

GEOHYDROLOGY OF ROCKS PENETRATED BY TEST WELL USW H-6, 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:

<i>Metric unit</i>	<i>Multiply by</i>	<i>To obtain inch-pound unit</i>
millimeter (mm)	0.03937	inch
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meter squared per day (m ² /d)	10.76	foot squared per day
milligram per liter (mg/L)	1 ¹	part per million
microgram per liter (µg/L)	1 ¹	part per billion
liter per second (L/s)	15.85	gallon per minute
liter (L)	0.2642	gallon
microsiemens per centimeter at 25° Celsius	1.000	micromhos per centimeter at 25° Celsius
degree Celsius (°C)	$^{\circ}\text{F} = 1.8 \text{ }^{\circ}\text{C} + 32$	degree Fahrenheit (°F)

¹Approximate for concentrations of dissolved solids less than about 7,000 milligrams per liter

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ABSTRACT

Test well USW H-6 is one of several wells drilled in the Yucca Mountain area near the southwestern part of the Nevada Test Site for investigations related to isolation of high-level nuclear wastes. This well was drilled to a depth of 1,220 meters. Rocks penetrated are predominantly ash-flow tuffs of Tertiary age, with the principal exception of dacitic(?) lava penetrated at a depth from 877 to 1,126 meters. The composite static water level was about 526 meters below the land surface; the hydraulic head increased slightly with depth.

Most permeability in the saturated zone is in two fractured intervals in Crater Flat Tuff. Based on well-test data using the transitional part of a dual-porosity solution, an interval of about 15 meters in the middle part of the Bullfrog Member of the Crater Flat Tuff has a calculated transmissivity of about 140 meters squared per day, and an interval of about 11 meters in the middle part of the Tram Member of the Crater Flat Tuff has a calculated transmissivity of about 75 meters squared per day. The upper part of the Bullfrog Member has a transmissivity of about 20 meters squared per day. The maximum likely transmissivity of any rocks penetrated by the test well is about 480 meters squared per day, based on a recharge-boundary model. The remainder of the open hole had no detectable production. Matrix hydraulic conductivity ranges from less than 5×10^{-5} to 1×10^{-3} meter per day.

Ground water is a sodium bicarbonate type that is typical of water from tuffaceous rocks of southern Nevada. The apparent age of the water is about 14,600 years.

INTRODUCTION

The U.S. Geological Survey is conducting investigations to determine the geologic and hydrologic suitability of Yucca Mountain, Nevada, as a possible site for a mined geologic repository for high-level nuclear wastes. These investigations are being conducted under the auspices of the U.S. Department of Energy, Nevada Operations Office under Interagency Agreement DE-AI08-78ET44802 and are part of the Nevada Nuclear Waste Storage Investigations project. This report presents hydrologic information obtained from test well USW H-6, one of a series of test wells drilled on and near Yucca Mountain.

Purpose and Scope

The purpose of this report is to characterize the geohydrology of saturated volcanic rocks penetrated by test well USW H-6. Drilling test wells designed for hydrologic testing is one approach for determining the suitability of the hydrologic system for storage of high-level nuclear waste at the Yucca Mountain site. This report contains hydrologic interpretations of saturated rocks penetrated in test well USW H-6 based on data obtained from borehole tests and supported by geological and geophysical information.

Location of Study Area

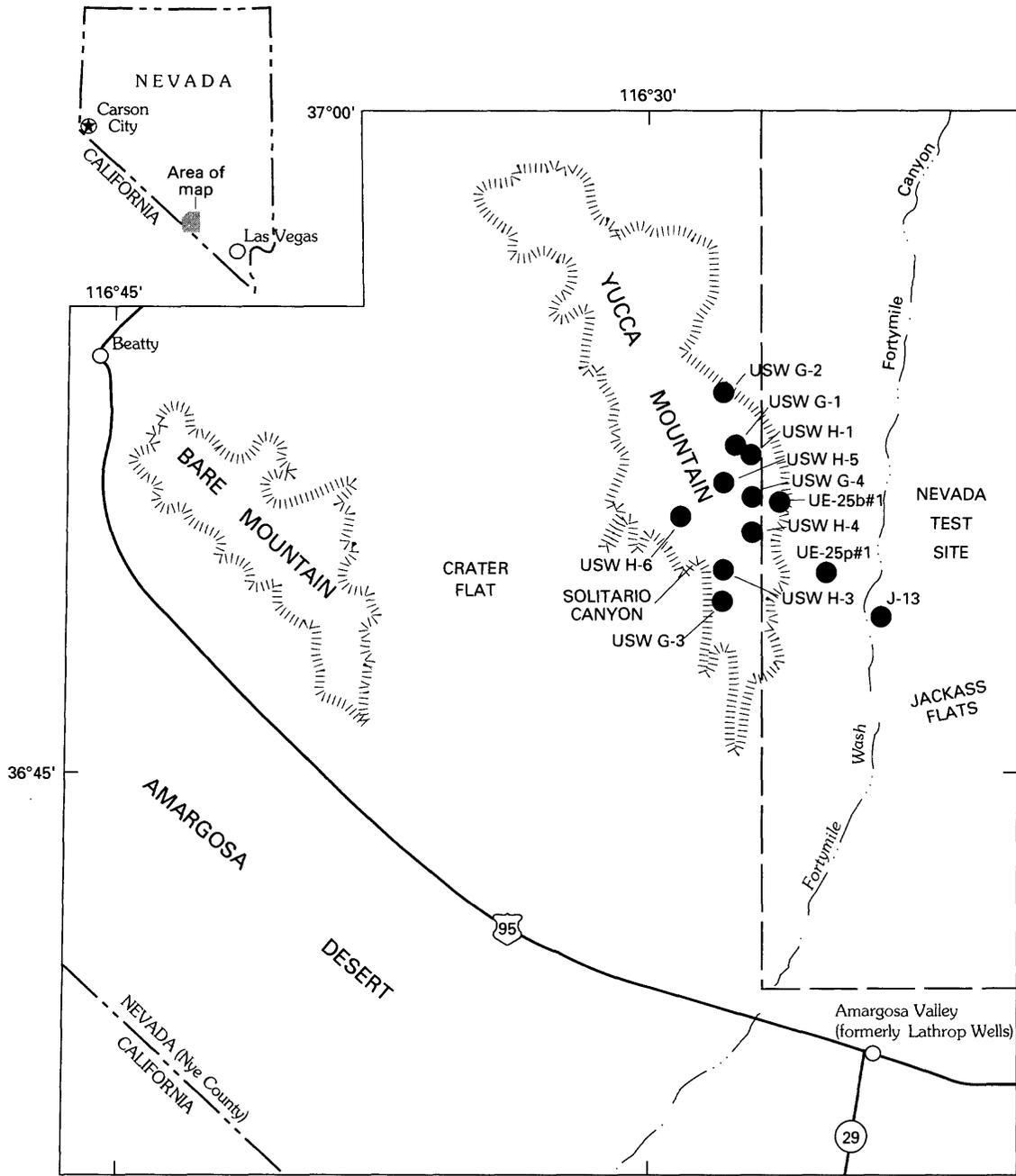
Test well USW H-6 is located on Yucca Mountain in Nye County, Nevada, in the southern part of the State, about 145 km northwest of Las Vegas, at Nevada State Coordinate System, central zone N 763,299 ft and E 554,075 ft (fig. 1). The altitude of land surface at the site is 1,302 m above sea level. Test well USW H-6 is west of the area on Yucca Mountain being considered as a possible waste repository. The well site is in a small canyon that drains eastward into Solitario Canyon, a larger, south-trending drainage system that is bounded on the eastern side by a large fault scarp (Lipman and McKay, 1965). The test well was drilled principally to determine if geohydrologic conditions east of the fault scarp, as determined by data from other test wells, also extend to the west.

Geohydrologic Setting

The area around Yucca Mountain is a desert region within the Basin and Range physiographic province. Rock units exposed in this area are sedimentary rocks of Precambrian and Paleozoic age, volcanic and sedimentary rocks of Tertiary age, and alluvial and playa deposits of Quaternary age (Winograd and Thordarson, 1975; Byers and others, 1976). Tertiary volcanic and sedimentary rocks, as well as previously deformed Precambrian and Paleozoic strata, have undergone large-scale normal block-faulting, that began with Miocene volcanism and continued into the Quaternary Period. This large-scale normal block-faulting, which produced the Basin and Range topography, is the most prominent tectonic feature in the area (Winograd and Thordarson, 1975, p. C13).

Yucca Mountain is composed primarily of Tertiary ash-flow tuffs. Test wells drilled on Yucca Mountain have not penetrated older rocks below the Tertiary tuff units, but test well UE-25p#1, about 5.7 km southeast of test well USW H-6 and about 1.5 km east of Yucca Mountain, penetrated Paleozoic dolomite at a depth of 1,244 m, on what is probably a structural high (Craig and Johnson, 1984).

Block-faulting, typical of the Basin and Range province, produced the present topography of Yucca Mountain. The western edge of the highest ridge of Yucca Mountain is bounded by a large fault scarp (Lipman and McKay, 1965). This scarp forms the eastern boundary to Solitario Canyon.



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

Figure 1.--Location of test well USW H-6 and other test wells in the vicinity.

Annual precipitation for the Yucca Mountain area is between 150 mm and 200 mm (Quiring, 1965). Precipitation is mainly from winter and spring frontal systems and summer thunderstorms. Because the area has a desert climate, and because evapotranspiration occurs rapidly, it is estimated that only about 3 percent of annual precipitation recharges the ground-water system (Rush, 1970). This recharge probably occurs only during major runoff-producing events.

The general direction of flow in the ground-water system beneath Yucca Mountain is south-southeastward; the flow eventually discharges in the Armagosa Desert to the southwest (Waddell, 1982, p. 3). Data indicate that rocks beneath Solitario Canyon are not a pathway for the flow of ground water, although the fault scarp is orientated in a southerly direction. Instead, the fault probably is a barrier to the eastward movement of ground water. This condition is indicated by a higher (40 to 50 m) water table to the west and north of the fault scarp than to the east of the fault scarp (Robison, 1984).

DRILLING AND TESTING OPERATIONS

The drilling of test well USW H-6 began on August 7, 1982. A total depth of 1,220 m was reached on September 30, 1982, without unusual drilling problems. The well was rotary drilled, using an air-foam fluid consisting of air, detergent, and water to minimize formation damage. A lithium chloride tracer was added to water used in drilling and testing operations. Circulation was lost for about 30 min at a depth of 1,130 m. The well was cored a total of 67 m at selected intervals at depths from 333 to 1,220 m. The well construction is shown in figure 2, and bit and casing data are listed in the following table:

Drilled interval (meters)	Bit diameter (millimeters)	Cased interval (meters)	Casing inside diameter (millimeters)
0 - 9	914	0 - 9	746
9 - 102	559	0 - 95	381
102 - 583	375	0 - 581	250
583 - 1216	222	open hole	
1216 - 1220	156	open hole	

A directional survey showed that the maximum hole deviation was 1.5 degrees. The bottom survey station at a depth of 1,204 m indicated that the well deviation was 16 m from vertical, at a direction of N. 88° 21' W. After drilling was completed, a suite of geophysical logs was run, casing was perforated, and the well was hydraulically tested. Testing consisted of pumping and recovery tests, a borehole-flow survey, and packer-injection tests. A composite water sample for chemical analysis was collected near the end of pumping. A detailed drilling and testing history is contained in the files of the engineering firm of Fenix & Scisson, Inc. (consultant of U.S. Department of Energy), Las Vegas, Nev.

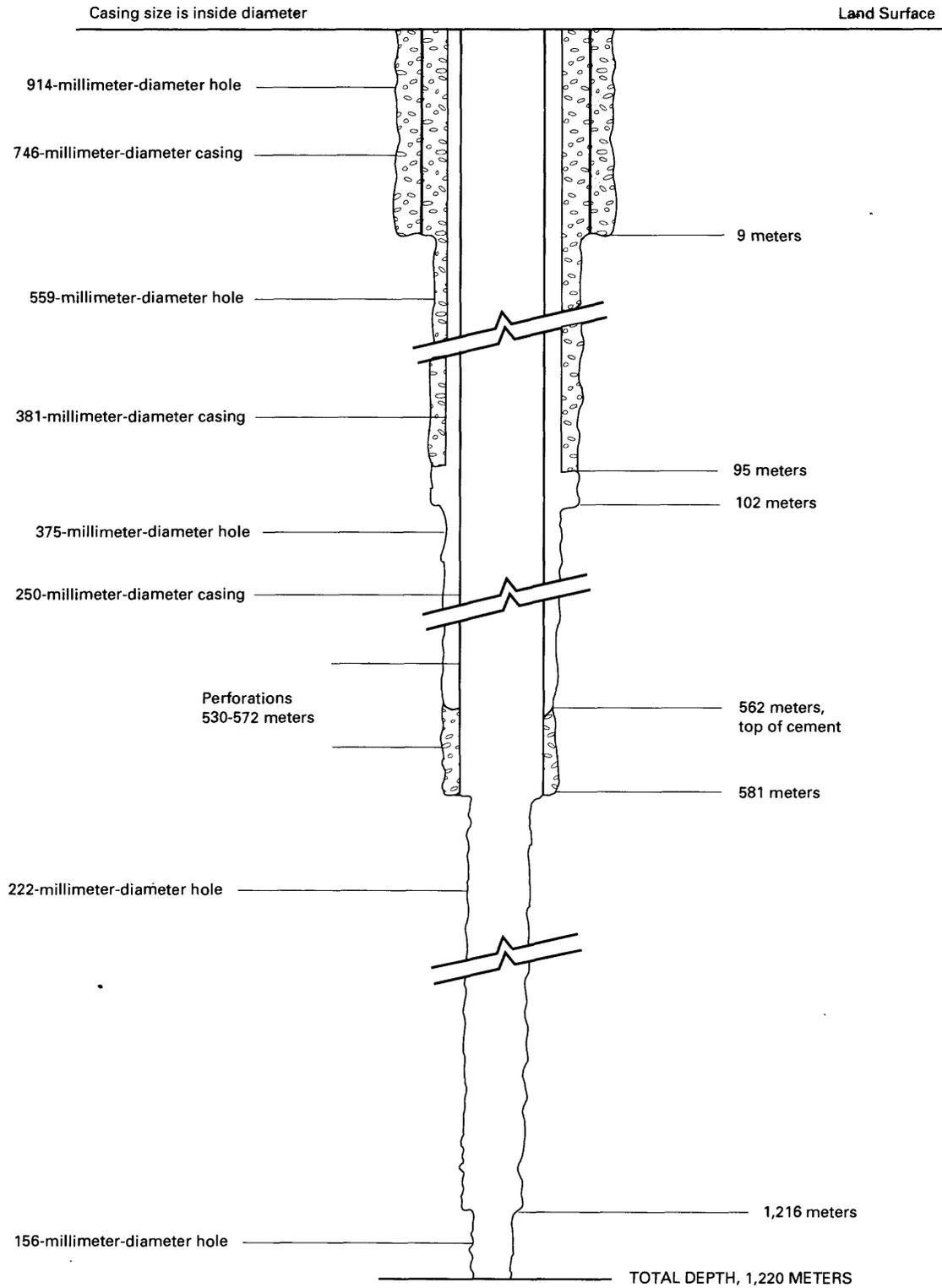


Figure 2.--Well construction.

Stratigraphy and Lithology

Rocks penetrated by test well USW H-6 are mainly nonwelded to densely welded ash-flow tuff units of Tertiary age. Exceptions to the sequence of ash-flow tuff units are a dacitic(?) lava, penetrated in the depth interval from 877 to 1,126 m, and seven tuff units that are thin-bedded or relatively reworked and unlithified or both; these tuff units are present at the base of most stratigraphic units (one is included in the tuffaceous beds of Calico Hills). A summary of major stratigraphic units and contacts is presented in table 1.

