Yucca Mountain, Nye County, Nev., to evaluate the hydrologic and geologic suitability of this site for storing high-level nuclear waste in an underground mined repository. These investigations are part of the Nevada Nuclear Waste Storage Investigations conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

Test drilling and hydraulic testing have been principal methods of investigation. This report presents hydrologic information about the rocks penetrated by test well USW H-4, one of several exploratory wells drilled in tuff, in or near the southwestern part of the Nevada Test Site.

Purpose and Scope

The primary goal of hydrologic studies at Yucca Mountain is to define hydrologic characteristics of welded and nonwelded tuffs in the southwestern part of the Nevada Test Site and to determine the potential of these rock types for the storage of nuclear wastes. This report presents detailed hydrological data, supporting geological and geophysical information, and hydrological interpretations for rocks penetrated by test well USW H-4, one of a series of wells designed to obtain data in the saturated zone.

Location of Well

Test well USW H-4 is about 45 km northwest of Mercury in southern Nevada. The well is in a southeastward draining, well-developed wash of Yucca Mountain, northwest of Jackass Flats (fig. 1). The well is about 6 km northwest of water-supply well J-13 and is at Nevada State Central Zone Coordinates N. 761,642.6 and E. 563,911.0. Altitude of the land surface at the well site is 1,248.9 m above sea level. Surveying was done by Holmes & Narver, Inc., Mercury, Nev. An exploratory core hole, USW G-4, was drilled 1,372 m north of this well and was completed on January 13, 1983 (Bentley, 1984).

Drilling Procedures and Well Construction

Drilling of test well USW H-4 started on March 22, 1982; total depth of 1,219 m was reached on April 28, 1982. Air foam was the rotary-drilling fluid, consisting of air, detergent, and water obtained from well J-13 (fig. 1).

Well deviation was less than 3° from the vertical; the bottom of the well was 13 m N.70°W. of the starting point at land surface. The bit, casing, and cementing data for test well USW H-4 are listed in table 1.

After the well was drilled to a depth of 564 m, geophysical logs were run, and water-level measurements were made; at this depth, a decision also was made to case the well. Sidewall coring, by shooting hollow retractable cylinders into the rock, also was attempted, with minimal success. The well was cased to a depth of 561 m and was cemented at its base. After the well was drilled to its total depth and again logged, the casing was perforated from 533 to 539 m, with six shots per m. Hydrologic tests then were conducted, mainly in the uncased part of the hole.

Geohydrologic Setting

Rocks exposed in the vicinity of the Nevada Test Site consist principally of sedimentary rocks of Precambrian and Paleozoic age, volcanic and sedimentary rocks of Tertiary age, and alluvial and playa deposits of Tertiary and Quaternary age (Winograd and Thordarson, 1975; Byers and others, 1976). Exposed rocks of Precambrian and Paleozoic ages have a total thickness of about 11,000 m; they are predominantly limestone and dolomite, but include marble,

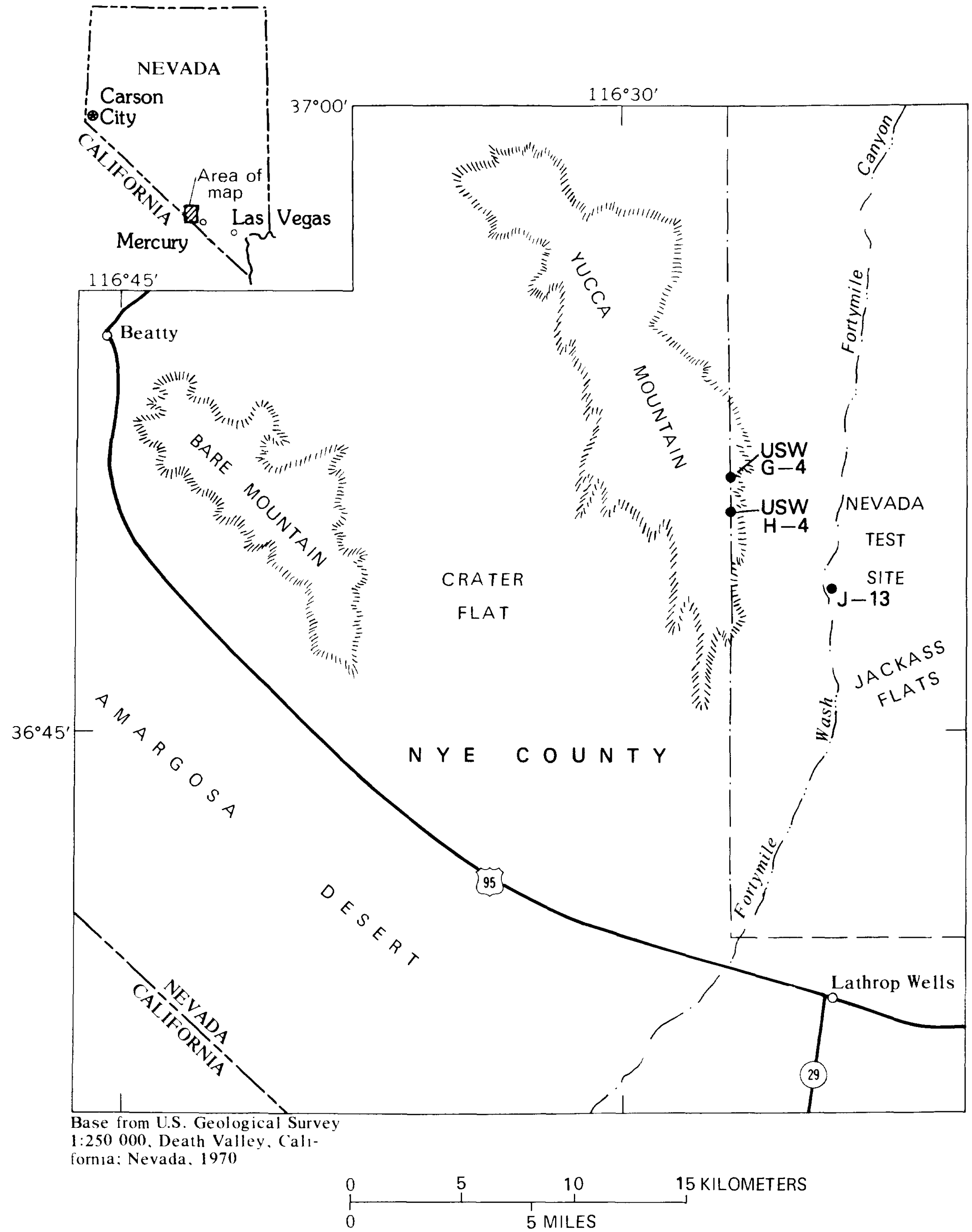

Figure 1.--Location of test well USW H-4 and nearby geographic features in southern Nevada.

Table 1.--*Bit, casing, and cementing data*

Drilled interval (meters)	Bit diameter (millimeters)	Cased interval (meters)	Casing, inside diameter (millimeters)	Intervals cemented		Volume of cement (cubic meters)
				From (meters)	To (meters)	
0-11	914	0-11	743	0	11	6.8
11-47	660	0-95	381	0	95	20.4
47-96	508					
96-564	375	0-561	253	548	561	2.8
564-1,219	222	[1]	---	---	---	----

[1] No casing set below a depth of 561 meters.

quartzite, argillite, shale, and conglomerate. These rocks were intruded by granitic stocks of Mesozoic and Tertiary age and basalt dikes of Tertiary and Quaternary ages. Most of the rocks of Tertiary age consist of welded, vitric, and zeolitic tuffs and rhyolite flows of Miocene age that were extruded from the Timber Mountain-Oasis Valley caldera complex, 7 km north of the test well. The alluvium of Tertiary and Quaternary age consists principally of detritus deposited in the intermontane basins, much of it as fan deposits.

Tuffs underlie Yucca Mountain to some undetermined depth in excess of that penetrated by test hole USW H-4. A tuff, the Tiva Canyon Member of the Paintbrush Tuff, crops out at the well site. The pre-Tertiary rocks under test well USW H-4 are unknown, but are most likely sedimentary rocks of Paleozoic age.

The test hole was drilled near a wash that drains the east side of Yucca Mountain. The drainage is toward Fortymile Wash, which is a tributary to the Amargosa Desert. The region is desert; Jackass Flats (fig. 1), at an altitude of about 1,000 m above sea level, receives an average annual precipitation of about 100 mm (Hunt and others, 1966, p. B5-B7). Because of its higher altitude, Yucca Mountain receives more precipitation than Jackass Flats when frontal storms move easterly across the area. The greatest precipitation occurs during spring and winter months. During the summer, widely scattered, intense thundershowers are common.

Runoff that results from rapid snowmelt or from summer showers collects in intermittent streams along the washes. The beds of the washes commonly are filled with sand, gravel, and boulders that rapidly absorb the infrequent flows. Most of the infiltrated water is returned to the atmosphere shortly after runoff, but small quantities percolate to depths beyond which evaporation and transpiration are effective. This water, therefore, is recharge that moves toward the water table. A large part of the ground water that flows underneath Yucca Mountain originates as recharge from precipitation that falls on the higher altitudes north of Yucca Mountain in the vicinity of Timber Mountain and flows laterally to and beneath the area (Blankennagel and Weir, 1973, pl. 3; Winograd and Thordarson, 1975, pl. 1; and Rush, 1970, pl. 1).

GEOLOGY

Lithology of Rocks Penetrated

A generalized lithologic description and thickness of the stratigraphic units penetrated by test well USW H-4 are tabulated in table 2. A detailed lithologic log has been given in a previous report (Whitfield and others, 1984). Seven major ash-flow tuffs were penetrated by test well USW H-4. In descending order, these are the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff, the ash-flow tuffs of Calico Hills, the Prow Pass, Bullfrog, and Tram Members of the Crater Flat Tuff, and the Lithic Ridge Tuff. All these ash flows contain zones of varying degrees of welding except the tuffs of Calico Hills, which are nonwelded. Between each of these major volcanic units are thin, nonwelded ash-flow tuffs, pyroclastic air-fall tuffs, and reworked tuffs. The Topopah Spring and Tram Members are about 300 m thick and were the thickest units penetrated. The Topopah Spring Member is mostly moderately to densely welded. Most other ash-flow tuffs are partially to moderately welded; the bedded tuffs generally are slightly indurated. Welding and induration characteristics of the penetrated rock are summarized in figure 2.