Table 1.--*Summary of major stratigraphic units penetrated by test well USW H-6*

[Condensed from Craig and others, 1983]

Unit	Thickness of interval (meters)	Depth to bottom of interval ¹ (meters)
Alluvium	9.1	9.1
Paintbrush Tuff		
Tiva Canyon Member	70.2	79.3
Bedded tuff (unnamed)	3.0	82.3
Pah Canyon Member	9.1	91.4
Topopah Spring Member	318.9	410.3
Bedded tuff (unnamed)	9.2	419.5
Rhyolitic lava and tuff of Calico Hills		
Tuffaceous beds of Calico Hills	38.9	458.4
Crater Flat Tuff		
Prow Pass Member	79.6	538.0(?)
Bedded tuff (unnamed)	9.1	547.1(?)
Bullfrog Member	131.1	678.2
Bedded tuff (unnamed)	9.1	687.3
Tram Member	187.2	874.5
Bedded tuff (unnamed)	2.7	877.2
Lava (unnamed)	248.7	1,125.9
Bedded tuff (unnamed)	4.3	1,130.2(?)
Lithic Ridge Tuff	89.7	1,219.9
	Total Depth	1,219.9

¹Depth to bottom of interval is reported to 0.1 meter to correspond to thickness of intervals; actual depths are probably ± 0.5 meter.

The thickest units penetrated by the test well were the Topopah Spring Member of Paintbrush Tuff, 319 m thick, and the dacitic(?) lava (unnamed), 249 m thick. The degree of welding is greatest in the Topopah Spring Member of the Paintbrush Tuff, which is characteristically moderately to densely welded. The least welded tuff units are the tuffaceous beds of Calico Hills

and the upper and lower parts of the Tram Member of the Crater Flat Tuff. Bedded tuff units are nonwelded and slightly indurated. Other tuff units in the sequence are mostly partially to moderately welded.

Water Levels

Water-level measurements were made in test well USW H-6 during drilling and hydraulic testing to: (1) Locate possible perched water zones; (2) determine the depth of the top of the saturated zone; and (3) determine any differences in hydraulic head at specific depth intervals. About 3 months after completion of the packer-injection tests, the bottom 33 m of the well was isolated from the upper part of the well by means of a packer. Periodic water-level measurements were then made in both intervals.

No perched-water zones were detected while drilling. A television-camera log of the unsaturated part of the hole showed a small quantity of water flowing from fractures in the depth interval from 305 to 335 m. Whether the observed water was drilling fluid or perched water is not known.

The first indication of reaching the saturated zone was a driller's report that water was thought to have been reached at a depth of about 526 m, because of a slight increase in penetration rate and pump pressure. This depth was later confirmed by water-level measurements, as well as by geophysical well logs. These water-level measurements are listed in table 2. They are divided into two groups: the first group consists of composite water levels; the second group consists of water levels measured in isolated intervals during packer-injection testing. The last measurement in each group is a measurement of water level above and below the packer installed at a depth of 1,187 m; these measurements were made to determine if hydraulic head near the bottom of the well was different from the composite hydraulic head above.

Results of water-level measurements indicated that the top of the saturated zone was at a depth of 526 m (776 m above sea level) in the lower part of the Prow Pass Member of the Crater Flat Tuff. Measurements made during packer-injection tests indicate a slight decrease in hydraulic head with depth to about 800 m, then an increase of about 1 m in the depth interval from 804 to 838 m, followed by a slight decrease to the bottom of the well. The depth at which the apparent 1-m increase in hydraulic head occurred corresponds to slightly below the bottom of the producing zone during pumping. Measurements made on December 29, 1983, about 14 months after completion of testing, indicated that the hydraulic head in the bottom 33 m was 2.2 m higher than composite head for the remainder of the well. It was inferred that water-level measurements made during testing, especially in the lower 400 m of the well, were not made under true static conditions. Drilling and testing operations may have affected the water-levels. Measurements made in late 1983 were more representative of equilibrium conditions near the well. The hydraulic head probably increased slightly with depth rather than decreased with depth. It was possible, based on available data, that a minor increase in hydraulic head occurred near a depth of 800 m.

Table 2.--Water-level measurements

Date	Depth interval (meters)	Depth to water ¹ (meters)	Method
<u>Composite levels</u>			
09/04/82	525 - 583	525.4	Television camera
09/05/82	525 - 583	527	Fluid-density log
10/01/82	525 - 1,220	525	Fluid-Density log
10/06/82	525 - 1,220	526.0	Float switch
10/20/82	525 - 1,220	526.0	Do.
12/15/82	525 - 1,220	527.7	Do.
12/29/83	525 - 1,187	526.4	Do.
<u>Isolated intervals (packer-injection tests)</u>			
10/17/82	581 - 607	525.6	Float switch
10/18/82	606 - 640	526.0	Do.
10/19/82	649 - 683	526.2	Do.
10/27/82	686 - 753	526.4	Do.
10/22/82	753 - 787	526.5	Do.
10/23/82	804 - 838	525.4+	Do.
10/23/82	835 - 869	525.5	Transducer
10/24/82	871 - 1,220	525.6	Transducer
10/24/82	1,118 - 1,152	525.9	Float switch
10/25/82	1,155 - 1,220	526.5	Do.
12/29/83	1,187 - 1,220	524.2	Do.

¹Depths to water include a correction of 0.05 meter due to hole deviation from vertical between land surface and the water table.

Pumping and Recovery Tests, and Borehole-Flow Survey

Two pumping tests and one recovery test were conducted in test well USW H-6 at the conclusion of drilling. During these tests, the well was cased to a depth of 581 m, with casing perforated in the depth interval from 530 to 572 m. The borehole was open to formation rock from a depth of 581 m to a total depth of 1,220 m. The composite static water level prior to each pumping test was 526 m below the land surface (776 m above sea level). The pump setting was identical for both pumping tests, with intakes at 552 m below the land surface. As indicated by the borehole-flow survey, which was made during the second pumping test, production was limited to the saturated zone above a depth of 803 m.

The fracture system in the aquifer was under confined conditions at the depths of primary production. Evidence for confined conditions consisted of small values of matrix hydraulic conductivity relative to values fracture hydraulic conductivity in the Crater Flat Tuff near the potentiometric surface and the lack of measurable bypass around packers during packer-injection testing near the top of the saturated zone.

Pumping Test 1

Pumping test 1 was conducted during October 1982 for 4,822 minutes at a rate of 28.4 L/s. Drawdown data were obtained for the first 4,184 minutes. At that time, the monitoring instrument was removed in preparation for a borehole-flow survey. Premature shutdown of the pump occurred at 4,822 minutes after pumping started. No recovery data were obtained, as the drawdown-monitoring instrument was still out of the well. Pumping test 2 was started 25 hours later, and conducted for 2,226 minutes at a rate of 26.6 L/s. Drawdown data were obtained for the first 116 minutes, and from 1,789 minutes after pumping started to the end of pumping. The drawdown-monitoring instrument was out of the well during an interval from 116 to 1,789 minutes while the temperature log and borehole-flow survey were made. Recovery of water level was monitored for 300 minutes after pumping stopped.

Analysis of data for pumping test 1 is shown in semilogarithmic form in figure 3; drawdown is along the vertical axis, and time is along the horizontal axis. The maximum drawdown measured was 17.8 m after 4,184 minutes. The data in figure 3 plot in two straight-line segments; the first segment was from about 0.7 to 2 minutes after pumping started, and the second segment was from 14 minutes to the end of test. Although the data plot is consistent with the early time and transitional time of a dual-porosity model, use of the first straight-line segment to calculate transmissivity results in an unrealistically large storage coefficient of greater than 1; the data probably were affected by wellbore storage and possibly by a variable flow rate during the first few minutes of the test.

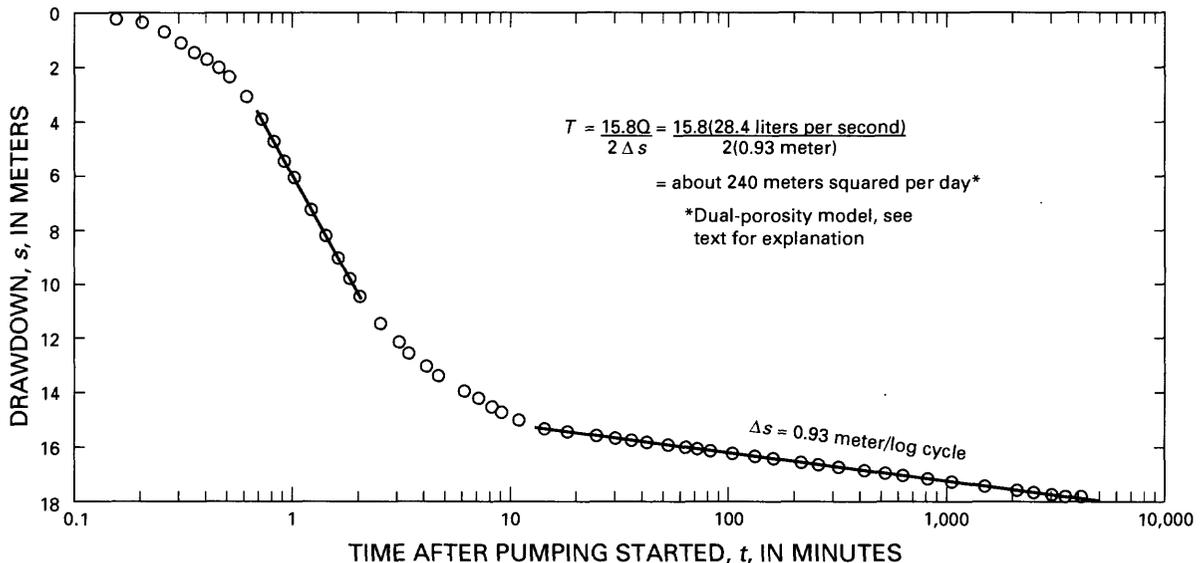


Figure 3.--Analysis of water-level drawdown, pumping test 1: depth interval from 526 to 1,220 meters; straight-line solution with dual-porosity model.

The lack of a third straight-line segment indicates that, if the conceptual model is valid, late time was not reached, and analysis would be restricted to the data from the transitional period (second segment). However, data from the transitional period can be used to obtain an estimate of transmissivity, with some qualifying assumptions.

If fractures in a dual-porosity system do not have "fracture skin," the slope of the transitional-time data on a semilogarithmic plot will be one-half of the true slope of the late-time data (Moench, 1984, p. 840). Fracture skin is a thin incrustation of material with minimal permeability that is deposited on the matrix-fracture interface and that decreases flow between the matrix and fractures. If fracture skin is present, the slope of the second segment may be much less than one-half the slope of the late-time data.

Data for pumping test 1 shown in figure 3 fit the second straight-line segment with little deviation. Transmissivity, using data from 14 minutes to near the end of pumping at 4,184 minutes, is calculated to be about 240 m²/d. This value, which is based on the assumption that no fracture skin exists, is one-half the value that would be calculated for the second straight-line segment by the method of Cooper and Jacob (1946):

$$T = \frac{15.8 Q}{2\Delta s} \quad (1)$$

where T = transmissivity, in meters squared per day;
 Q = discharge, in liters per second; and
 Δs = change in drawdown over one log cycle of time, in meters.
 The factor 2 doubles the slope of the transitional-time data to equal the assumed slope of late-time data.

Water entering the well was assumed to have been from fractures only; calculation of fracture hydraulic conductivity would require knowledge of the size of fracture apertures, but this information was not available.

One alternative interpretation involves hydrologic boundaries; after about 14 minutes of pumping (fig. 3), the slope may represent a recharge boundary. A large fault scarp (Lipman and McKay, 1965), is located approximately 1,000 m east of the well site at the land surface. At depths of primary production, 616 to 631 m and 777 to 788 m (see section entitled "Borehole-Flow Survey"), a fault dip of 60° to the west (Lipman and McKay, 1965) would place the fault about 640 and 550 m, respectively, from the well bore. This fault may have been a hydrologic boundary of increased transmissivity. Apparent transmissivity, based on this boundary model, and calculated by the method of Cooper and Jacob (1946) for the second line segment would be about 480 m²/d. This alternative is less likely to be applicable than a dual-porosity model. Many pumping-test results for test wells in the Yucca Mountain area are similar to those for test well USW H-6 (test well UE-25b#1, Lobmeyer and others, 1983, p. 28; test well USW H-1, Rush and others, 1983, p. 25; test well USW G-4, Bentley, 1984, p. 27; and test well UE-25p#1, Craig and Johnson, 1984, p. 13). It is doubtful that all tests in these test wells were affected by a recharge boundary but, rather, that some form of a fracture-controlled model is appropriate.

A second alternative model is a homogeneous porous medium. Early-time data are attributed to wellbore storage and pumping-rate variations during startup. Later data may be matched with the Theis curve. Calculations of transmissivity and storage coefficient can be made by the standard Theis method (Ferris and others, 1962):

$$T = \frac{6.9 Q W(u)}{s} \quad (2)$$

where T = transmissivity, in meters squared per day;
 Q = discharge, in liters per second;
 $W(u)$ = well function of u , a dimensionless match point; and
 s = drawdown, a match point, in meters.

The storage coefficient is determined by the following equation:

$$S = \frac{4Ttu}{r^2} \quad (3)$$

where S = storage coefficient, dimensionless;
 T = transmissivity, in meters squared per day;
 t = time, a match point, in days;
 u = match point, dimensionless; and
 r = distance to point of drawdown measurement, radius of pumped well as used here, in meters.

A limitation of this interpretation, using the data from pumping test 1, is that, if a reasonable storage coefficient of about 4×10^{-4} is arbitrarily assumed in order to guide the data match with the type curve, the fit is unsatisfactory (fig. 4). A better fit is shown in figure 5, but the calculated storage coefficient of 3×10^{-10} is unrealistically small to have physical meaning. The late-time part of the Theis curve is relatively flat and the data-type curve match could be shifted horizontally slightly in either figure 4 or 5, but the fit would still be unsatisfactory.

Similar plots of pumping-test data from three wells on the Nevada Test Site are instructive. The drawdown-versus-time data for these three wells and for pumping test 1 of test well USW H-6 are shown in figure 6. Data from test well UE-25b#1 were used by Moench (1984) to illustrate the use of a dual-porosity model with fracture skin. Test well UE-25b#1 is 3.8 km northeast of test well USW H-6, on the east side of Yucca Mountain (fig. 1). This well is similar to USW H-6 in completion and is located in a similar geologic setting. The most significant difference is that test well UE-25b#1 has five main zones of production, whereas test well USW H-6 has two. Data for well 67-68 and 88-66 are from data in figures 11 and 17 in Winograd and Thordarson (1975). These wells are about 50 km to the southeast and northeast, respectively, and are completed in fractured carbonate rocks of Paleozoic age. All four wells had a similar response, one that is consistent with a dual-porosity model. Apparent storage coefficients calculated by matching the transitional-time

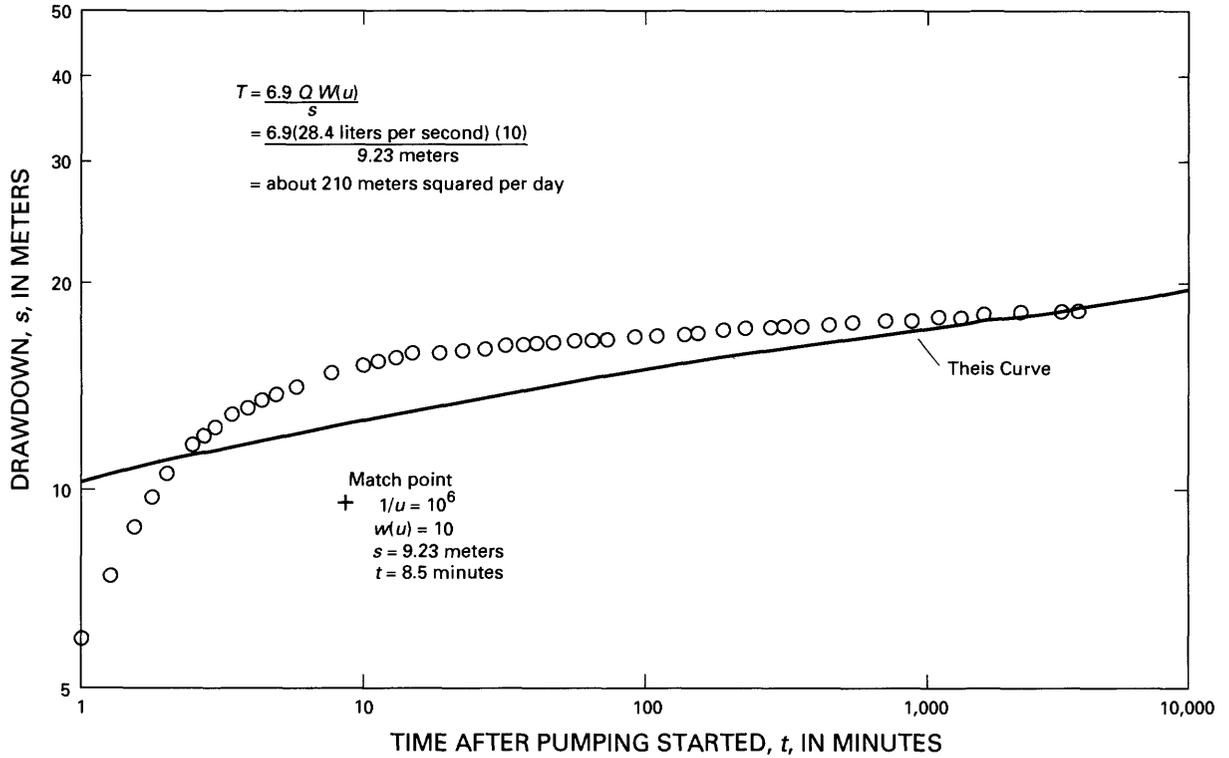


Figure 4.--Analysis of water-level drawdown, pumping test 1: depth interval from 526 to 1,220 meters; Theis method with an arbitrarily assumed storage coefficient of about 4×10^{-4} .

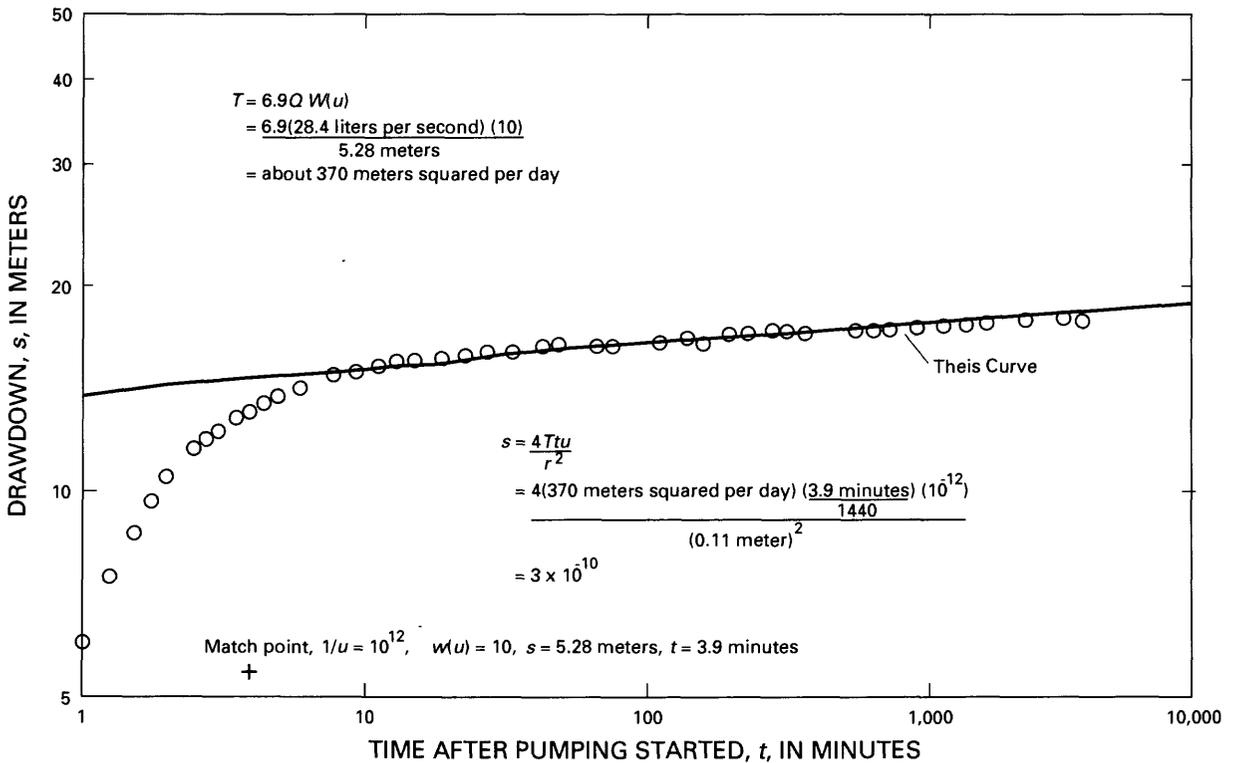


Figure 5.--Analysis of water-level drawdown, pumping test 1: depth interval from 526 to 1,220 meters; Theis method.

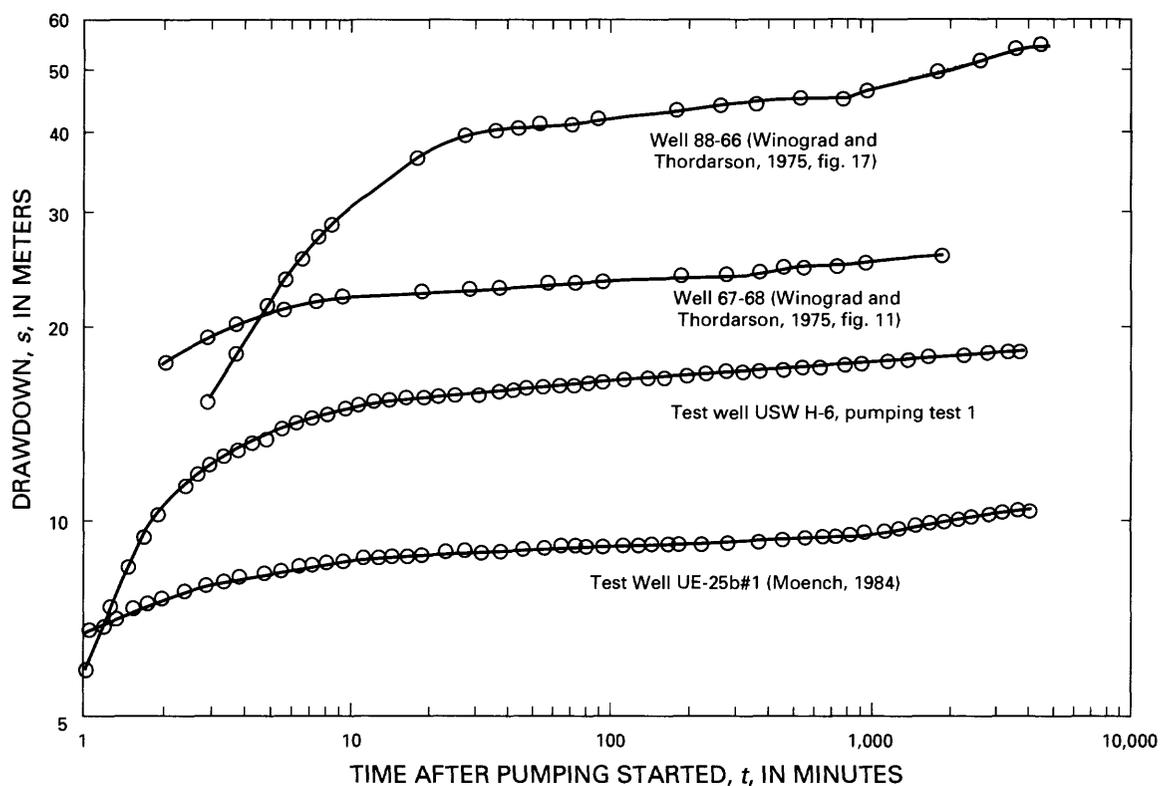


Figure 6.--Comparison of pumping-test data from three wells completed in apparent dual-porosity systems with data for pumping test 1 of test well USW H-6.

data with the Theis curve ranged from 4×10^{-9} to 1×10^{-11} . Although an analysis that is beyond the scope of this report would be required to confirm any relation between the apparent storage coefficient of transitional-time data and a dual-porosity model, a dual-porosity model probably is more appropriate for the analysis of pumping test 1 than that of homogeneous porous medium.

Results of pumping test 1 indicate that the most reasonable value of transmissivity probably is about $240 \text{ m}^2/\text{d}$. Transmissivity may be as large as $480 \text{ m}^2/\text{d}$, if a recharge-boundary model is applicable, and less than $240 \text{ m}^2/\text{d}$ if fracture skin is present and has affected the responses.

Pumping Test 2

Analysis of data for pumping test 2 is shown in figure 7. Data are similar to those from pumping test 1. Transmissivity is calculated to be about $230 \text{ m}^2/\text{d}$ using a dual-porosity model without fracture skin as was used in the analysis of test 1 in figure 3. The calculated transmissivity using a recharge-boundary model is about $460 \text{ m}^2/\text{d}$. Ending data of pumping test 2

(fig. 7) were anomalous. These data did not plot on a continuation of a straight line from data prior to 116 minutes, and they also indicated a steeper slope for a part of the data. The anomalies are attributed to inaccuracy in re-positioning the drawdown-monitoring instrument after a borehole-flow survey and to water-sampling operations that affected the discharge rate.

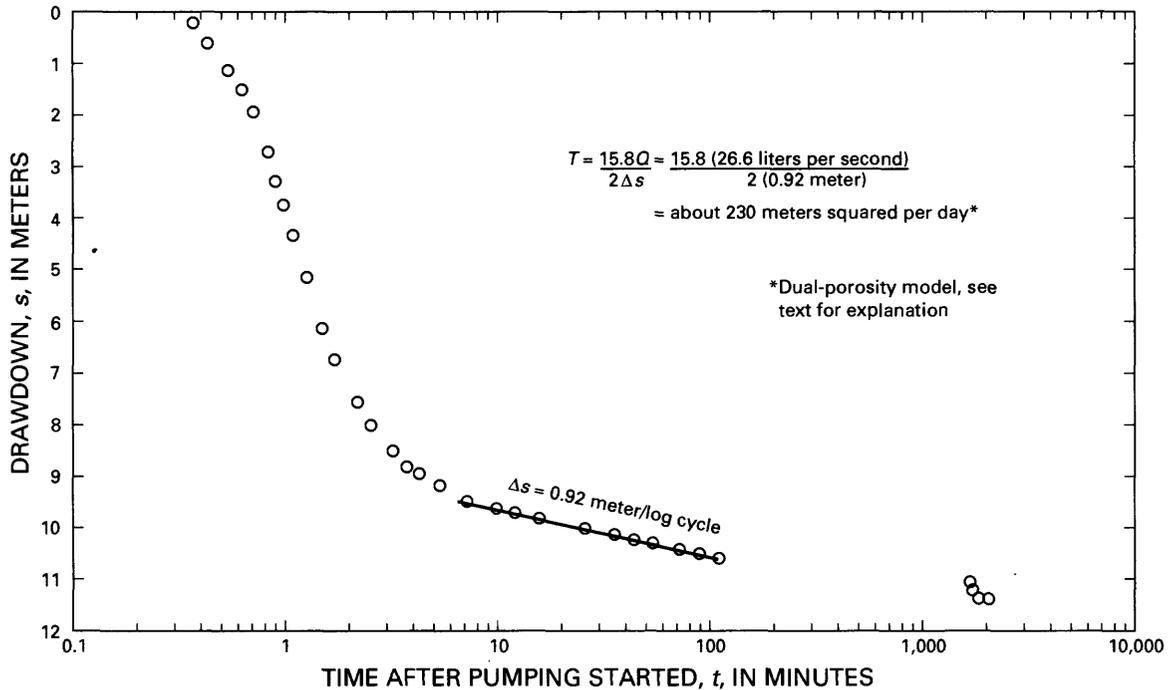


Figure 7.--Analysis of water-level drawdown, pumping test 2: depth interval from 526 to 1,220 meters; straight-line solution with dual-porosity model.

Borehole-Flow Survey

During pumping test 2, a borehole-flow survey was made to determine which zones in the well were producing water. This survey was useful in determining relative productivity of the zones, and it served as a guide for selecting intervals for packer-injection tests. Iodine-131 was injected in small quantities into the well below the water table. Movement of the radioactive slug was monitored as it moved between two gamma-ray detectors. The rate of flow for each depth interval was calculated by multiplying the cross-sectional area of the borehole, as determined from a caliper log, by the velocity of the slug. This process was repeated by moving the tool up the well, until all the zones of production were defined. A more complete description of the technique for borehole-flow surveys is given by Blankennagel (1967). Depth and corresponding stratigraphy versus percentage of total flow are shown in figure 8.

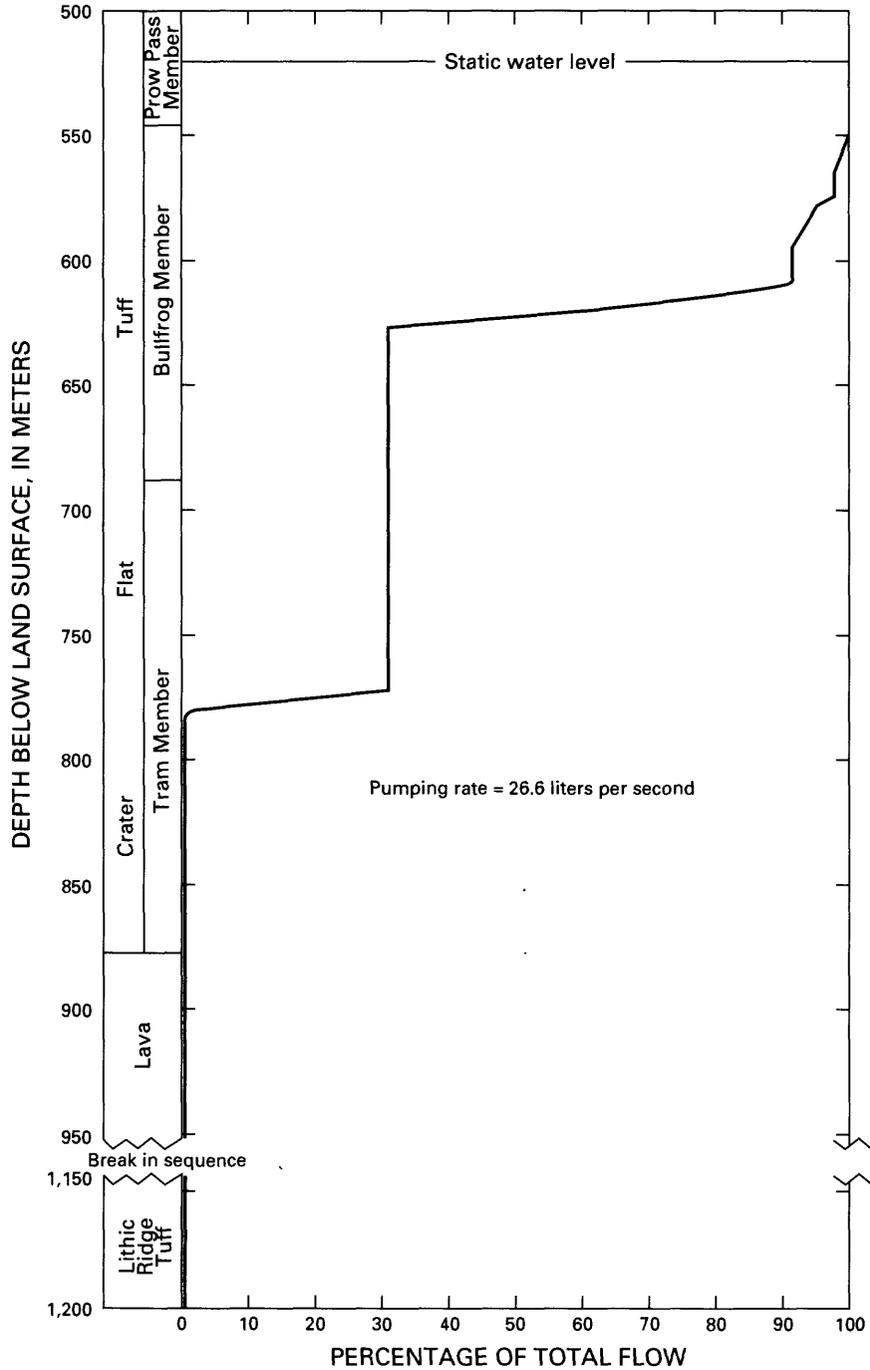


Figure 8.--Borehole-flow survey, showing percentage of pumping rate produced by intervals.