Two geologic factors are related to fracturing of the penetrated rock: (1) Older rocks would be expected to be more fractured, because they have been exposed to more periods of mechanical stresses; and (2) densely welded rock is more brittle than less welded rock and would be expected to break (rather than undergo ductile deformation) from mechanical stress. Based on core and drilling characteristics, the second factor probably dominates, in that the densely welded Topopah Spring Member of the Paintbrush Tuff is extensively fractured and, therefore, has more fracture permeability. The Topopah Spring Member probably has less matrix porosity than the other stratigraphic units, because it is more densely welded. In the remainder of the report, stratigraphic members are referred to without reference to the formation of which they are a part; these relationships are shown in table 2.

Geophysical-Log Interpretation

Geophysical well logs were run in test hole USW H-4 in order to: (1) Determine a more exact depth of the major lithologic changes; (2) obtain porosity and fracture data; and (3) gage the diameter of the open hole for selecting packer seats. The types of logs and the depth intervals logged are listed in table 3. Some of these logs are not discussed further because they did not contribute directly to defining the geohydrology of the stratigraphic units.

Table 2.--*Generalized lithologic log*

[Modified from Richard W. Spengler, U.S. Geological Survey, written commun., 1982]

Depth (meters)	Thickness (meters)	Stratigraphic unit	Lithology
		<u>Paintbrush Tuff</u>	
0-62	62	Tiva Canyon Member	Tuff, ash-flow, medium gray and dark-yellowish brown, densely welded to nonwelded; vitric, only lower part of member penetrated.
62-65	3	Bedded tuff	Tuff, bedded, reworked, slighty lithified, vitric.
65-400	335	Topopah Spring Member	Tuff, ash-flow, light brownish-gray to pale red, nonwelded to densely welded and devitrified; top and base are vitric; zones of abundant lithophysal cavities are common.
		<u>Rhyolite Lava and Tuff of Calico Hills</u>	
400-480	80	Tuffaceous beds of Calico Hills (informal)	Tuff, ash-flow, very pale orange to moderate-orange pink, nonwelded to partially welded, zeolitized; volcanic lithic fragments common.
480-496	16	Bedded tuff	Tuff, bedded, yellowish-gray, slightly indurated, zeolitized.
		<u>Crater Flat Tuff</u>	
496-690	194	Prow Pass Member	Tuff, ash-flow, yellowish-gray, light-gray, and dusky yellow, partially welded and devitrified (lower part zeolitic); mudstone lithic fragments common.
690-693	3	Bedded tuff	Tuff, bedded, zeolitized.
693-806	113	Bullfrog Member	Tuff, ash-flow, medium-gray and light-brown, nonwelded to moderately welded, devitrified, mudstone and volcanic lithic fragments common.
806-812	6	Bedded tuff	Tuff, bedded, zeolitized.

Table 2.--*Generalized lithologic log*--Continued

Depth (meters)	Thickness (meters)	Stratigraphic unit	Lithology
		Crater Flat Tuff--Continued	
812-1,155	343	Tram Member	Tuff, ash-flow, grayish-yellow-green, light-gray, and light-brownish-gray, devitrified, lower part zeolitized, nonwelded to partially welded, volcanic lithic fragments common throughout.
1,155-1,164	9	Bedded tuff.	Tuff, bedded, zeolitic.
		Lithic Ridge Tuff	
1,164-1,219	55	Lithic Ridge Tuff	Tuff, ash-flow, grayish-orange, moderately yellowish-brown, partially welded, zeolitized; pumice and volcanic, lithic fragments common. Base of tuff not penetrated.

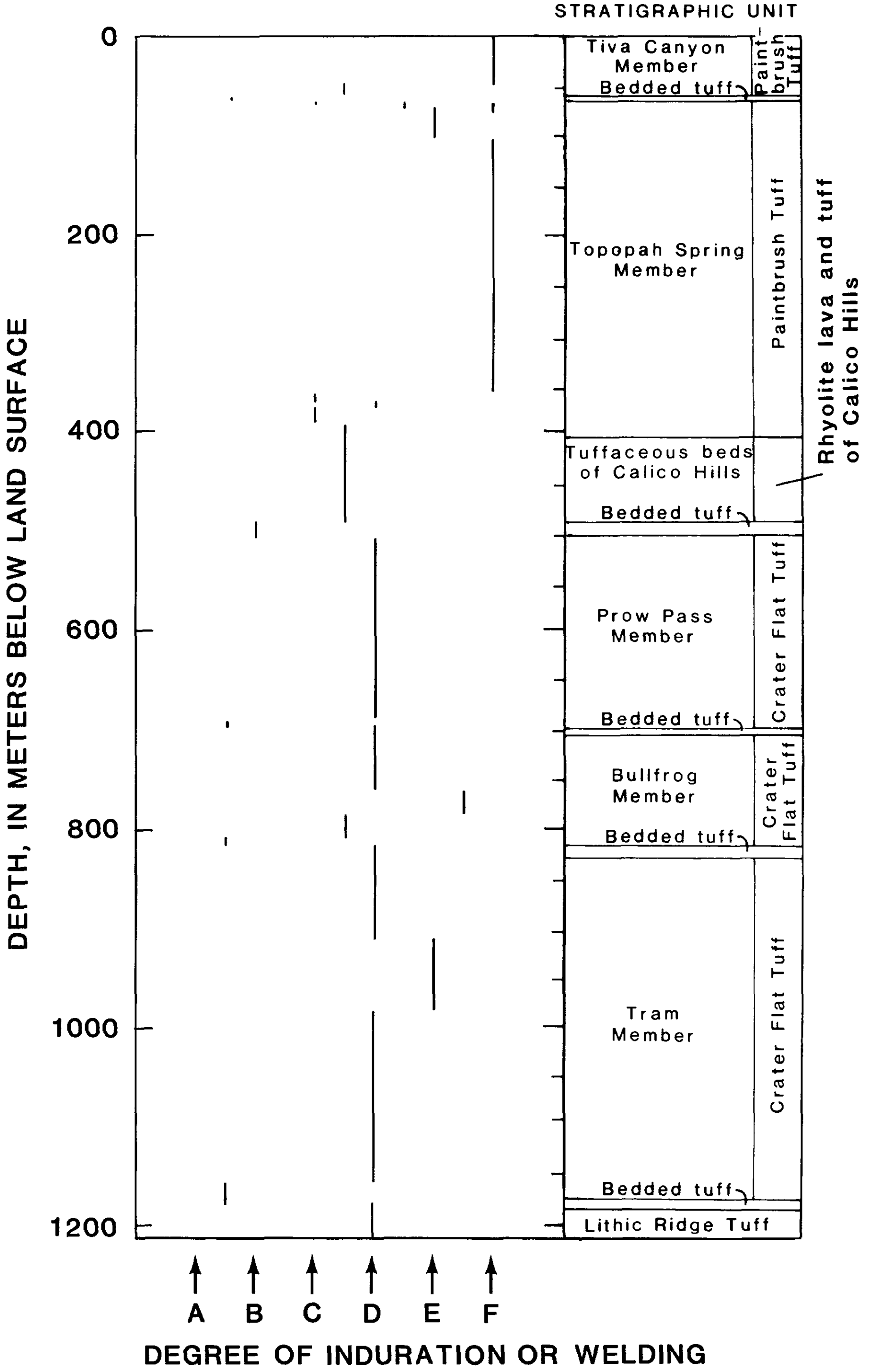

Figure 2.--Generalized distribution of induration or welding of rocks penetrated. (Induration: A, slightly; B, moderately; Welding: C, nonwelded; D, partially; E, moderately, F, densely).

Table 3.--*Geophysical well logs*

Geophysical log	Depth interval (meters)
Borehole-compensated acoustic fraclog gamma ray	576-1,218
Borehole-compensated acoustilog gamma ray	576-1,218
Caliper	93-95
Do.	79-560
Do.	549-1,218
Do.	546-1,216
Densilog gamma ray	500-1,219
Do.	556-1,216
Density, borehole compensated	76-561
Electric	546-1,219
Epithermal neutron porosity	27-567
Do.	30-561
Fluid density for water location	515-524
Do.	504-527
Gamma ray	0-561
Do.	27-563
Geophone survey	556-1,216
Induction	6-94
Induction	91-560
Do.	91-560
Neutron, borehole compensated	500-1,219
Radioactive-tracer survey	488-1,219
Spectralog gamma ray	0-1,219
Temperature	0-561
Do.	549-1,219
Television--camera videotape	0-505

Caliper logs determine a vertical profile of hole diameters. A vertical distribution of the depths where out-of-gage zones of the hole occurred is shown by black lines in figure 3. For each penetrated stratigraphic unit, the percentage of borehole wall that is out-of-gage is shown in table 4. Out-of-gage is defined in this report as a diameter 100 mm greater than the diameter of the bit used to drill the hole. Out-of-gage zones of the wellbore exceeding 300 mm generally cannot be tested by inflatable packers. Some of the enlarged zones identified by the caliper log were created by rock fracturing; these zones are summarized in table 5. The videotape from the television camera showed clearly that some enlarged zones were created by rock fracturing.