Results of the survey indicated two zones of primary production, both in the Crater Flat Tuff. During the survey, the total flow rate was 26.6 L/s. The depth interval from 616 to 631 m in the Bullfrog Member produced 60 percent of the total flow. The depth interval from 777 to 788 m in the

Tram Member produced 32 percent of total flow. The depth interval from 581 to 604 m produced about 6 percent of the total flow; the depth interval behind perforated casing, above a depth of 572 m, produced about 2 percent of the total flow. Both of these intervals were in the upper part of the Bullfrog Member. No measurable flow (greater than 0.05 L/s) was detected below a depth of 803 m.

Recovery Test 2

Data for recovery test 2 are shown in figure 9, as residual drawdown versus time since pumping started, divided by time since pumping stopped.

The authors cannot explain the abnormally rapid recovery rate, nor did they find an applicable explanation in the literature. The anomalous recovery rates does not appear to be due to the entry of lower density water into the well during the pumping period.

...Some mechanism other than temperature-induced density changes must be operating. Outgassing has not been noted in the sampled waters. Until the significance of the anomalous recovery rate is understood, the authors elect not to utilize transmissibility values obtained from the recovery curves.

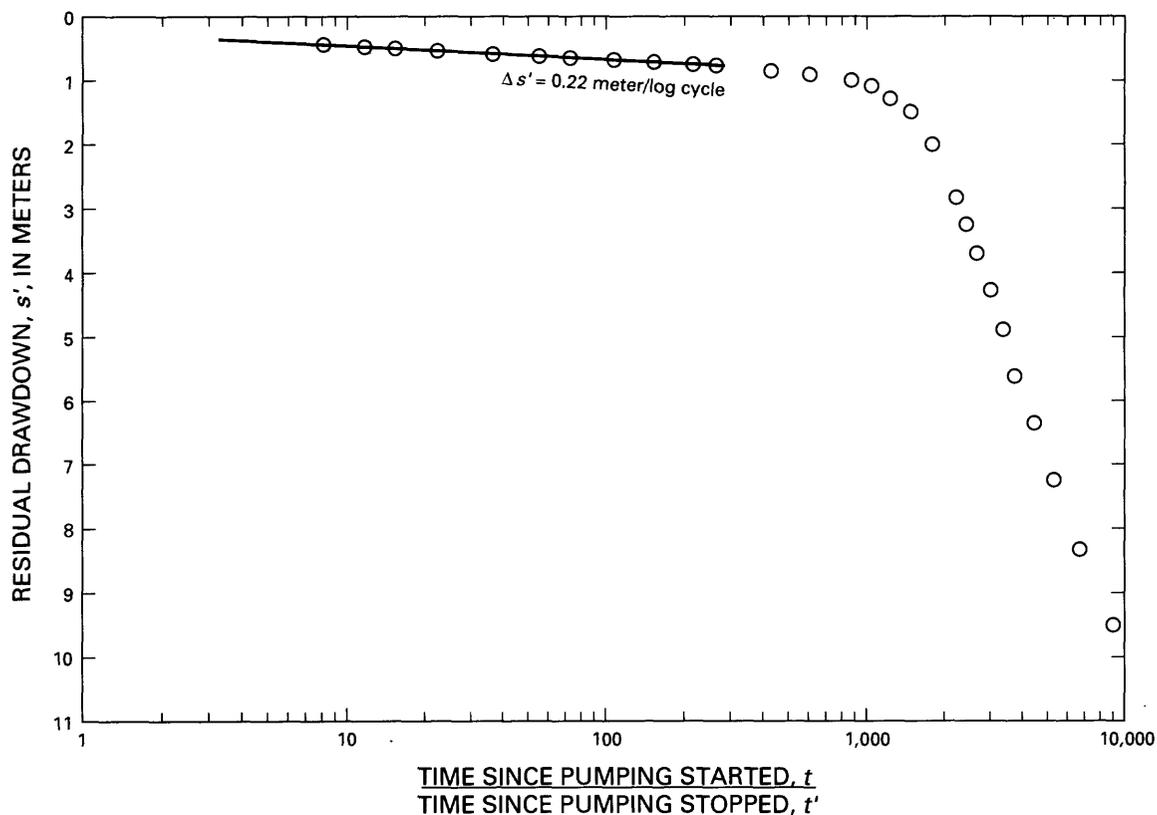


Figure 9.--Water-level recovery, pumping test 2: depth interval from 526 to 1,220 meters.

The above statement, from Winograd and Thordarson (1975, p. 25) describes the dilemma of these authors; they were referring to six different pumping tests conducted in fractured carbonate rocks of Paleozoic age, which all had responses similar to those of test well USW H-6. Data for each test indicated an abnormally rapid recovery during the first few minutes of the recovery period. In addition, the slope of late-time recovery data (small values of t/t') was less than the corresponding times of drawdown for each well, as was the case for test well USW H-6. The authors of the present report prefer to note that transmissivity calculated from recovery test 2 would be about four times greater than that calculated from drawdown data, and not use recovery-derived transmissivity further.

Pumping and Recovery Tests 3 and 4

During June and July 1984, additional pumping and recovery tests were conducted in the two depth intervals that yielded the most production during previous pumping, as defined by the borehole-flow survey (fig. 8). The deepest interval was isolated by means of a retrievable plug placed below it at a depth of 834 m and a packer set above it at a depth of 753 m. After testing the deeper interval, the upper interval was isolated by a retrievable plug at a depth of 645 m and a packer at a depth of 608 m. Sketches of the designs for pumping tests 3 and 4 are shown in figures 10 and 11.

Pumping test 3 tested the depth interval from 753 to 834 m. The interval was pumped at a rate of 13.4 L/s for 15,540 minutes. Analysis of drawdown data (fig. 12) indicated that calculated transmissivity of this interval is 76 m²/d, based on a dual-porosity model without fracture skin. This value is in agreement with a calculated transmissivity of about 75 m²/d, based on pumping tests 1 and 2, and the borehole-flow survey. Late-time data consistent with typical dual-porosity characteristics were not observed, and data scatter was greater during pumping test 3 than during previous tests.

Data for recovery test 3 are shown in figure 13. The data indicate that the water level recovered rapidly, rose to about 8 m above pre-pumping water level at 2.5 minutes after pumping stopped, and then declined to slightly below the pre-pumping level. The response probably was not representative of natural conditions, such as temperature changes. The basis for the foregoing conclusion is: (1) During a period of pumping prior to pumping test 3, the pump stopped inadvertently, and recovery was recorded on an analog recorder that indicated no recovery above pre-pumping level; (2) any expansion resulting from temperature changes in the water column while pumping would not account for the measured response. The cause of the erratic response during recovery test 3 is unknown.

Pumping test 4 was conducted in the depth interval from 608 to 645 m. The interval was pumped at 14.5 L/s for 1,385 minutes, at which time the pump shut off. The pump was re-started within a few minutes at an increased rate of 14.8 L/s and was pumped for an additional 14,315 minutes. Data are shown in figure 14 as a continuous test. The data indicate an unusual response during early time that was similar to inertial effects modeled by Bredehoeft and others (1966), but a 22-minute period of pumping (fig. 14) after completion of recovery test 4 did not have the same response. Possibly, the variable-speed

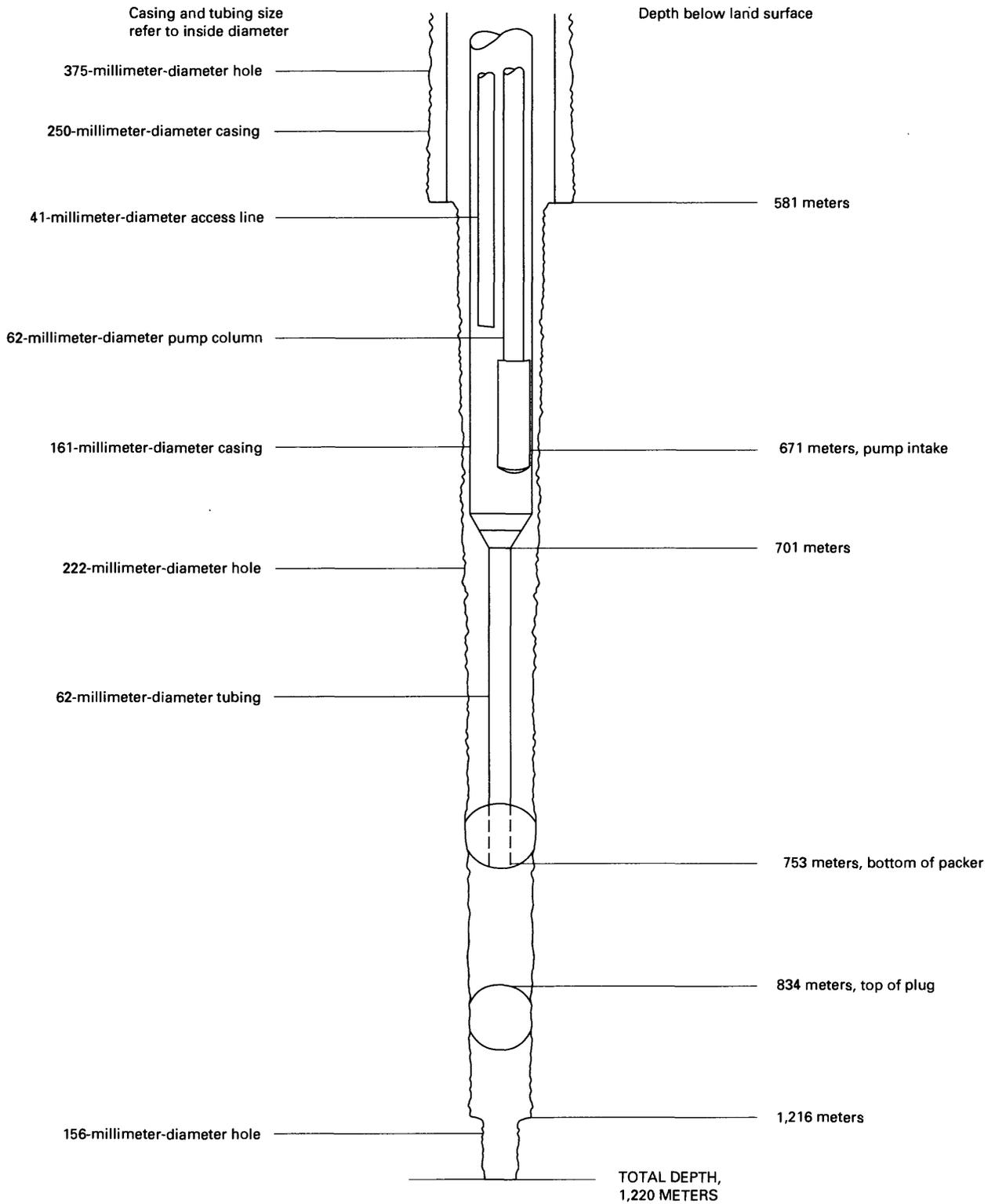


Figure 10.--Sketch of design for pumping test 3.

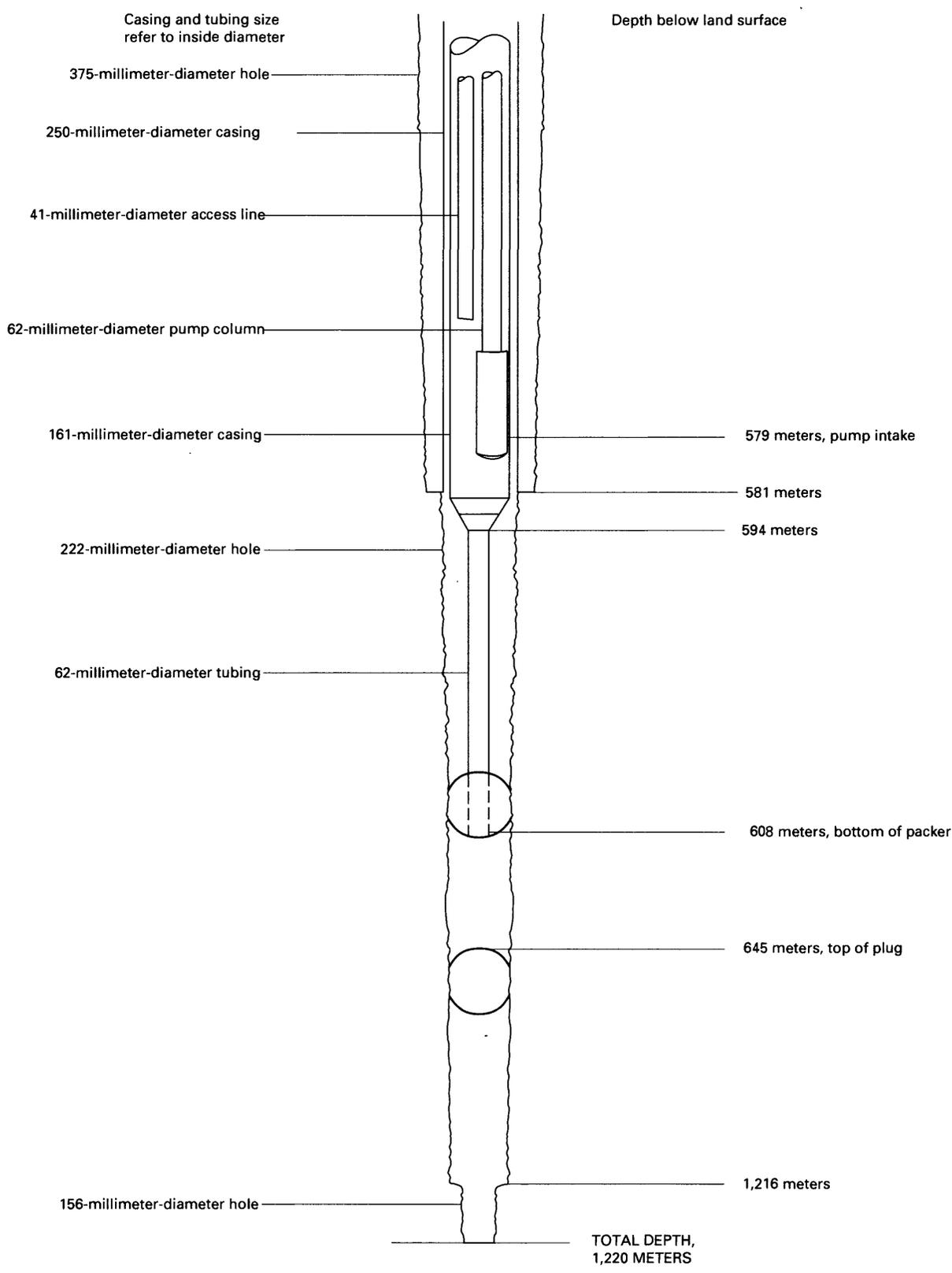


Figure 11.--Sketch of design for pumping test 4.