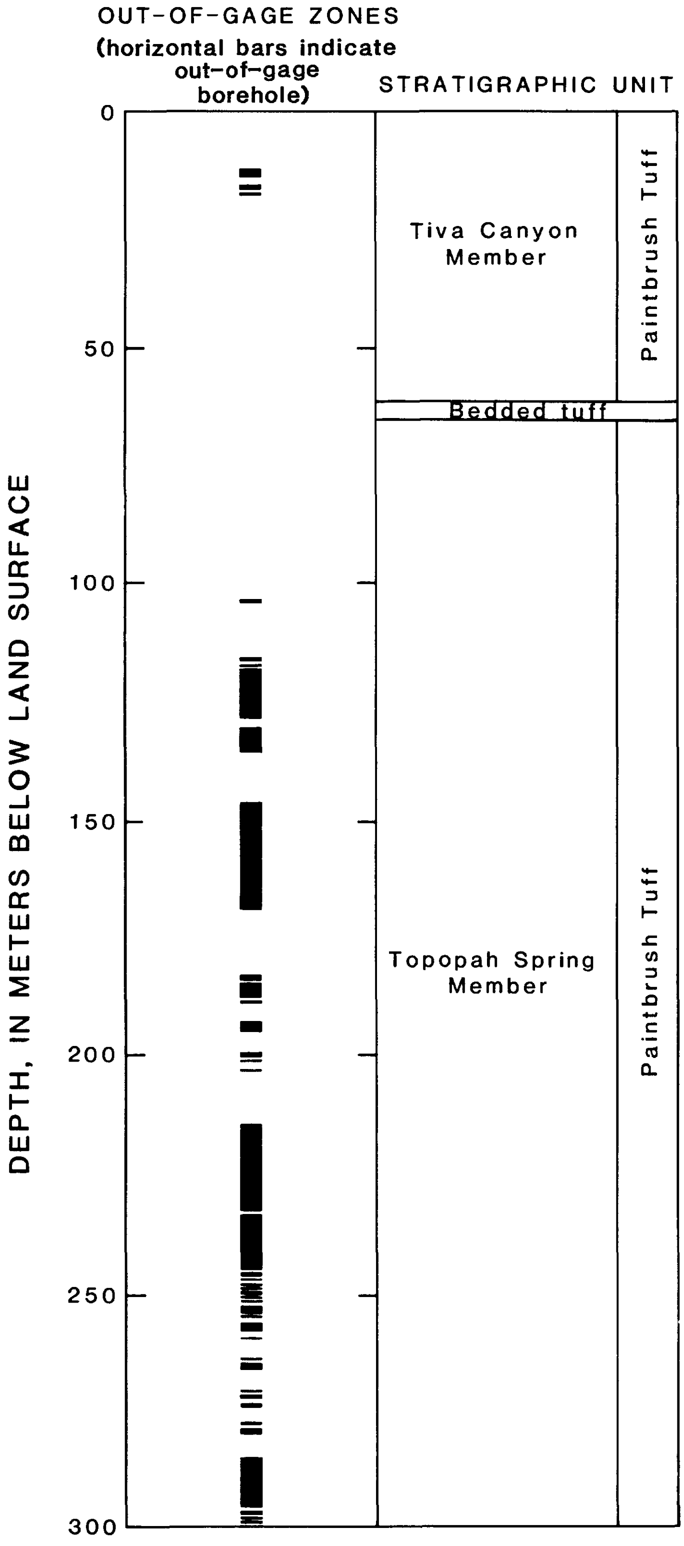

Figure 3.--Generalized vertical distribution of out-of-gage borehole.

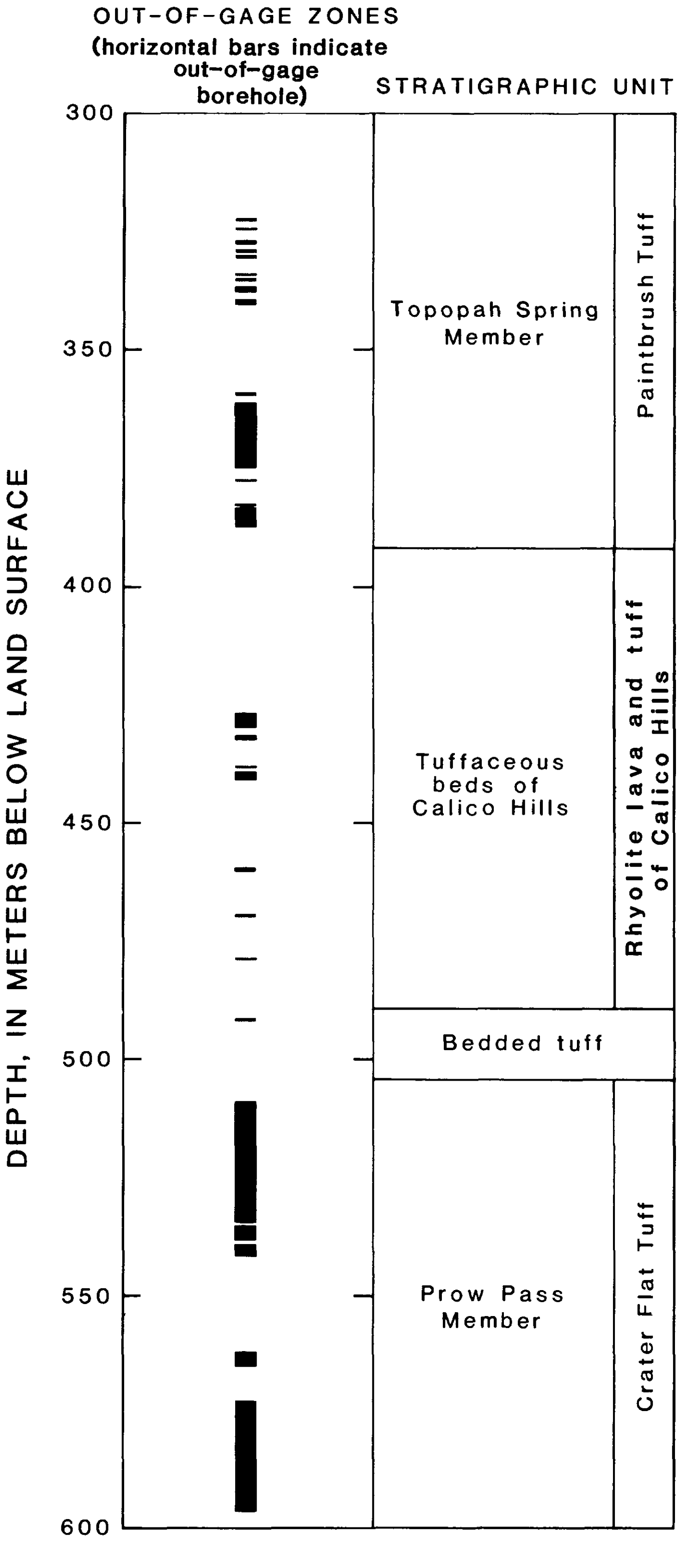

Figure 3.--Generalized vertical distribution of out-of-gage borehole--Continued

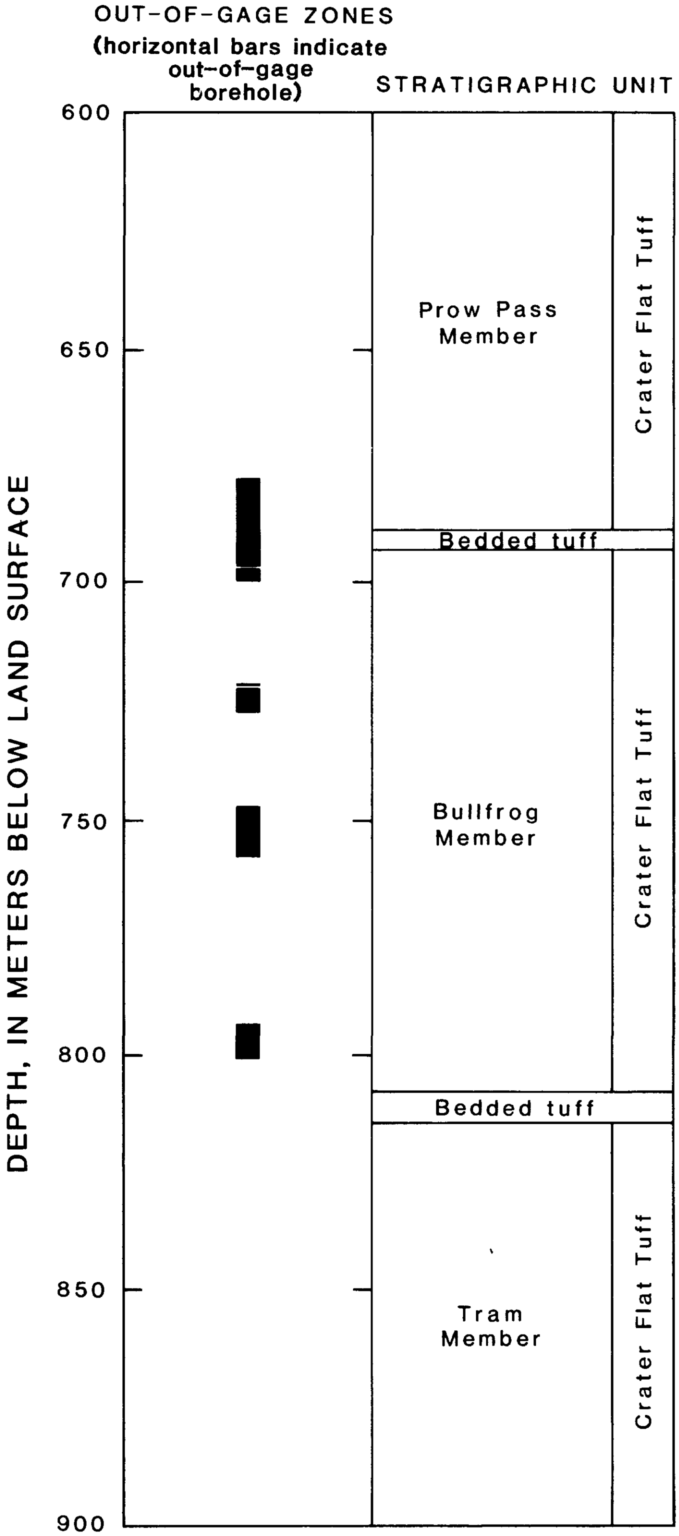

Figure 3.--Generalized vertical distribution of out-of-gage borehole--Continued

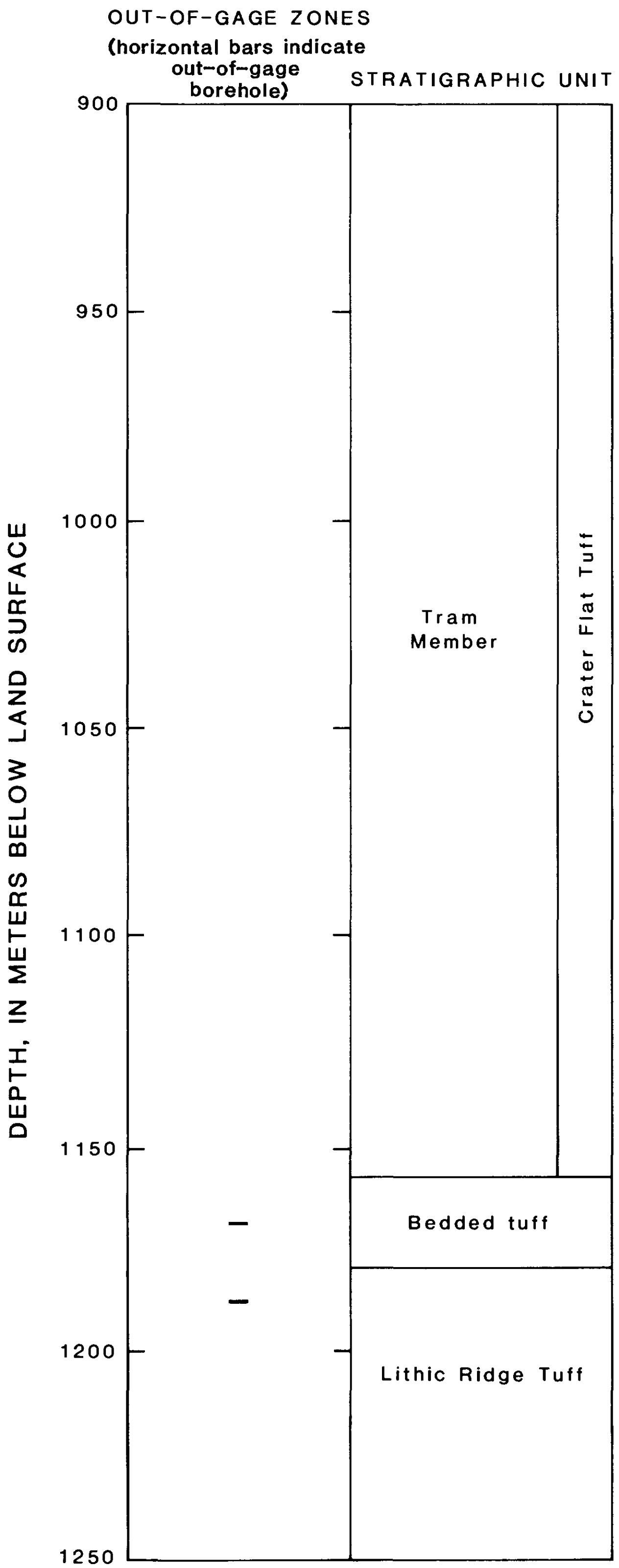

Figure 3.--Generalized vertical distribution of out-of-gage borehole--Continued

Table 4.--*Percentage of borehole that is out-of-gage in stratigraphic units*

Stratigraphic unit	Percent of unit out-of-gage	Distribution within stratigraphic unit
Tiva Canyon Member of Paintbrush Tuff[1]	3.0	Near top part of base of this member.
Topopah Spring Member of Paintbrush Tuff	37	Throughout unit, except top.
Tuffaceous beds of Calico Hills	7	Mainly at midinterval.
Prow Pass Member of Crater Flat Tuff	38	In upper one-half and at base.
Bullfrog Member of Crater Flat Tuff	25	Evenly spaced throughout unit.
Bedded unit below Tram Member of Crater Flat Tuff[2]	4	In middle of bedded unit.
Lithic Ridge Tuff	1	Near top of unit.

[1] Below casing, starting at a depth of 10.7 meters.

[2] Underlying bedded unit included in this interval.

Table 5.--*Enlarged borehole intervals associated with fractures*
[Based on caliper-log interpretations]

Stratigraphic unit	Depth interval (meters)	Interval thickness (meters)	Remarks
Tiva Canyon Member of Paintbrush Tuff[1]------	11-21	10	Near base of casing.
Topopah Spring Member of Paintbrush Tuff----	104-105	1	Seven fractured zones occur.
	117-137	20	
	147-169	22	
	183-203	20	
	216-300	84	
	323-340	17	
	358-387	29	
Tuffaceous beds of Calico Hills----------	427-441	14	Middle of unit.
Prow Pass Member of Crater Flat Tuff[2]-----	506-542	36	Lower interval continues into underlying unit.
	567-604	37	
	671-701	30	
Bullfrog Member of Crater Flat Tuff------	719-728	9	Fractured V-shaped areas are rough in upper part of unit, smooth and curved in lower part.
	736-765	29	
	789-806	17	
Tram Member of Crater Flat Tuff-------------	None	0	No fractured intervals identified in this unit.
Lithic Ridge Tuff-------	1,186-1,189	3	Only upper part of unit penetrated.
	1,202-1,207	5	
	1,214-1,215	1	

---

[1] Below casing, starting at a depth of 10.7 meters.
[2] Last interval includes a thin basal zone of bedded and reworked tuff.

A vertical profile of the wellbore indicating percentage of porous rock with depth was estimated by using both density and neutron logs. For the purpose of defining the general distribution of rock with greater than average porosity, that is, rock having porosity greater than the middle of the range indicated by the logs, the rock sequence penetrated was divided into 40 equal depth intervals, each about 30 m thick. Using the two types of logs, each depth interval was evaluated for percentage of relatively porous rock; that is, rock having porosity greater than the average for the rocks penetrated by the well. These interpretations of the density and neutron logs were combined into a single, generalized graph of percentage of porous rock (fig. 4). This graph only approximates the percentage of porous rock and does not give absolute porosity values. Borehole-compensated density and neutron logs respond to both matrix and fracture porosity. Below the water table, the density and neutron logs produced results that were similar to each other throughout most of the penetrated sequence. Above the water table, only the density log was used to determine the percentage of porous rocks. This method was developed using techniques described by Schlumberger Limited (1972, p. 37-55) and Birdwell Division (1973, p. OF90-OF188).

The occurrence of a large percentage of porous rock at or near the stratigraphic contact may be related to four features: (1) The poorly lithified bedded or reworked tuff at the base of most units probably is more porous than the ash-flow tuffs; (2) the upper part of each ash-flow tuff unit may have cooling or tectonic fractures creating fracture porosity; (3) weathered rock, near the upper contacts of stratigraphic units, may have increased percentage of porous rock; and (4) the degree of welding is least near the top or bottom of welded ash-flow tuff resulting in more porous rock near contacts of stratigraphic units.

The upper part of the hole, from 0 to 800 m, appears to have a relatively large percentage of porous rock, as determined from the density log. The lower part of the Tiva Canyon and Topopah Spring Members range from 15 to 46 percent of porous rock, which appears to be the result of fracturing in these members. However, although this percentage appears to be large, it probably is misleading, because the hole is out-of-gage. The tuffaceous beds of Calico Hills have porous rock ranging from 8 to 28 percent. The Prow Pass Member shows a rather large percent of porous rock, 17 to 38 percent; this percentage also could be due to fracturing. In the Bullfrog Member, a substantial decrease occurs in porous rock, except near the base where it is 29 percent. The Tram Member shows a medium percent of porous rock near its upper contact, 17 percent; then it decreases, 1 to 3 percent. In the Lithic Ridge Tuff, the percent of porous rock is small, 2 to 4 percent. The bedded tuffs that separate the above members generally have a small percentage of porous rock.

The following conclusions are made from the graph (in descending stratigraphic sequence) (fig. 4): (1) The Tiva Canyon and Topopah Spring Members (from 0 to 392 m below land surface) contain a large percentage of porous rock, mainly due to fractures; (2) the tuffaceous beds of Calico Hills have a smaller percentage of porous rock; (3) the Prow Pass Member has a rather large percentage of porous rock throughout; (4) the Bullfrog Member has a small percentage of porous rock, although it is larger near its contacts; and (5) the Tram Member and the Lithic Ridge Tuff have a small percentage of porous rock.