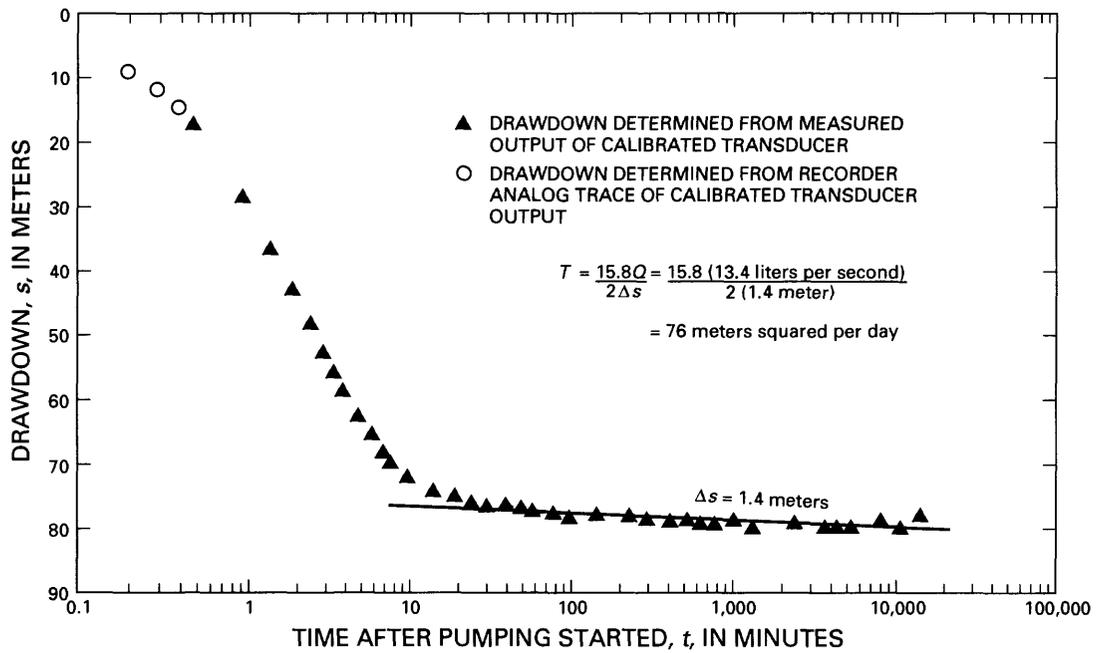


Figure 12.--Analysis of water-level drawdown, pumping test 3: depth interval from 753 to 834 meters; straight-line solution with dual-porosity model.

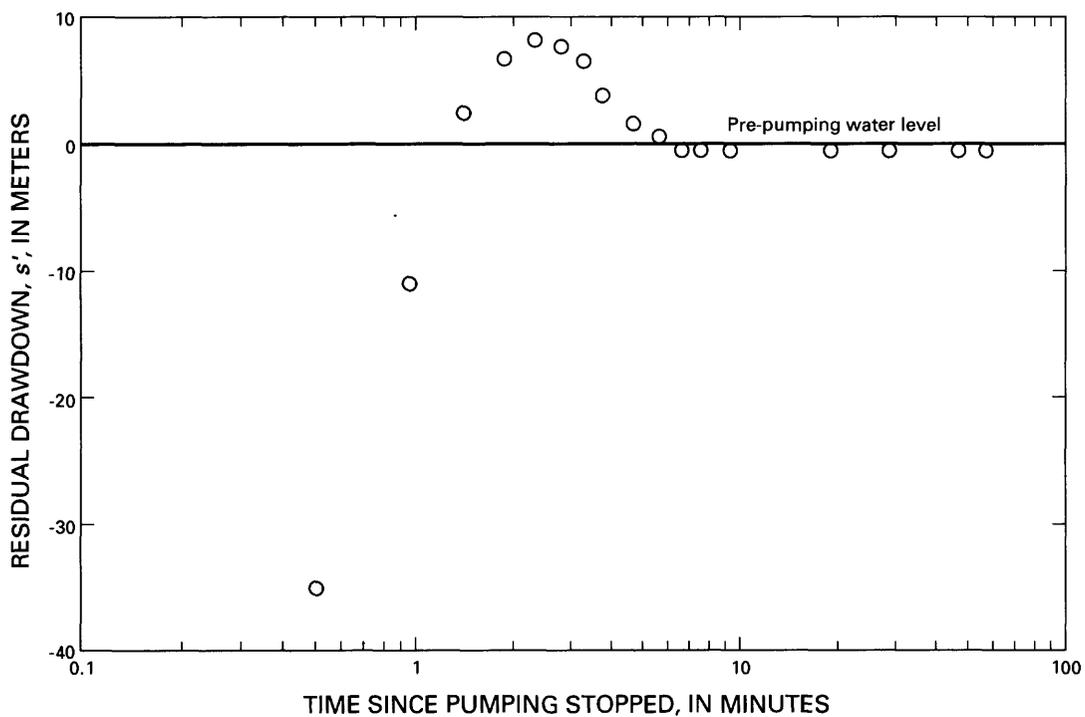


Figure 13.--Residual drawdown, recovery test 3: depth interval 753 to 834 meters.

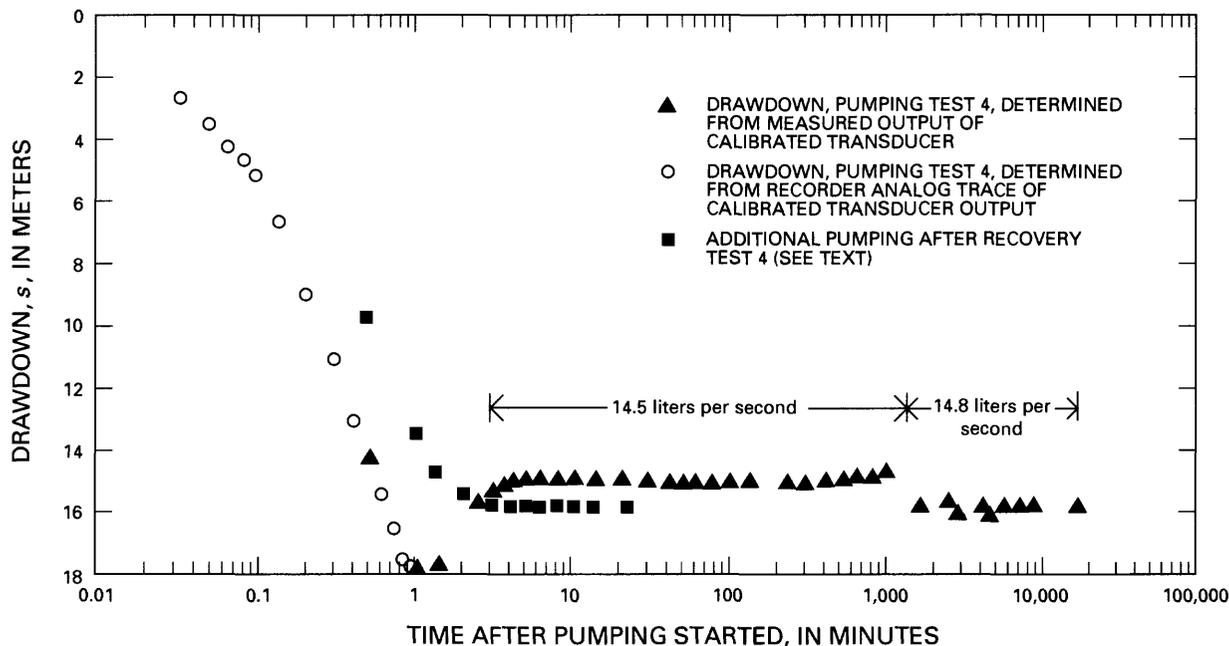


Figure 14.--Water-level drawdown, pumping test 4:
depth interval from 608 to 645 meters.

pump control was adjusted (unnoticed) by support personnel resulting in less discharge about 1 minute after pumping started during pumping test 4. An analysis of drawdown data was not made because of the lack of slope in the data. The lack of slope may indicate substantial transmissivity, but recovery-test data, as discussed below, are consistent with recovery test 2.

Recovery test 4 was monitored for 30 minutes; results are shown in figure 15 as residual drawdown versus time since pumping started divided by time since pumping stopped. Recovery was rapid, as in recovery test 2. The slope of the line shown in figure 15 indicates a transmissivity of about four times the expected value, based on pumping tests 1 and 2, but the value is consistent with the results of recovery test 2.

Packer-Injection Tests

Packer-injection (slug) tests were conducted in various intervals of the well for two purposes: (1) To obtain data on distribution of hydraulic head; and (2) to obtain data for determination of distribution of transmissivity. Tests were conducted either for intervals isolated between packers or for intervals from the bottom packer to the bottom of the hole. Water was injected by filling tubing with water that was connected to the packer tool and then opening the tool to either the between-packer interval or below-packer interval, thus allowing the water to drain into the formation while the decline of hydraulic head was monitored by means of a pressure transducer

suspended inside the tubing at a depth slightly below the normal static water level. Because the volume of water injected was relatively small, the radius of investigation was correspondingly small.

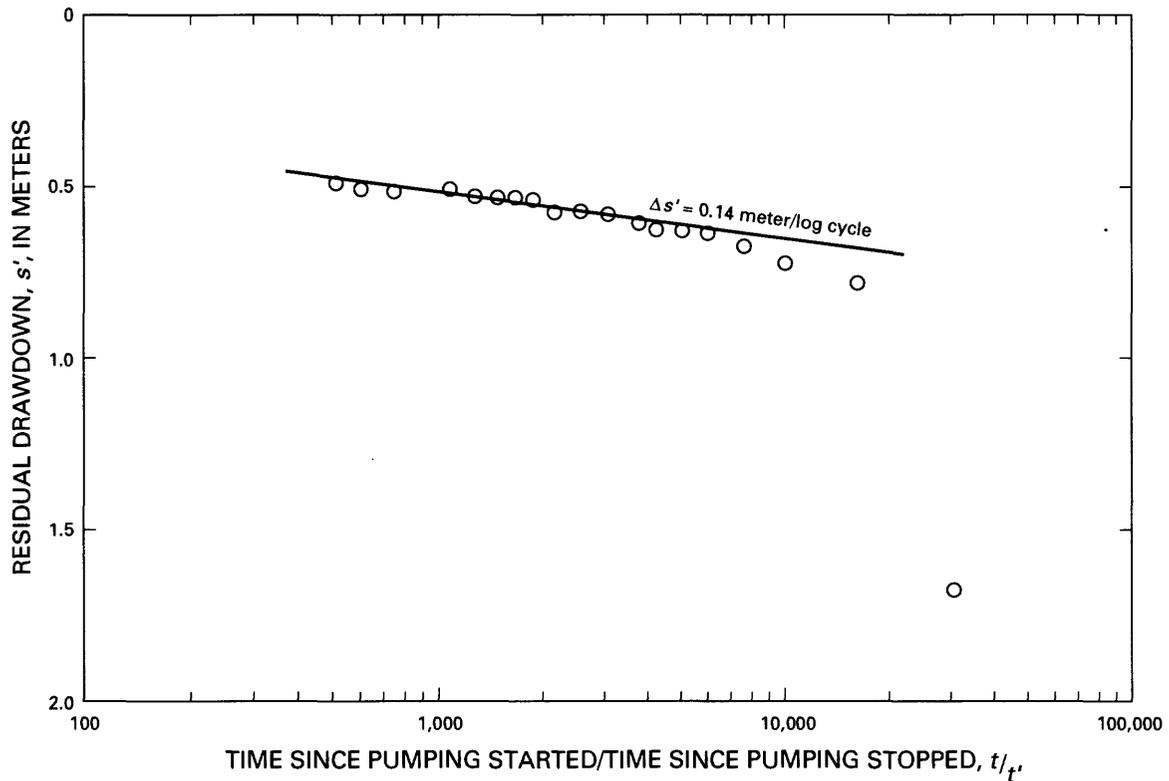


Figure 15.--Water-level recovery, recovery test 4:
depth interval from 608 to 645 meters.

A limiting factor during testing was the packer-injection tool. Because of the tool design, transmissivity values greater than about $5 \text{ m}^2/\text{d}$ could not be determined (C.O. Stokley, TAM International, oral commun., 1983). Apparently this was the case in two of the tests. This design limitation was used to determine if the decline in water level during testing resulted from formation characteristics or tool design: (1) If the static water level was reached in about 5 minutes or more, the response resulted from formation characteristics; and (2) if the static water level was reached in less than 5 minutes, response was affected by tool design and indicated that the transmissivity of the interval tested was greater than about $5 \text{ m}^2/\text{d}$.

The transmissivity of those intervals for which data could be matched to a type curve was determined by the methods of Cooper and others (1967) and Papadopulos and others (1973). Assumptions for their methods are discussed in these cited references. The decline of water level during each test, shown as the ratio of hydraulic head above the static water level at a given time (H), to hydraulic head above the static water level at the time of injection (H_0),

versus time since injection began, is shown in semilogarithmic form in figures 16 to 26. The ratio H/H_0 is along the vertical, or arithmetic, axis; t , time is along the horizontal, or logarithmic, axis. Hydraulic head above the static water level at the time of injection is shown as the value equal to H_0 . Packer-injection tests 7 through 10 were made with about one-half the hydraulic head of packer-injection tests 1 through 6 in an attempt to decrease anomalous results (discussed below). A family of type curves was used to obtain a best fit with the data. A match line was selected on the logarithmic scale of the type-curve graph, with a value of 1.0. Then, the corresponding match line of time, t , on the data curve was determined.

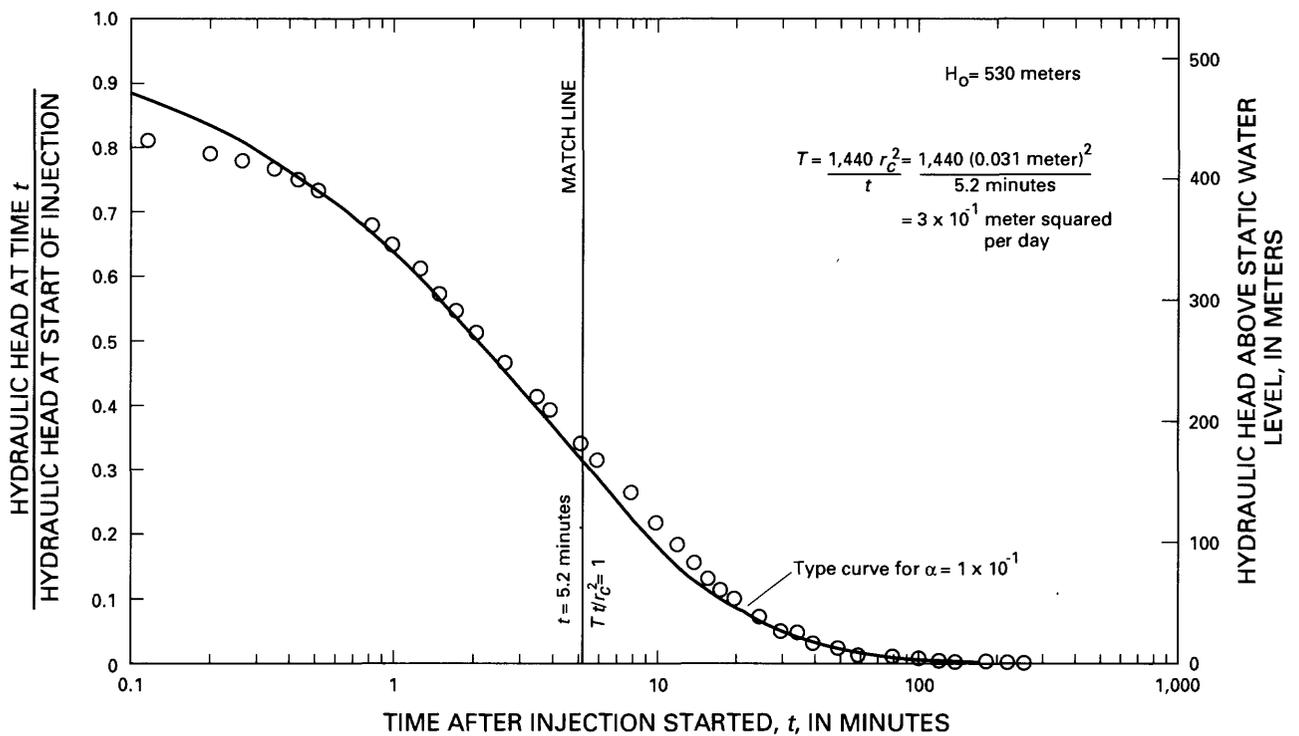


Figure 16.--Analysis of packer-injection test 1:
depth interval from 581 to 607 meters.