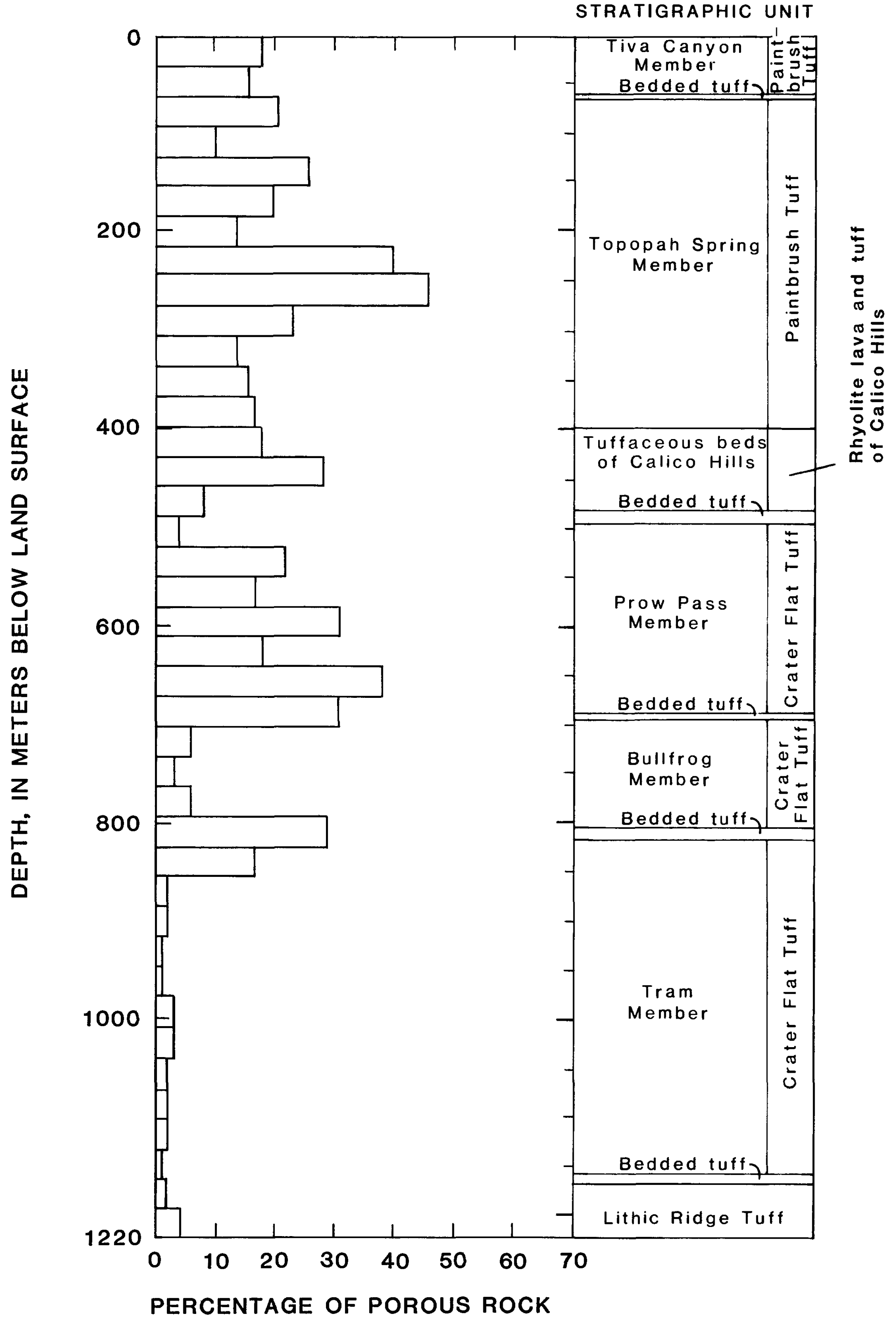

Figure 4.--Vertical distribution of percentage of porous rock that is greater than average porosity as determined from density and neutron logs.

HYDROLOGY

Discussions of water-level monitoring during and after drilling are included in this section of the report. During drilling, the quantity of soap and intake water from well J-13 was recorded. Hydrologic results obtained from pumping tests are discussed in a subsequent section. No results of injection tests are included because the testing method was not suitable for the relatively large transmissivities present in the tested intervals.

Ground-water flow through fractured tuffs, such as those at Yucca Mountain, is not as well understood as flow through porous media, such as sand, sandstone, and gravel. Flow through fractured tuff is much less predictable because of diverse lateral and vertical changes in fracture densities, interconnections, apertures, orientations, spacing, and continuity. Furthermore, the field methods and techniques necessary to collect and analyze several of these fracture parameters are not presently available. Thus, the uncertainties in fracture-flow predictions are great in both time and space (Bredehoeft and Maini, 1981, p. 293-294). A conceptual model of the ground-water system both in the general Yucca Mountain area and at this test well site is presented in the following paragraphs, based on model concepts of Rush and others (1984, p. 22).

The following assumptions are made in the conceptual model for the general flow system in the Yucca Mountain area:

1. Tuffaceous rock containing the primary-matrix porosity is nearly homogeneous and isotropic and is of great areal extent. Primary porosity is intergranular and principally is controlled in ash-flow tuffs by degree of welding and degree of alteration.

2. Secondary porosity is controlled by fractures. These fractures generally are vertical or at steep angles and may be spatially random (Baecher, 1983, p. 329) in the saturated zone and are the result of tensional and shear failure caused by mechanical deformation during tectonic activity or fracturing while cooling. The volume of water stored in fractures is relatively small in comparison to that stored in the matrix. On a small scale, the tectonic fracture permeability is anisotropic. However, the fracture permeability, due to cooling joints only, probably would be isotropic in plan view as well as homogeneous, because only random fracture strikes would be observed (Scott and others, 1983, p. 315).

3. Primary and secondary porosity may be decreased by precipitation of minerals.

4. Flow to the well is through the fracture network only; however, flow probably occurs between pores and fractures. Hydraulic conductivity of fractures is several orders of magnitude larger than hydraulic conductivity of the matrix.

5. Distances between fractures are small in comparison with the dimensions of the ground-water system under consideration.

6. In ash-flow tuffs, zones of approximately the same degree of welding have approximately the same density of fracturing (Scott and others, 1983, p. 309), with greater fracture density in more welded tuffs. Where dense fracture spacing occurs, water moves in fractured ash-flow tuffs in a similar matter as water in a granular porous media (Freeze and Cherry, 1979, p. 73).

At test well USW H-4, the following assumptions were made in the conceptual model for the flow system at this test well site:

1. Generally, the same assumptions are made as for the general flow system in the Yucca Mountain area listed above.

2. The major additional assumption at this well site is that there are both long tension fractures that are subsidiary to the major north-northeast-striking fault located 110 m to the southeast (Lipman and McKay, 1965) and possibly long nonhomogeneous linear fractures in the northwest-trending wash in which well USW H-4 is located.

3. In addition, the major fractures that conduct water probably are widely spaced in the tension fracture zone related to the fault.

4. During pumping tests, porous-media solutions for the homogeneous equivalent model in the Yucca Mountain area (Rush and others, 1984) may only be used after long periods when the response to pumping indicates a pseudoradial-flow period. During this pseudoradial-flow period, radial-flow equations may be used to calculate transmissivity in the area beyond the large elliptical zone of linear flow (Ragahavan and Hadinoto, 1978; Jenkins and Prentice, 1982).

Thus, the conceptual model for this well site is based on the mathematical model of a single vertical fracture located in a region in which the outer boundaries are maintained at a constant pressure and fluid crosses the outer boundaries as a uniform flux (Raghavan and Hadinoto, 1978). Because there are several vertical or very steep fractures penetrated by this well, this conceptual model was only used to explain the linear-flow period during pumping tests in which the vertical fractures controlled flow. This period was characterized by a straight line with a slope equal to 0.5 on a log-log graph, referred to as the one-half slope line.

The authors believe that the key phenomenon that controls the pumping test is the linear-flow period in which most of the water is derived from fracture storage. The pseudoradial-flow period during both drawdown and recovery of water level is indicated by the straight-line graphs of water level on semilogarithmic paper.

Drilling-Fluid Use

To minimize the invasion and plugging of fracture and matrix porosity while drilling the well, bentonite and polymer-base drilling muds were not used. Instead, air foam, consisting of a small volume of detergent and water and a large volume of unmeasured air, was used as the drilling medium. Approximately 30,000 L of detergent and 3,150,000 L of water were used to drill this test well. Additional water was injected into the borehole during injection tests.

The use of drilling fluid is shown in figure 5. Variations in fluid-use rate generally are related to fluid losses in rock penetrated. Because permeable zones receive more infiltration than less permeable zones, the fluid-use rate, as indicated by changes in slope in figure 5, was used as an approximate index of permeability.

At depths of about 55 and 536 m, fluid loss occurred during logging periods, when no drilling was in progress. The following general hydrologic conclusions are drawn from the data: (1) Fluid-use rate was large to a depth of 55 m, indicating that the wellbore was most permeable in the Tiva Canyon Member; (2) the graph steepened below 55 m, indicating less fluid used due to lower permeability from 55 to 385 m, in the Topopah Spring Member; (3) additional steepening of the graph at a depth of 385 to 680 m indicated a further decrease in permeability in the tuffaceous beds of Calico Hills to the base of the Prow Pass Member; (4) below 680 m, down to a depth of 800 m, the graph flattened indicating more permeability in the Bullfrog Member; and (5) from 800 to 870 m, the graph steepened, indicating less permeability in the upper part of the Tram Member. Below 870 m, drilling-fluid use increased; however, a substantial volume of fluid was spent in regaining circulation throughout this interval.

Water Levels

Water-level measurements in test well USW H-4 were made after drilling, and before, during, and after the pumping and injection tests. Water-level measurements were made to determine: (1) Depth to the saturated zone; (2) a composite hydraulic head for the test hole; and (3) a vertical profile of hydraulic heads for the different water-producing zones. Measurements were made during drilling in an attempt to locate perched-water zones above the water table. A summary of depth where either ground water or drilling fluid was encountered in the unsaturated zone and where water-level measurements were made in the saturated zones during well construction, prior to running injection tests, is presented in table 6.

Pumping Tests

Drawdown and recovery tests were made during several preliminary short-term pumping tests, followed by the long-term main pumping test, pumping test 6; all these tests were for the depth interval from 519 to 1,219 m. Preliminary pumping tests indicated that pronounced water-level fluctuations from temperature and water-density changes affected the height of the water column in the well. It is assumed that the density of water in the borehole decreased because water with a higher temperature was pumped from the rock formation below, replacing the denser, cooler water by less dense, warmer water. This effect was first noted in test well 73-66 at the Nevada Test Site (Winograd, 1970). A 4.6-m rise in water level, rather than a decline in water level, occurred while pumping this well. This large rise in water level

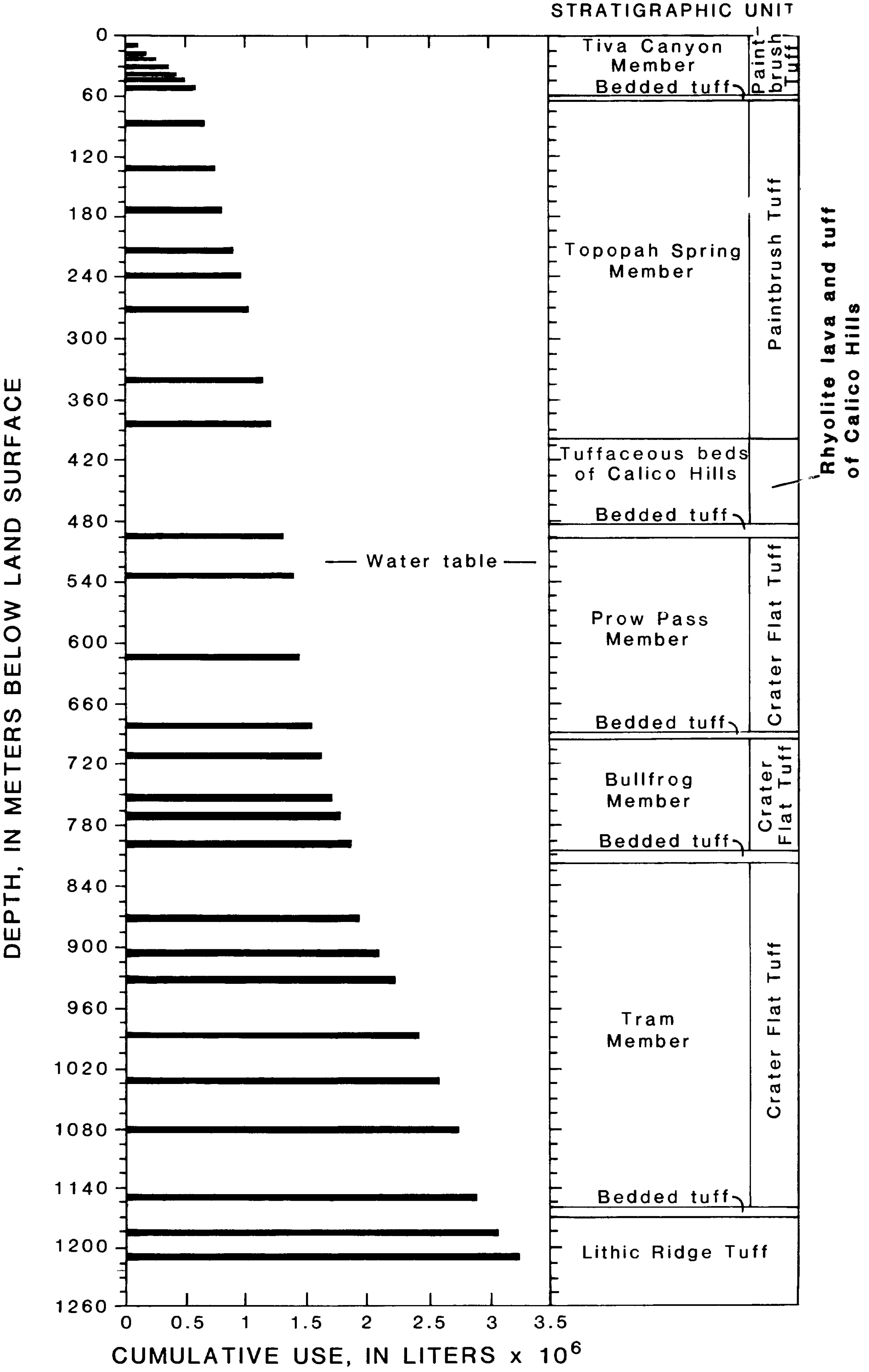

Figure 5.--Drilling-fluid use.

Table 6.--*Summary of water-level measurements during drilling and water-level measurements for pumping and packer-injection tests*

[Altitude of land surface at well is 1,248.9 meters; water level accurate to ±0.5 meter]

Depth of hole or packed off interval (meters)	Date of measurement	Depth of water below land surface (meters)	Altitude of water surface above sea level (meters)	Remarks
[1]338	4/08/82	338	911	Topopah Spring Member of Paintbrush Tuff. Possibly perched water or lost circulation, airlifted <0.03 liter of water per second for 5 minutes.
[1]564	4/11/82	519.01	729.89	Prow Pass Member of Crater Flat Tuff. Water level measured when drill hole was 564 meters deep.
[1]564	4/13/82	518.98	729.92	Prow Pass Member of Crater Flat Tuff. Water level measured when drill hole was 564 meters deep, after running geophysical logs.
[1]564	4/15/82	519.98	729.92	Prow Pass Member of Crater Flat Tuff. Water level measured when drill hole was 564 meters deep, just before casing down to the water level.
[1]1,219	5/07/82	519.05	729.85	Composite water-level measurement made just before pumping.
[1]1,219	5/22/82	519.10	729.80	Composite water level measurement after pumping tests and just prior to packer-injection tests.
[2]604-652	6/03/82	519.71	729.19	Prow Pass Member of Crater Flat Tuff.
[2]652-701	6/03/82	519.53	729.37	Prow Pass and Bullfrog Members of Crater Flat Tuff.
[2]703-735	5/29/82	519.04	729.86	Bullfrog Member of Crater Flat Tuff.
[2]735-767	5/30/82	518.78	730.12	Do.
[2]783-832	6/04/82	519.47	729.43	Lower part of Bullfrog Member and upper part of Tram Member of Crater Flat Tuff.
[2]836-855	5/27/82	519.16	729.74	Tram Member of Crater Flat Tuff.
[2]855-873	5/27/82	519.47	729.43	Do.
[2]873-892	5/26/82	519.42	729.48	Do.
[2]892-910	5/26/82	518.88	730.02	Do.
[2]910-928	5/24/82	519.31	729.59	Do.
[2]931-1,219	5/26/82	519.42	729.48	Do.
[2]1,174-1,192	5/23/82	519.31	729.59	Lithic Ridge Tuff.

[1] Depth during drilling and pumping.

[2] Depth during packer-injection tests.

occurred when water at a lower depth with a higher temperature (22° to 28°C higher) was pumped into the well casing (Winograd, 1970).

In test well USW H-4, anomalous rises in water level during pumping and declines in water level during recovery occurred 5 to 6 minutes after the pump started or stopped. For example, during pumping test 2, the water level appeared to recover above the static water level, followed by a marked decline in the water level toward static water level after 5 minutes (fig. 6). The principal pumping test (test 6) showed similar anomalous water-level changes during both drawdown and recovery (fig. 7). The variations in drawdown for the first 45 minutes of the test were due in part to variations in discharge of from 23 to 11 L/s.

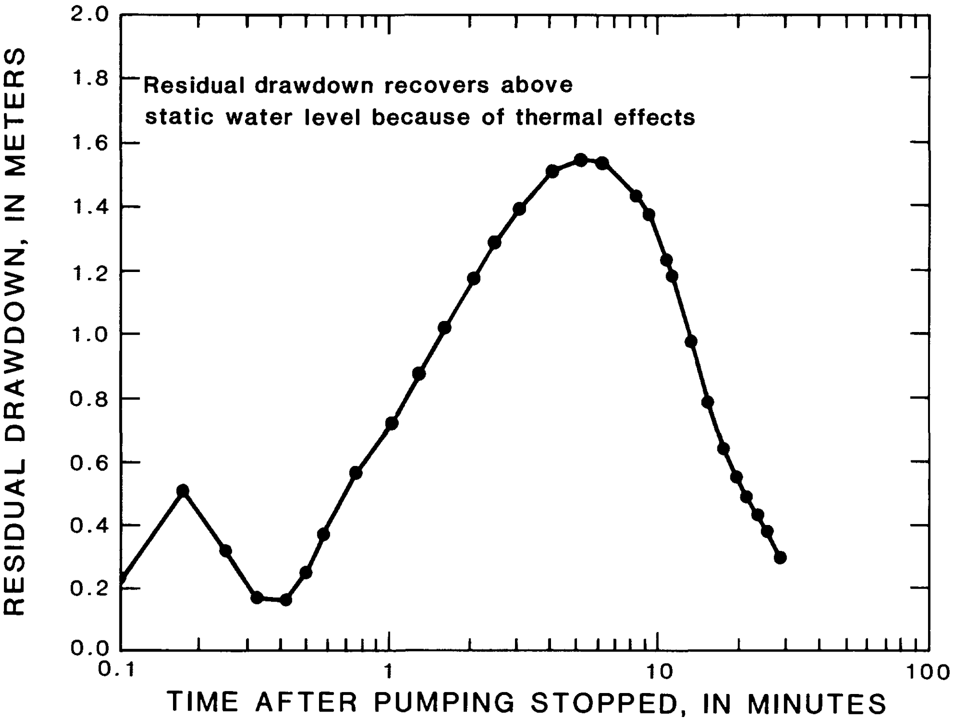

Figure 6.--Water-level recovery versus time for pumping test 2, depth interval from 519 to 1,219 meters.

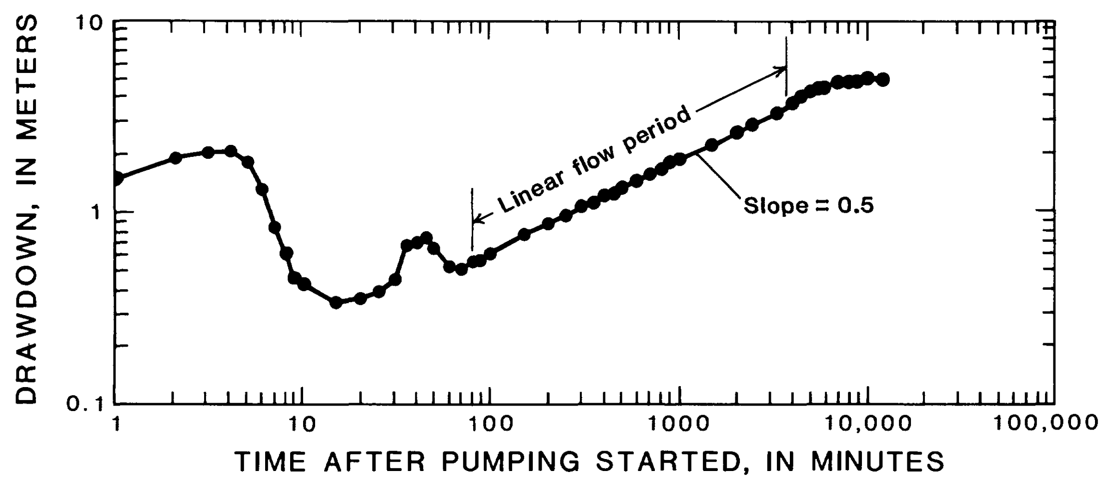

Figure 7.--Water-level drawdown versus time for pumping test 6, depth interval from 519 to 1,219 meters.