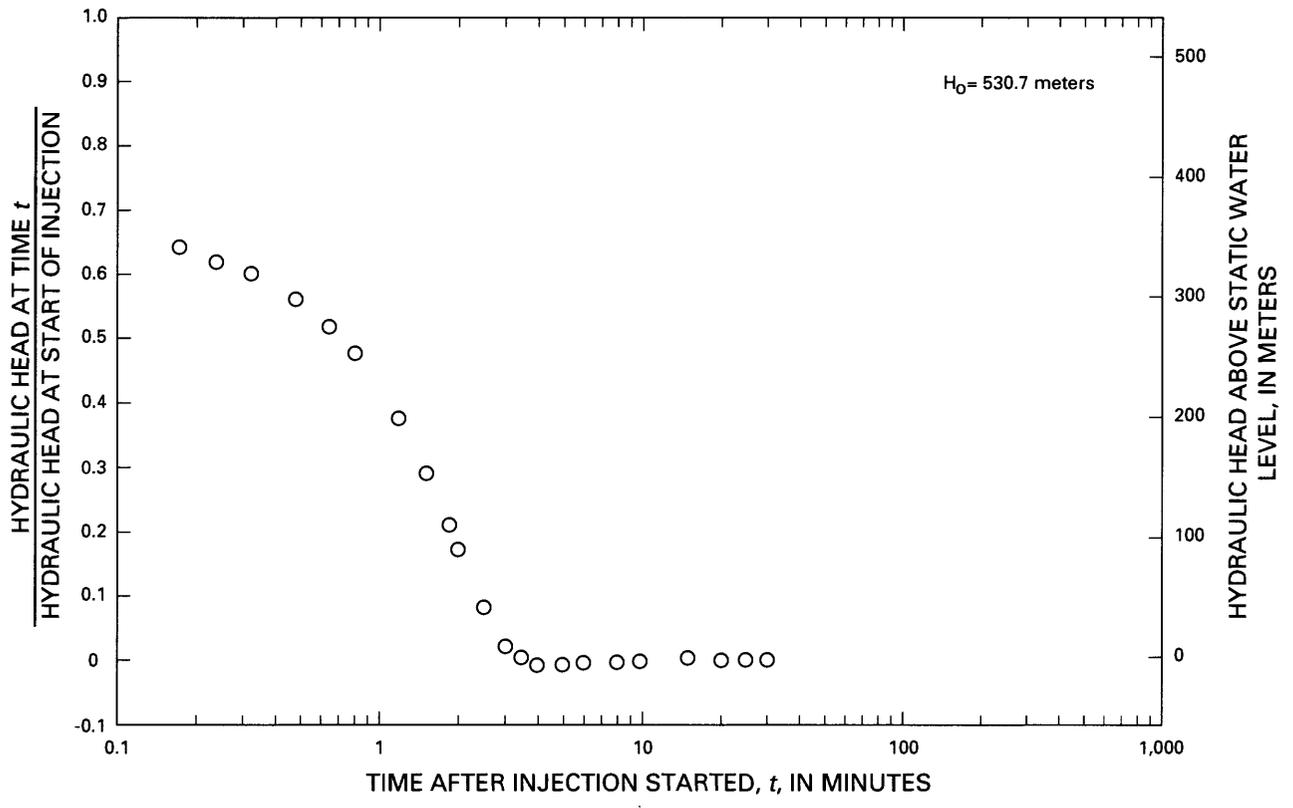


Figure 17.--Data for packer-injection test 2:
depth interval from 606 to 640 meters.

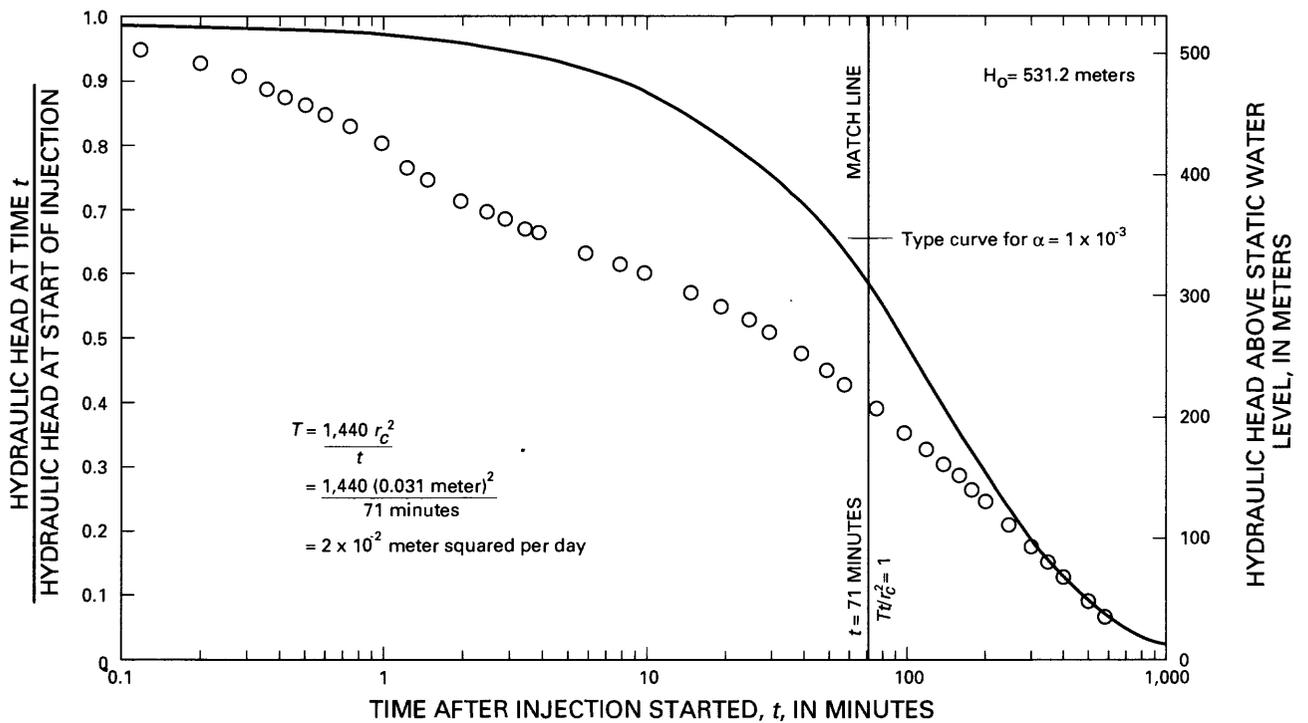


Figure 18.--Analysis of packer-injection test 3:
depth interval from 649 to 683 meters.

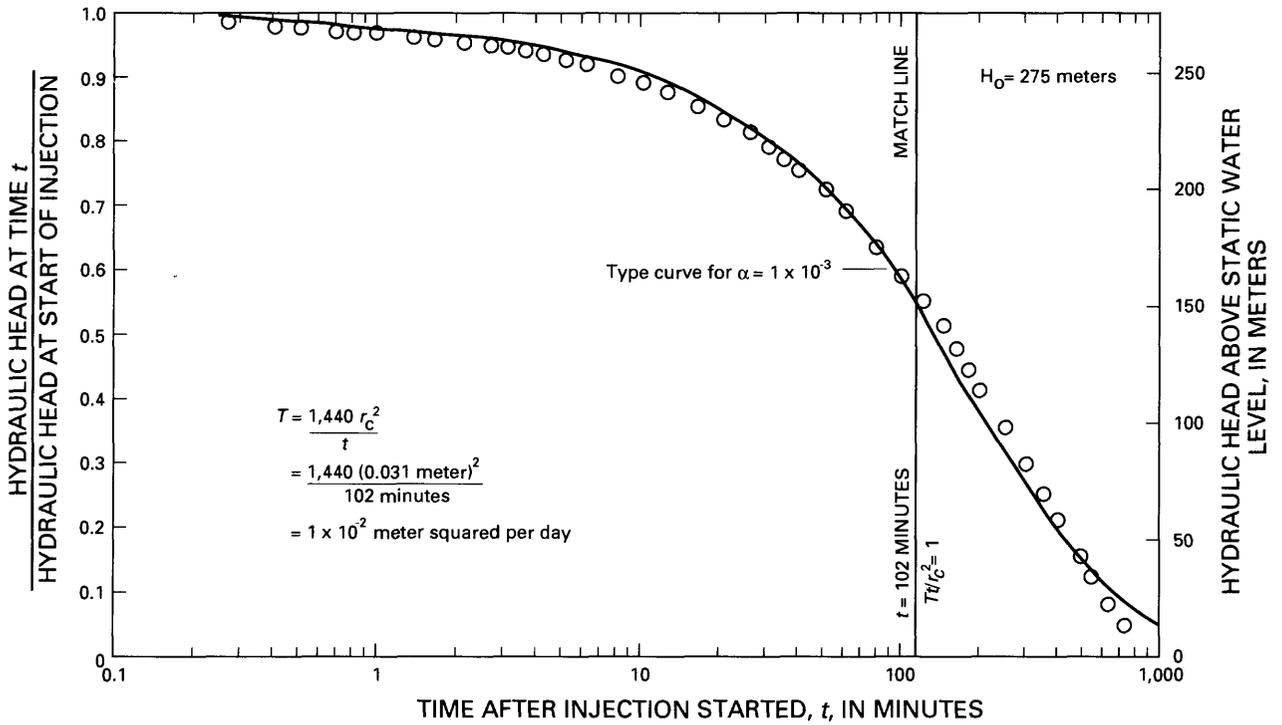


Figure 19.--Analysis of packer-injection test 3A:
depth interval from 649 to 683 meters.

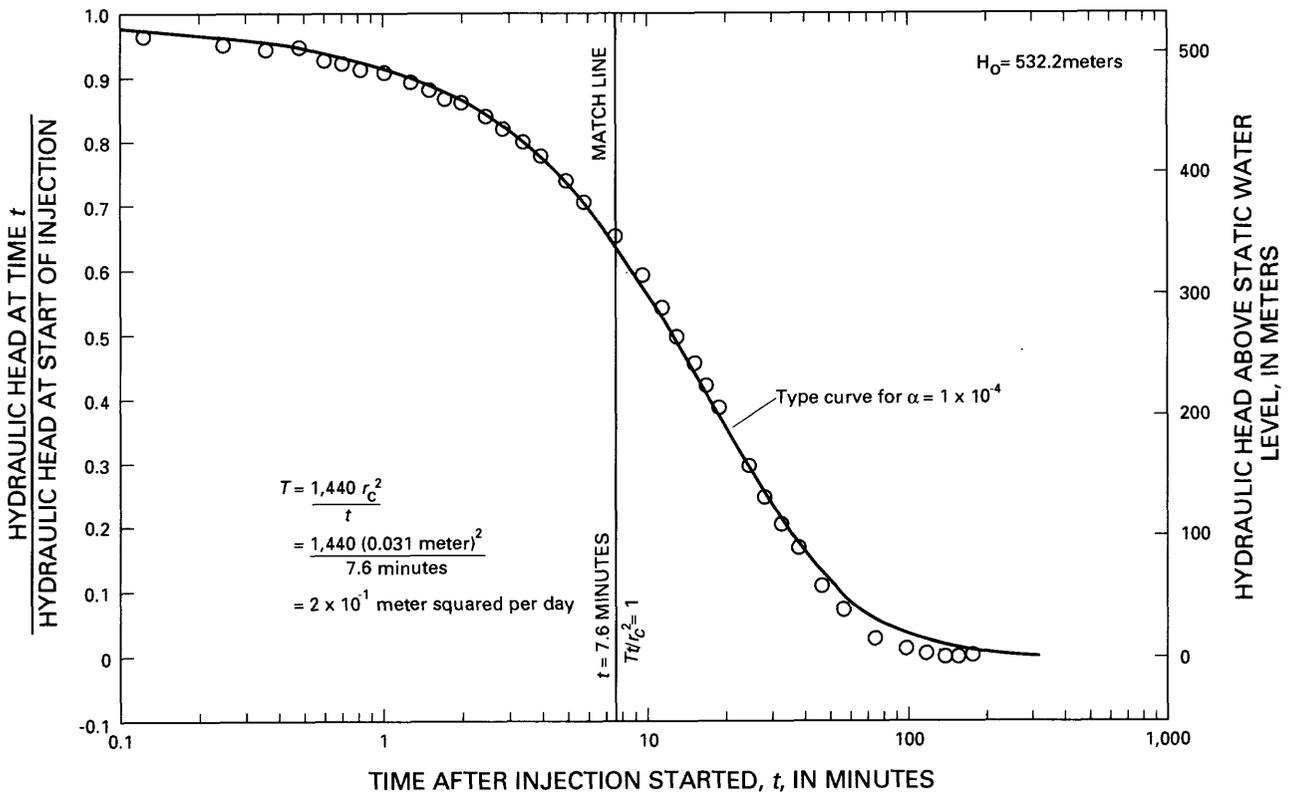


Figure 20.--Analysis of packer-injection test 4:
depth interval from 686 to 753 meters.