The pumping rate for pumping test 6 was 17.4 L/s; the pumping period was 12,818 minutes. The water probably was pumped from several intervals of fractured tuff. Pumping test 6 was analyzed for aquifer transmissivity and hydraulic conductivity, using both the Jacob straight-line method (Jacob, 1947; Lohman, 1972) and the Theis-recovery method for recovery (Ferris and others, 1962). The Raghavan and Hadinoto (1978) type curve was especially useful for indicating a linear-flow period in vertical fractures, as shown by the straight-line slope equal to 0.5 on log-log paper, commonly referred to as a half-slope line, that occurs from 80 to 3,000 minutes or more (fig. 7); the semilogarithmic straight-line part does not occur until after 3,000 minutes of pumping (Raghavan and Hadinoto, 1978, fig. 3). Thus, the straight-line method was applied to the latter part of the drawdown curve from 8,000 to 11,000 minutes, as presented in the semilogarithmic plot in figure 8. The slope of the straight line is $\Delta s = 1.4$ m, a slope close to the 0.81 m predicted for the straight line in the pseudoradial-flow period of Raghavan and Hadinoto (1978).

The Theis-recovery method of analysis was used for pumping test 6 by drawing the slope between 100 and 1,000 minutes during which temperature effects probably were small (fig. 9). Results of the pumping-test analyses are transmissivity of 200 m^2/d and average hydraulic conductivity of 0.29 m/d, using the straight-line method, and a transmissivity of 790 m^2/d and hydraulic conductivity of 1.1 m/d, using the Theis-recovery method.

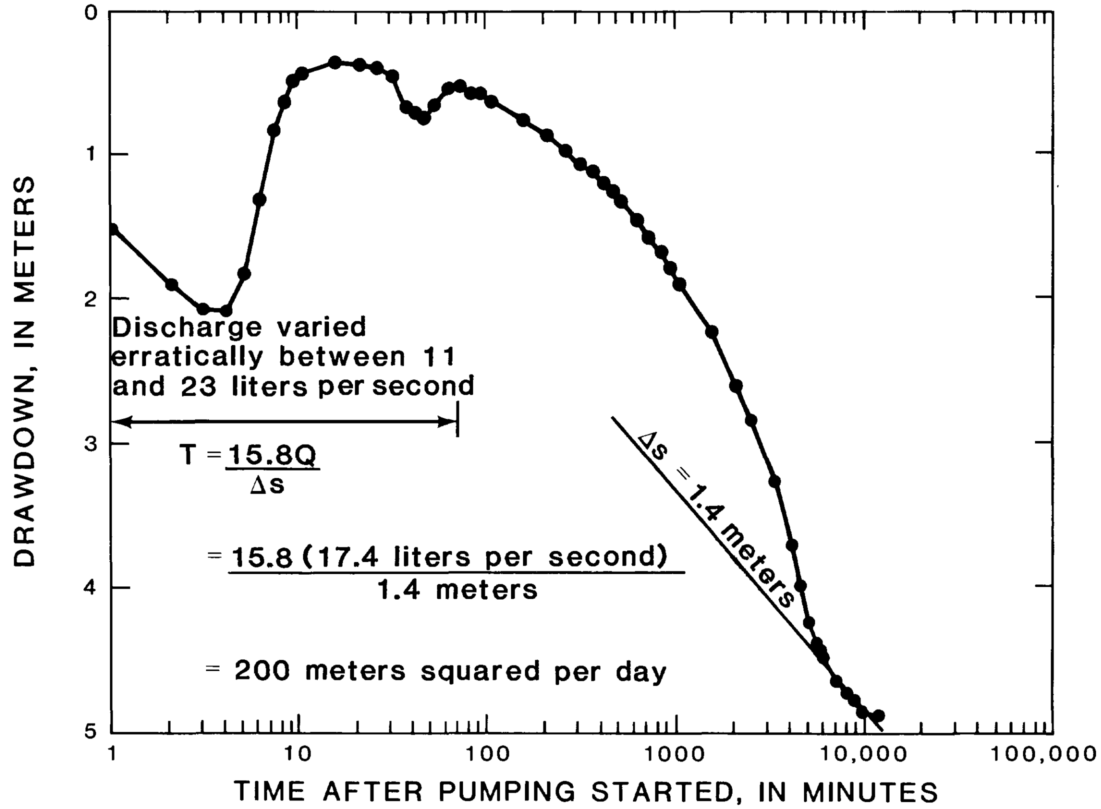

Figure 8.--Analysis of water-level drawdown versus time for pumping test 6, depth interval from 519 to 1,219 meters, using the straight-line method of analysis.

Radioactive-Tracer, Borehole-Flow and Temperature Survey

A radioactive-tracer flow survey was used to determine the locations of production zones in the saturated part of the well and their flow rates, while the well was stressed by pumping. These data were used to determine the zones to be tested by drill-stem tests and to help analyze the pumping tests. A schematic diagram of this flow survey is shown in figure 10.

A radioactive slug of iodine-131 was released into the well and tracked past two gamma-ray detectors to determine the velocity of the water. This velocity multiplied by the cross-sectional area of the hole determined the rate of flow in the well at this interval. The rate of flow varied across intervals that contributed water to the well. By these changes, the water-yielding zones were identified.

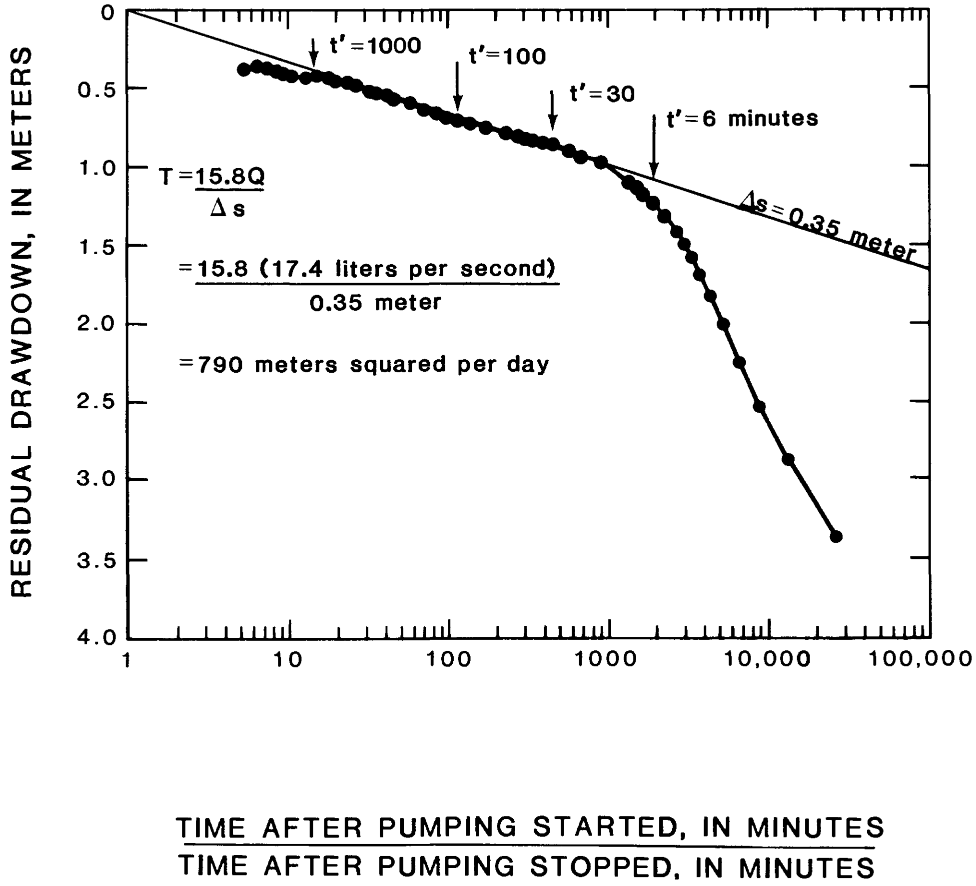

Figure 9.--Analysis of water-level recovery versus time for pumping test 6, depth interval from 519 to 1,219 meters.

The survey was started when the water level during pumping was changing very little with time. After pumping test 6 had been going for 45 hours and 40 minutes at a continuous rate of 17.2 L/s, the borehole-flow survey began. A water-temperature profile of the wellbore also was recorded while pumping continued during the flow survey. The slope of the temperature gradient curve closely paralleled that of the flow-rate curve (fig. 10).

The borehole survey indicated that the water-producing zones extended from the water surface at 519 m, in the Prow Pass Member, to the bottom of the test hole at 1,219 m in the Lithic Ridge Tuff. Thin bedded tuffs at the base of the Prow Pass Member, Bullfrog Member, and Tram Member produced little or no water.

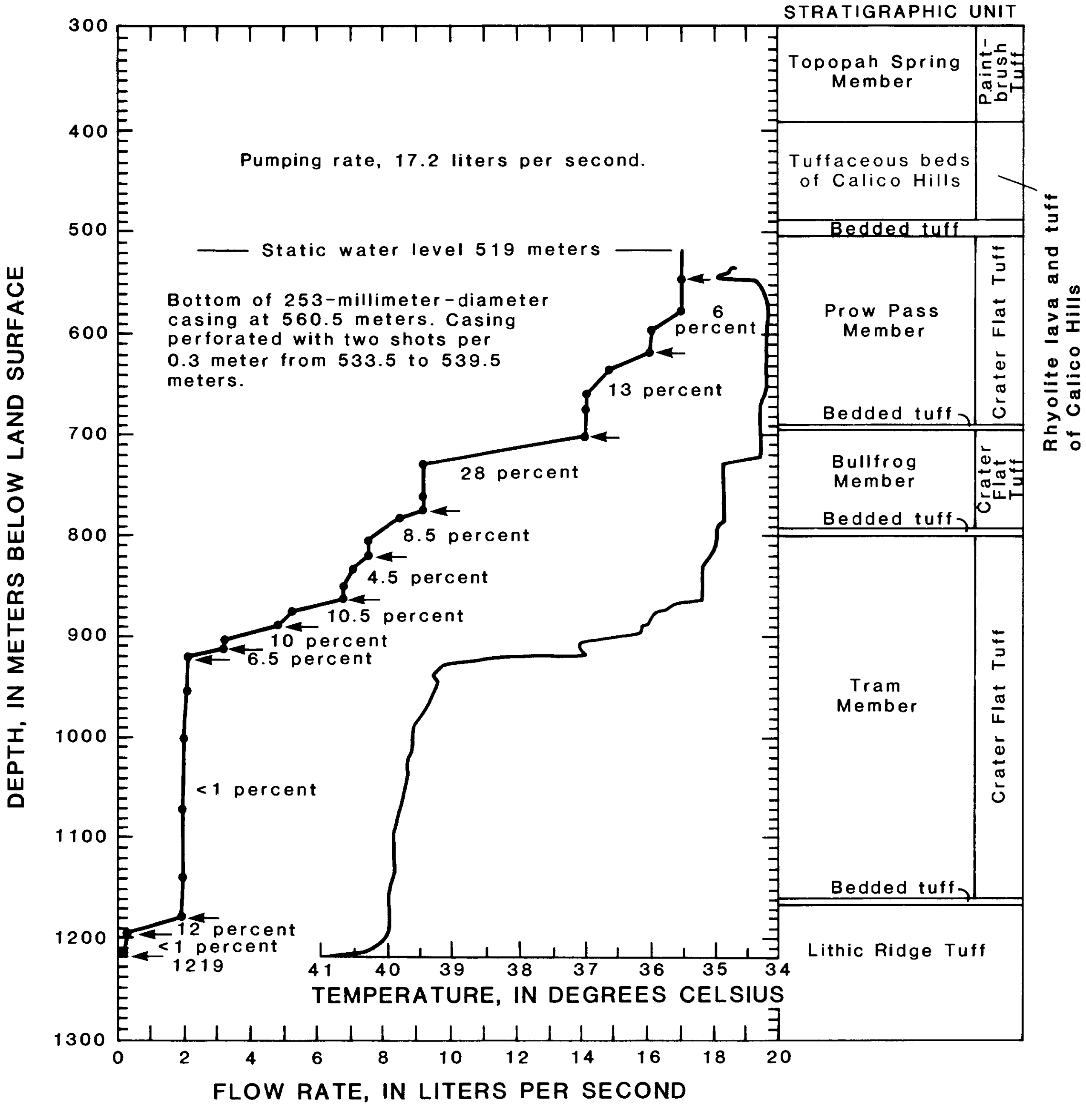

Figure 10.--Borehole-flow and temperature survey showing percentage of pumping rate produced by intervals from 555 to 1,219 meters.

The most productive geologic unit is the Bullfrog Member, which produced 36.5 percent of the water in the well. The upper part of the Bullfrog Member from 721 to 731.5 m produced 28 percent of the water pumped; it may have had hydraulic connection with the overlying bedded unit at some distance from the wellbore.

Another zone that produced significant quantities of water is in the upper part of the Tram Member, which yielded 32 percent of the water. This productive zone consists of three intervals between 864 to 920 m. This yield also probably is related to permeability created by fractures or faults.

Nineteen percent of the water pumped was produced from 625 to 635.5 m near the bottom of the Prow Pass Member. This yield may result from hydraulic connection with the bedded tuff underlying the Prow Pass Member. The basal part of the Bullfrog Member, from 789.5 to 803 m, produced 12 percent of the water pumped. This productivity rate probably can be related to hydraulic connection with the bedded unit underlying the Bullfrog Member. The top of the Lithic Ridge Tuff, from 1,214.5 to 1,219 m, produced 12-percent of the water produced that probably was from the fractures.

Values of apparent transmissivity and apparent hydraulic conductivity were determined for the producing intervals, using pumping test 6 and the radioactive-tracer survey. Hydraulic coefficients in table 7 were computed by proportioning the transmissivity values obtained from the pumping test to the productive zones as determined by the radioactive-tracer survey. Because the borehole was not screened and the pumping rate was not excessive, it is assumed that no appreciable hydraulic-head losses occurred during the pumping test. Intervals in the Bullfrog Member have the highest overall permeability for a given stratigraphic unit. Other high permeability zones were thin intervals (less than 16 m) occurring in the Prow Pass Member, Tram Member, and Lithic Ridge Tuff. These thin, high permeability zones probably can be related to extensive fracture systems.

GROUND-WATER QUALITY

A water sample was collected on May 17, 1982, near the end of pumping test 6, for chemical analysis of major constituents and carbon-14 age dating. This water sample represented the chemistry of water produced from the water table (519 m) to the total depth of the well (1,219 m) (table 8). Approximately 14,700,000 L of water were pumped prior to collecting the water sample The water was clear and colorless, but still soapy from the drilling detergent. A lithium chloride spike was added to water used in drilling and injection tests. Because the background concentration of lithium in the water pumped from the aquifers is very low, the lithium concentration obtained periodically during pumping indicated when the well was producing mostly formation water. About 36 percent of this water was produced from the Bullfrog Member, and about 32 percent of this water was produced from the Tram Member, both in the Crater Flat Tuff.

Table 7.--*Distribution of transmissivity and hydraulic conductivity based on pumping test and radioactive-tracer, borehole-flow survey*

Stratigraphic unit (See table 2)	Depth interval (meters)	Percent of production	Thickness of zone (meters)	Using T = 200 meters squared per day	
				Transmissivity of zone (meters squared per day)	Hydraulic conductivity of zone (meters per day)
Crater Flat Tuff					
Prow Pass Member	561-584	5.8	23.5	11.5	0.49
Do.	623-639	9.3	16.0	18.6	1.16
Do.	643-669	3.5	21.0	6.9	.33
Prow Pass Member and bedded tuff	680-707	.6	27.0	1.1	.04
Bullfrog Member	707-733	27.9	26.0	55.9	2.15
Do.	779-785	4.1	6.0	8.2	1.37
Do.	785-805	5.2	20.0	10.4	.52
Tram Member	820-834	2.9	14.0	5.7	.41
Do.	834-852	1.7	18.0	3.4	.19
Do.	863-876	9.3	13.0	18.6	1.43
Do.	876-881	.6	5.0	1.2	.24
Do.	881-892	.6	11.0	2.3	.12
Do.	892-905	9.9	13.0	19.8	1.52
Do.	911-922	5.8	11.0	11.6	1.05
Do.	922-928	.6	6.0	1.2	.20
Do.	957-1,003	.6	46.0	1.4	.03
Lithic Ridge Tuff	1,181-1,194	10.2	13.0	20.4	1.57
Do.	1,194-1,213	.7	19.0	1.3	.07
Do.	1,213-1,219	.8	6.0	1.6	.27

Table 8.--*Chemical analysis of water sample*[1]

[All units are milligrams per liter unless otherwise indicated]

Chemical constituents or physical properties	Concentration or value
Bicarbonate (HCO_3) (on site)	173
Bicarbonate (HCO_3) (laboratory)	171
Calcium (Ca)	17
Carbon 13-12 ratio ($\delta^{13}C$)[2]	-7.4
Carbon-14 (H_2O) age	17,200
Chloride (Cl)	6.9
Deuterium-hydrogen ratio ($\delta^{2}H$)[3]	-104.0
Fluoride (F)	4.6
Lithium (Li)	.13
Magnesium (Mg)	.29
Oxygen 18-16 ($\delta^{18}O$)[4]	-14.0
pH (laboratory), units	7.9
pH (on site), units	7.4
Potassium (K)	2.6
Residue on evaporation	248
Silica (SiO_2)	46
Sodium (Na)	73
Specific conductance (on site), microsiemens[5]	340
Specific conductance (laboratory), microsiemens[5]	381
Strontium (Sr)	.027
Sulfate (SO_4)	26
Temperature, degrees Celsius	34.8
Tritium, picocuries per liter	<10
Cations, milliequivalents per liter	4.114
Anions, milliequivalents per liter	3.785
Difference, percent	4.16

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[1] Chemical analysis made by U.S. Geological Survey laboratory, Denver, Colo.; water sample collected on May 17, 1982.

[2] Deviation of carbon 13-12 ratio of sample from PeeDee Belemnite standard (PDB), in parts per thousand.

[3] Deviation of deuterium-hydrogen ratio of sample from standard mean ocean water (SMOW) relative to SMOW, in parts per thousand.

[4] Deviation of oxygen 18-16 ratio of sample from standard mean ocean water (SMOW) relative to SMOW, in parts per thousand.

[5] Equivalent to micromhos per centimeter at 25° Celsius.

The water is typical of water produced from the tuffaceous rocks of southern Nevada, in that it is predominantly a sodium bicarbonate type containing small concentrations of calcium and sulfate (Winograd and Thordarson, 1975, p. C97). It also is slightly alkaline and contains a large concentration of dissolved silica. The water, in general, is a potable water suitable for most uses. Carbon-14 age dating indicates the age of the water to be about 17,000 years before present. Oxygen 18 and 16 and deuterium-hydrogen determinations indicate a cold climatic regime similar to that which existed about 17,000 years before present.

CONCLUSIONS

Results of hydrologic monitoring by means of drilling, geophysical logs, pumping tests, and injection tests indicate these conclusions:

1. Tuffs in the Topopah Spring Member of the Paintbrush Tuff have the thickest, most densely welded section; the tuffaceous beds of Calico Hills have the least degree of welding.
2. The water table is at a depth of 519 m below land surface, in the upper part of the Prow Pass Member of the Crater Flat Tuff. No noticeable head differences occurred with depth. A possible perched-water zone occurred in the lower part of the Topopah Spring Member of the Paintbrush Tuff.
3. The most permeable parts of the saturated zone were from the depth interval 721 to 731.5 m in the upper part of the Bullfrog Member of the Crater Flat Tuff, and from the depth interval 864 to 920 m in the upper part of the Tram Member of the Crater Flat Tuff.
4. Hydraulic coefficients (calculated using several methods) determined by means of a pumping test for the saturated section of this test well ranged from 200 to 790 m^2/d for transmissivity and 0.29 to 1.1 m/d for hydraulic conductivity.
5. A composite water sample of all the producing zones in this test well was collected for analysis. Results of this analysis indicate that it was predominantly a sodium bicarbonate type of water, typical of water produced from tuffaceous rocks of southern Nevada.

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