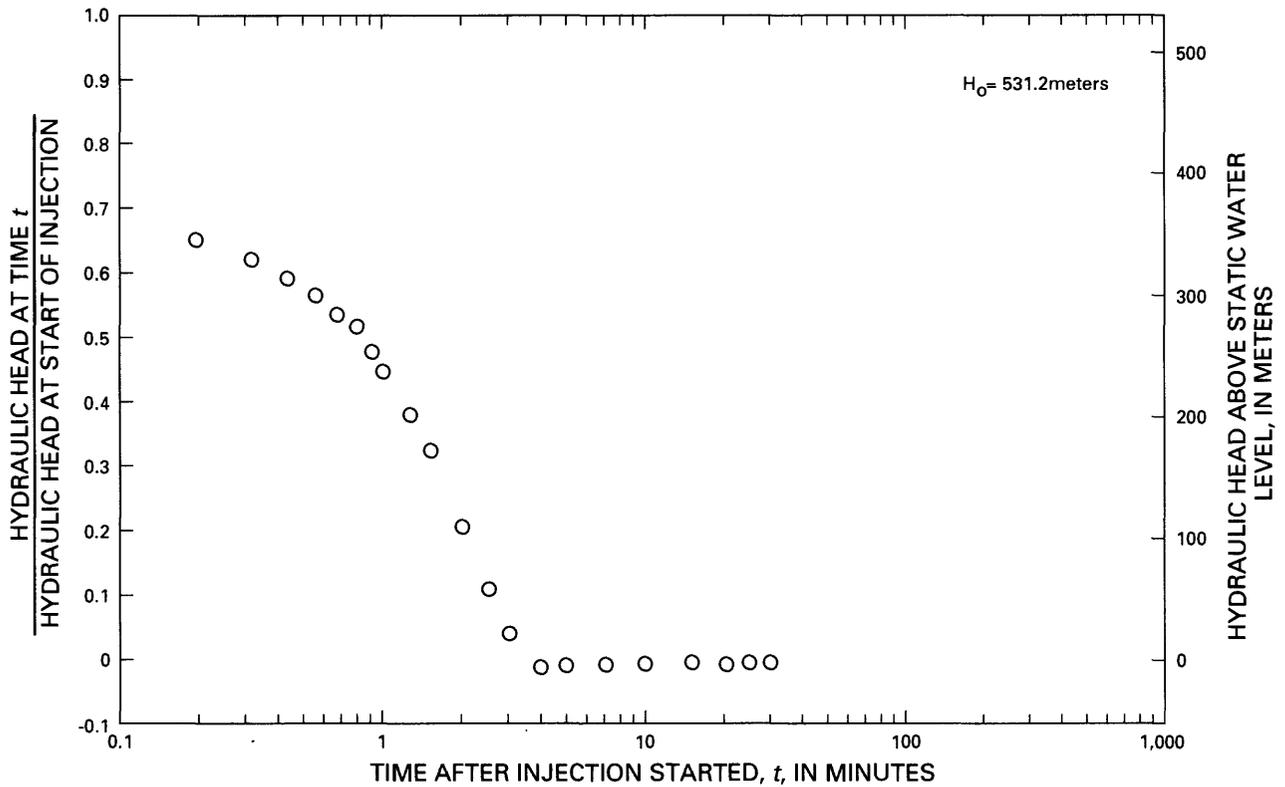


Figure 21.--Data for packer-injection test 5:
depth interval from 753 to 787 meters.

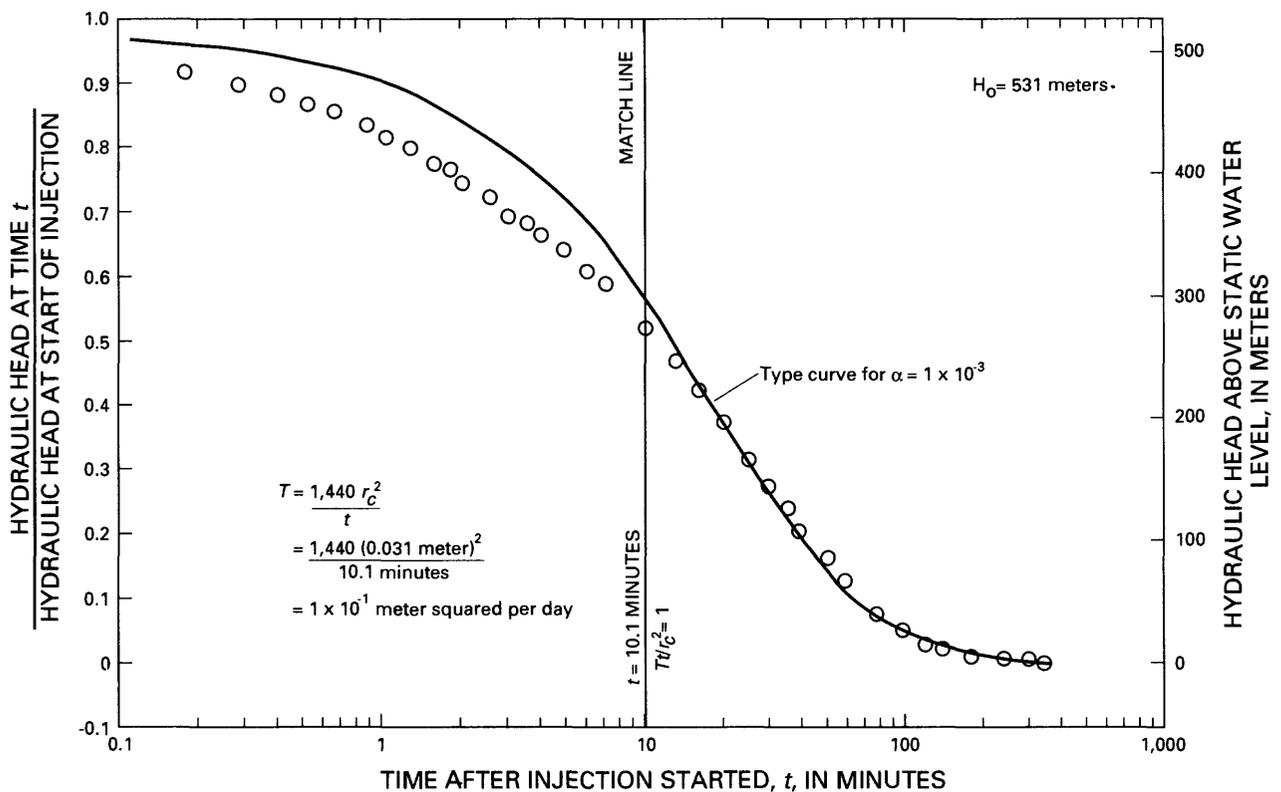


Figure 22.--Analysis of packer-injection test 6:
depth interval from 804 to 838 meters.

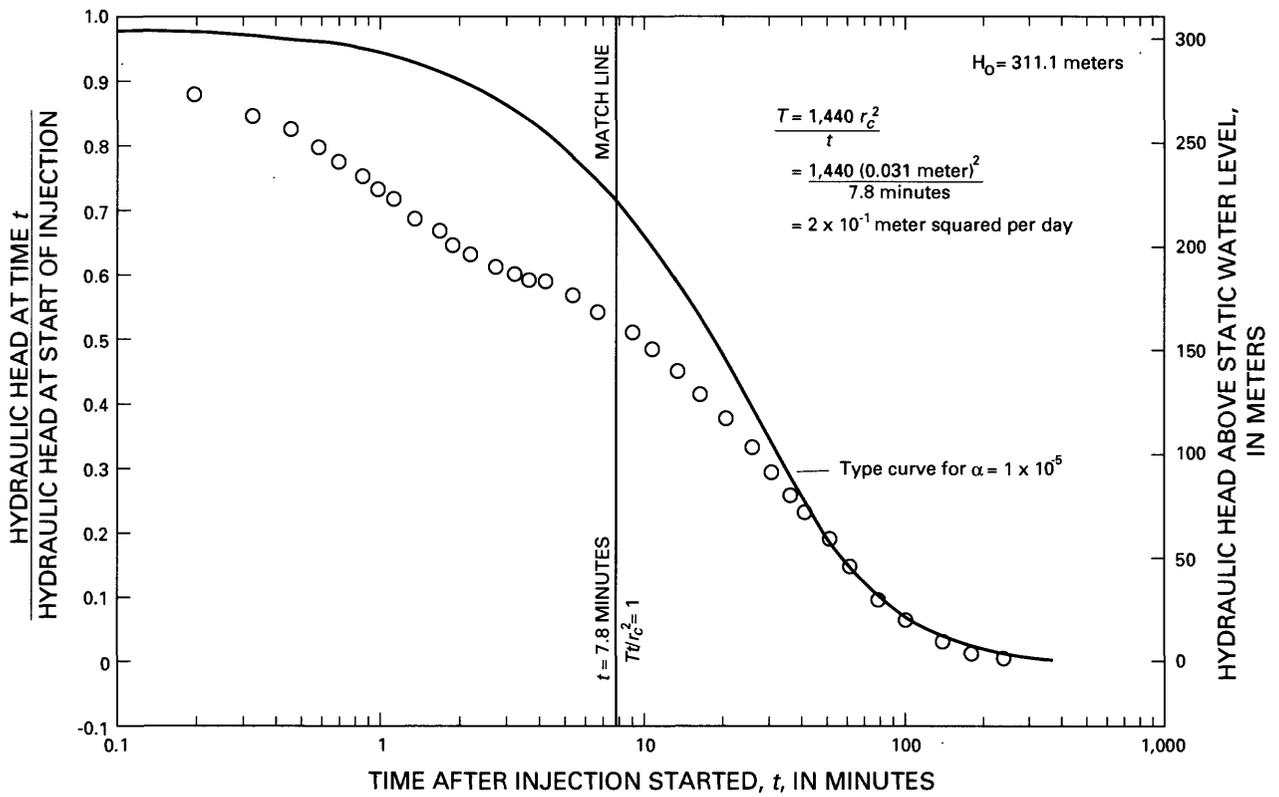


Figure 23.--Analysis of packer-injection test 7:
depth interval from 835 to 869 meters.

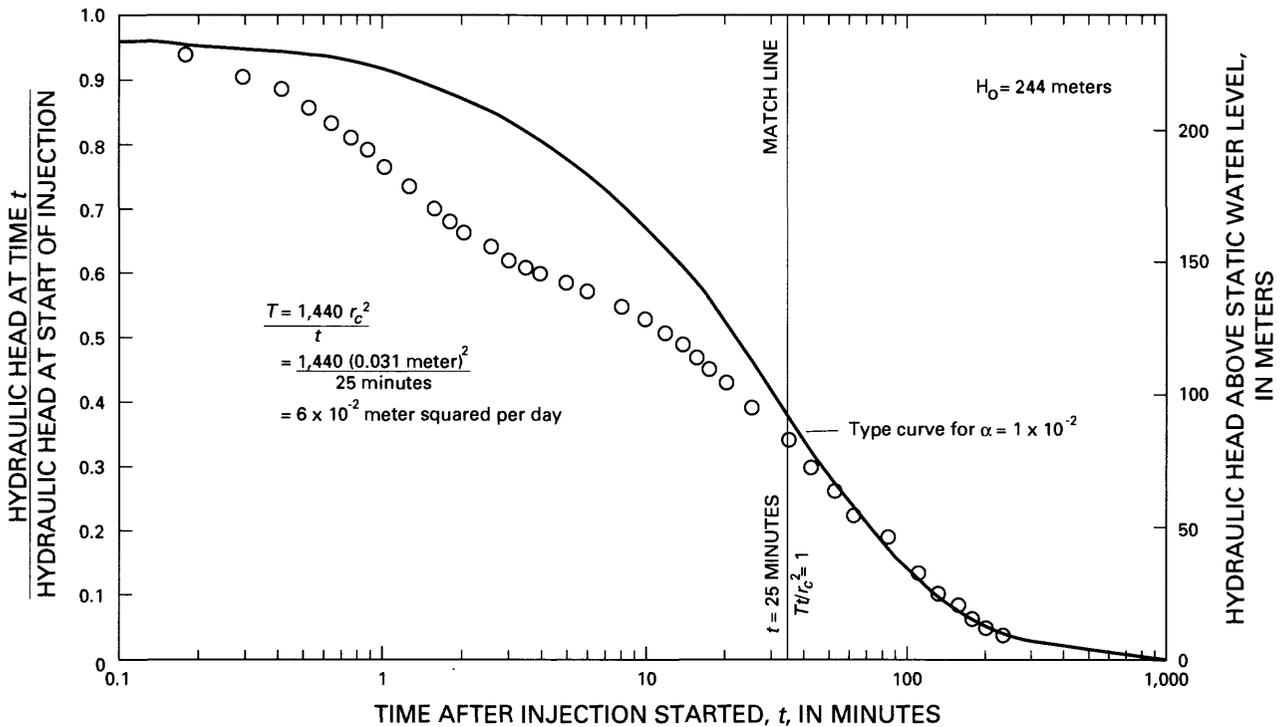


Figure 24.--Analysis of packer-injection test 8:
depth interval from 871 to 1,220 meters.

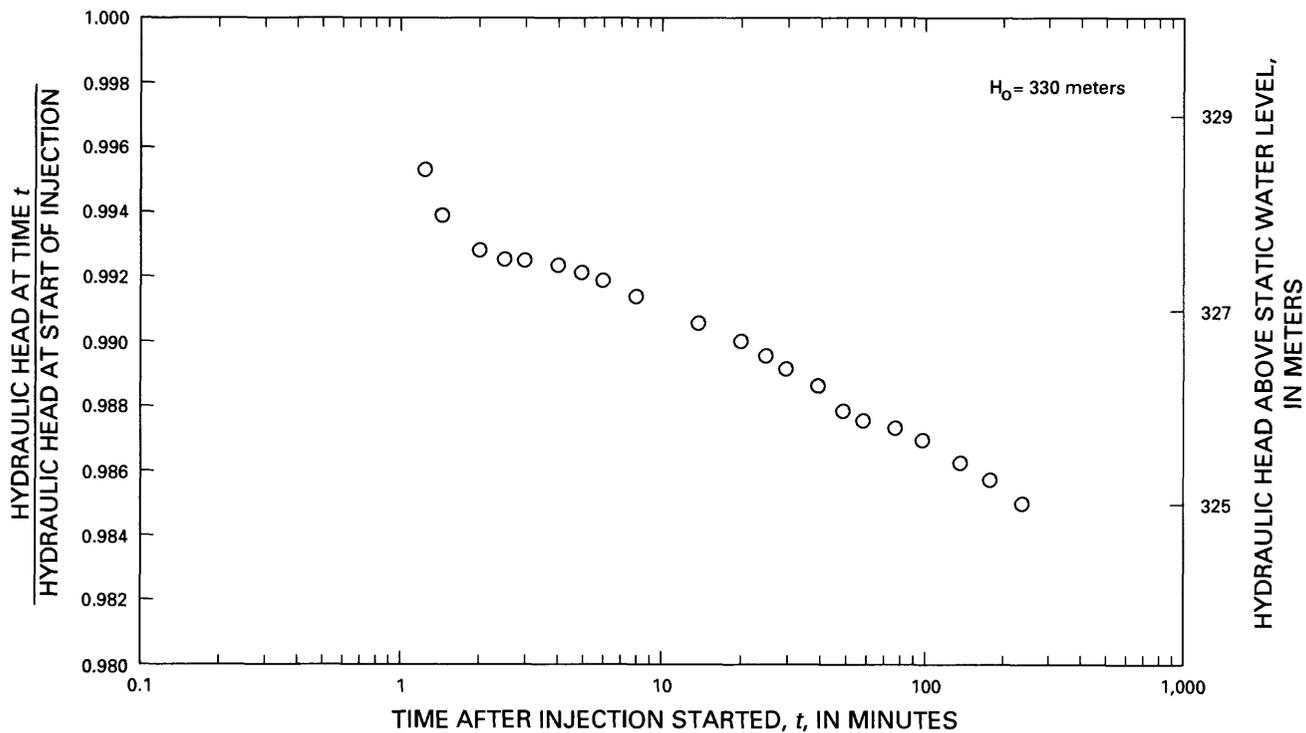


Figure 25.--Data for packer-injection test 9:
depth interval from 1,118 to 1,152 meters.

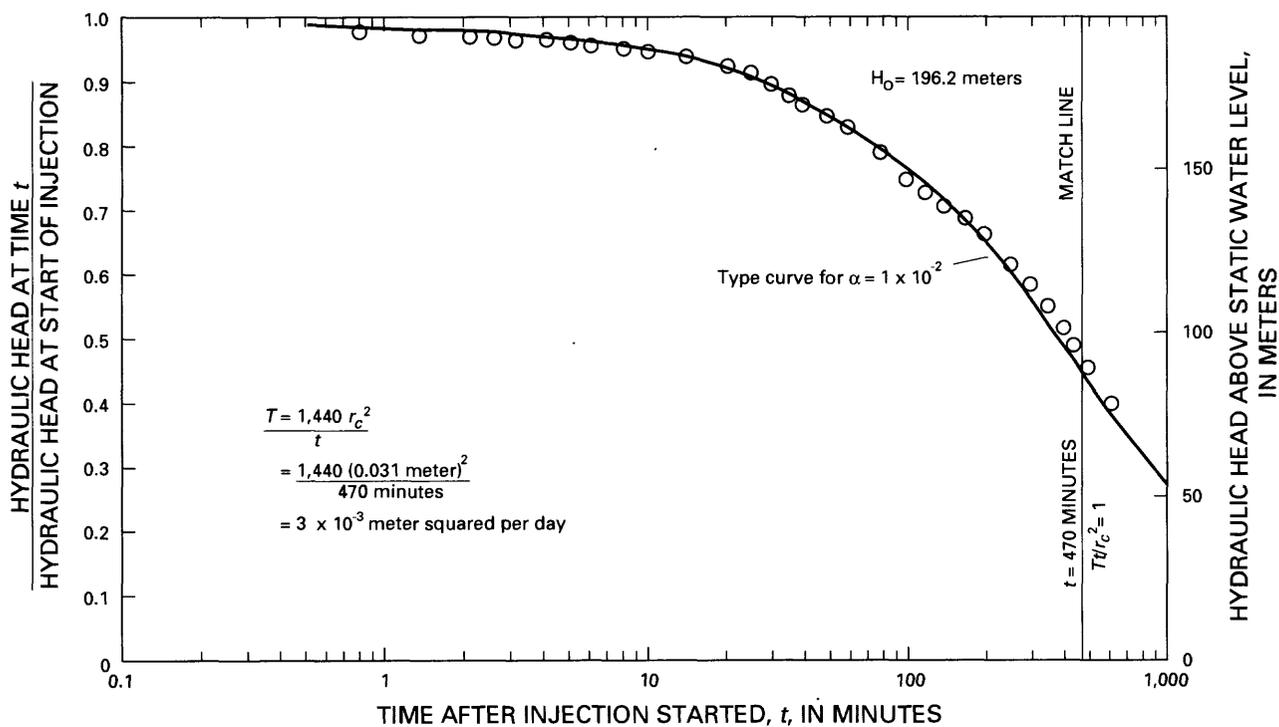


Figure 26.--Analysis of packer-injection test 10:
depth interval from 1,155 to 1,220 meters.

As Cooper and others (1967) point out, the shapes of the type curves differ only slightly when α differs by an order of magnitude, where α is the product of the storage coefficient and the ratio of the radius squared of the open hole to the radius squared of the casing in the interval within which the water level fluctuates. Shifting from one type curve to an adjoining type curve results in a change in the storage coefficient by an order of magnitude, whereas the change in calculated transmissivity is much less.

Cooper and others (1967) recommend that the storage coefficient be estimated, based on knowledge of the local hydrogeologic system, thereby providing an estimate of the α value and type curve to use for matching the data plot.

Calculation of transmissivity was by the following equation (Cooper and others, 1967, p. 267):

$$T = \frac{1440 r_c^2}{t} \quad (4)$$

where T = transmissivity, in meters squared per day;
 r_c = radius of tubing in interval within which water level fluctuates, in meters; and
 t = match line of time since injection started, in minutes.

Packer-injection tests produced some anomalous results. Significant deviations from expected data curves occurred during tests 3, 7, and 8 (figs. 18, 23, and 24). These tests yielded data curves that were double-humped. Deviations from the expected shape are attributed to a long initial water column that substantially overpressured the tested intervals.

The practice of filling the injection tubing to the top of the tubing, a few meters above land surface, has advantages: (1) The water level can be observed easily without measuring devices, to determine if packers or tubing are leaking; and (2) when the tubing is filled, it is easy to observe when the water column is degassed. However, analysis of packer-injection tests performed in test well USW H-6 indicate disadvantages of using a long water column that had not been apparent during previous testing of other wells near Yucca Mountain:

1. The water column may temporarily increase fracture apertures; this effect probably is what results in double-humped curves.
2. During tests of zones with greater relative permeability, velocities of water flowing past the pressure transducer in the injection tube may be fast enough to give erroneous readings.
3. Inertial effects may be significant during the early part of some tests. Inertial effects are not accounted for by the method of Cooper and others (1967).

Based on packer-injection tests at test well USW H-6, the following seems to be applicable for any future testing of fractured rocks with deep water levels:

1. Use the shortest practical water column, probably on the order of tens of meters.

2. If possible, compare results of testing an interval, or intervals, with water columns of different heights, starting with the shortest water column. Possibly start as low as 10 m above static-water level.

Results of packer-injection tests are summarized in table 3. Also listed in table 3 are the estimated α value, assuming a specific storage of $3.3 \times 10^{-6}/m$, and the α value of the type curve used to match the data curve. During curve matching, the estimated α curve was used as a guide. The apparent best fit with either the estimated α curve or the next larger or smaller α curve was used in all but two tests. The estimated α value for test 1 was 9×10^{-5} , whereas the best fit was with the α curve for 1×10^{-1} ; results of this test are questionable. The best match of data from test 10 with a type curve was achieved with a α curve two orders of magnitude greater than the estimated α value. The data fit to the type curve was good and probably indicates that the assumed specific storage was too small for test interval 10.

Test interval 2, in the middle part of the Bullfrog Member of the Crater Flat Tuff, and test interval 5, in the middle part of the Tram Member of the Crater Flat Tuff, had an apparent transmissivity greater than $5 \text{ m}^2/\text{d}$. The time to reach static water level in each test was about 4 minutes. The remaining test intervals had a calculated transmissivity less than $1 \text{ m}^2/\text{d}$, with most values being about $1 \times 10^{-1} \text{ m}^2/\text{d}$ or less. The depth interval from 649 to 683 m was tested twice: (1) The first time (test 3), the tubing was filled to 531 m above the static water level; and (2) The second time (test 3A), the tubing was filled to 275 m above the static water level. Although the calculated values of transmissivity of 2×10^{-2} and 1×10^{-2} were in reasonable agreement for the two tests, the type-curve match for test 3 is so poor that it cannot be considered valid. Test 9 in the depth interval from 1,118 to 1,152 m indicated that this interval is not permeable. Testing was conducted for 240 minutes, at which time testing was stopped, with 1.5 percent of the water column dissipated. A check of pressure-gage readings in the test interval indicated that the data were valid. No numerical value of transmissivity was obtained, but the transmissivity of the interval probably is negligible.

Results of tests 3A, 4, 10, and perhaps 6 are probably the closest to true values, based on the fit of data curves to type curves and reasonableness of results. The results of tests with double-humped data curves (tests 3, 7 and 8) are questionable, as are the results of test 1. Values of horizontal hydraulic conductivity were calculated for data that matched a type curve by dividing the computed values of transmissivity by the length of the test interval; values ranged from 1×10^{-2} to $5 \times 10^{-5} \text{ m/d}$. Values of about $1 \times 10^{-2} \text{ m/d}$ probably reflected a component of fracture hydraulic conductivity, whereas values of about $5 \times 10^{-5} \text{ m/d}$ were probably representative of matrix hydraulic conductivity.

Table 3.--Results of packer-injection tests

[--, no data or remarks; >, greater than]

Test no.	Depth of interval (meters)	Stratigraphic unit (see table 1 for associated formation and unit rank)	Estimated α value ¹ (dimensionless)	α value of type curve matched to data (dimensionless)	Calculated transmissivity (meters squared per day)	Calculated horizontal hydraulic conductivity (meters per day)	Time to reach static-water level ² (minutes)	Remarks
1	581-607	Bullfrog Member	9×10^{-5}	1×10^{-1}	3×10^{-1}	1×10^{-2}	250	--
2	606-640	Bullfrog Member	1×10^{-4}	--	>5	(³)	4	Transmissivity determined to be >5 m ² /d based on tool limitation (see text).
3	649-683	Bullfrog Member and underlying bedded tuff	1×10^{-4}	1×10^{-3}	2×10^{-2}	6×10^{-4}	See remarks	Test stopped after 590 minutes, with 93 percent of water column dissipated.
3A	649-683	Bullfrog Member and underlying bedded tuff	1×10^{-4}	1×10^{-3}	1×10^{-2}	4×10^{-4}	See remarks	Test stopped after 720 minutes, with 95 percent of water column dissipated.
4	686-753	Tram Member	2×10^{-4}	1×10^{-4}	2×10^{-1}	3×10^{-3}	140	--
5	753-787	Tram Member	1×10^{-4}	--	>5	(³)	4	Transmissivity determined to be >5 m ² /d, based on tool limitation (see text).
6	804-838	Tram Member	1×10^{-4}	1×10^{-3}	1×10^{-1}	4×10^{-3}	300	--
7	835-869	Tram Member	1×10^{-4}	1×10^{-5}	2×10^{-1}	5×10^{-3}	240	--
8	871-1,220	Bedded tuff, unnamed lava, and Lithic Ridge Tuff	1×10^{-3}	1×10^{-2}	6×10^{-2}	2×10^{-4}	See remarks	Test stopped after 210 minutes, with 95 percent of water column dissipated.
9	1,118-1,152	Bedded tuff and Lithic Ridge Tuff	1×10^{-4}	--	Negligible	(³)	See remarks	Test stopped after 240 minutes, with only 1.5 percent of water column dissipated (see text).
10	1,155-1,220	Lithic Ridge Tuff	2×10^{-4}	1×10^{-2}	3×10^{-3}	5×10^{-5}	See remarks	Test stopped after 620 minutes, with 61 percent of water column dissipated.

¹See text for discussion. Assumed specific storage of 3.3×10^{-6} /m.

²Time after injection started, when water level in tubing reached an approximate static-water level.

³Not calculated.

Results of the packer-injection tests were not inconsistent with results of the pumping tests and the flow survey, as summarized in table 4. Transmissivity determined from pumping tests was separated into intervals of the packer-injection tests, by percentage of production for each interval, as determined by the borehole-flow survey. In the two intervals for which the borehole-flow survey indicated primary production, injection tests indicated values of transmissivity greater than 5 m²/d. In intervals for which the borehole-flow survey detected no production, calculated values of transmissivity, based on injection tests, were about 1×10⁻¹ m²/d or less. In the depth interval from 581 to 607 m, a transmissivity of about 14 m²/d was calculated from results of the pumping test and the borehole-flow survey, whereas a value of 3×10⁻¹ m²/d was calculated from the injection-test results. Results for this interval were expected to be similar to results for tests 2 and 5.

Table 4.--Comparison of calculated values of transmissivity determined from pumping tests and the borehole-flow survey to those determined from packer-injection tests

[>, greater than; ~, about]

Depth interval (meters)	Transmissivity (meters squared per day)		Stratigraphic unit (see table 1 for associated formation and rank of unit)
	Pumping tests and borehole-flow survey	Packer-injection tests	
581 - 607	14	3×10 ⁻¹	Bullfrog Member
606 - 640	140	>5	Bullfrog Member
649 - 683	No flow detected	~1×10 ⁻²	Bullfrog Member and underlying bedded tuff
686 - 753	No flow detected	2×10 ⁻¹	Tram Member
753 - 787	75	>5	Tram Member
804 - 838	No flow detected	1×10 ⁻¹	Tram Member
835 - 869	No flow detected	2×10 ⁻¹	Tram Member
871 - 1,220	No flow detected	6×10 ⁻²	Bedded tuff, unnamed lava and Lithic Ridge Tuff

GROUND-WATER CHEMISTRY

A water sample for chemical analysis was collected near the end of pumping test 2. At time of collection, about 1.2×10⁷ L of water had been withdrawn from the well during combined periods of pumping. Because of distribution of permeability, the sample mainly represented water from depth intervals from 616 to 631 m, and from 777 to 788 m. Results of the chemical analysis are listed in table 5. The water is a sodium bicarbonate type, which is typical of water from tuffaceous rocks of southern Nevada (Winograd and Thordarson, 1975, p. C97). Isotope-ratio determinations for oxygen-18 and oxygen-16 and for deuterium-hydrogen indicated that the ground water was derived from precipitation. Carbon-14 determination indicated that the sample had an apparent age of about 14,600 years.

Table 5.--Results of chemical analysis¹ of water sample collected during pumping of depth interval from 526 to 1,220 meters

[All units are milligrams per liter unless otherwise indicated; date of collection, 10/16/82]

Physical properties or chemical constituents	Value or concentration
Specific conductance, field (microsiemens per centimeter at 25° Celsius)	379
pH, laboratory (units)	8.3
pH, field (units)	8.1
Temperature (degrees Celsius)	37.8
Calcium (Ca)	4.1
Magnesium (Mg, micrograms per liter)	90
Sodium (Na)	86
Potassium (K)	1.3
Bicarbonate (HCO ₃), field	182
Sulfate (SO ₄)	29
Chloride (Cl)	7.6
Fluoride (F)	4.7
Silica (SiO ₂)	48
Residue on evaporation	263
Lithium (Li, micrograms per liter)	82
Strontium (Sr, micrograms per liter)	8
Oxygen-18/oxygen-16 ($\delta^{18}O$) ²	-13.8
Deuterium/hydrogen (δ^2H) ³	-106
Carbon-13/carbon-12 ($\delta^{13}C$) ⁴	-7.5
Carbon-14 (percent of modern standard)	16.3
Tritium (picocuries per liter)	<10
Cations (milliequivalents per liter)	3.996
Anions (milliequivalents per liter)	4.053
Difference (percent)	-0.71

¹Chemical analyses made by U.S. Geological Survey laboratory, Denver, Colorado.

²Deviation of oxygen-18/oxygen-16 ratio of sample from standard mean ocean water (SMOW) relative to SMOW, in parts per thousand.

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

⁴Deviation of carbon-13/carbon-12 ratio of sample from Peedee belemnite standard (PDB) relative to PDB, in parts per thousand.

FACTORS CONTROLLING WATER PRODUCTION

Water production in the saturated zone of test well USW H-6 was coincident with fractured, partially, and partially to moderately welded tuff units. The reverse was not necessarily true; that is, not all fractured, partially welded tuff units produced water. To define causes of these permeable zones in rocks near the well, the relation between stratigraphy, observed fractures, degree of welding, relatively porous rocks, and major water production was examined (fig. 27). Because the borehole-flow survey indicated that production was limited to the saturated zone above a depth of 803 m, only the depth interval from 525 to 850 m is shown (fig. 27).

Fractures shown (fig. 27) were those observed on a television-camera log. Tuff units with a greater degree of welding generally had a greater number of fractures. As the degree of welding increased, brittleness also increased, and the tuff units fractured more easily under stress. Stresses were likely due to regional tectonic activity associated with the Basin and Range province, nearby volcanic activity, and cooling and compaction of ash-flow units (Carr, 1974).

The general distribution of relatively porous rocks was determined by an examination of borehole-compensated density, neutron, and acoustic logs. Relatively porous rocks were defined as those having porosity greater than an approximate mean porosity for rocks penetrated in the well, as recorded by each log. Density and neutron logs indicated both matrix and fracture porosity, whereas acoustic logs responded only to matrix porosity (Asquith and Gibson, 1982, p. 66-67). These logs were not calibrated relative to the porosity of the ash-flow tuff units, so no attempt was made to use the logs quantitatively. The relative porosity was established by selecting an approximate mean value for each log. Logs were divided into intervals that were consistent with intervals of semiuniform welding, and a percentage of rocks in each interval greater than the norm was determined. If all rocks in an interval had a porosity greater than the norm, then the percentage (see fig. 27, column 4) was 100. Conversely, if none of the rocks in an interval had a porosity greater than the norm, then the percentage was 0. Where it was obvious from examination of caliper logs that density and neutron logs were responding to extreme hole enlargement rather than porosity, the response was ignored. Percentages obtained from each log were combined into one value for each interval as shown in figure 27. The values represent the sum of subjective analyses; however, they probably are representative of the distribution of the relatively porous rocks penetrated in the well.

Based on the data shown (fig. 27), it was concluded that most permeability is associated with fractures, but not all fractures are permeable. Matrix permeability is small. Porosity and permeability of these rocks generally are inversely related. Porosity is greatest near the top and bottom of ash-flow tuff units and is the least near the center. Permeability, as indicated by water production, is greatest near the center of units, where the degree of welding is greatest.

Additional indirect evidence that permeability is primarily due to fractures was indicated by values of matrix hydraulic conductivity for rocks penetrated by test well USW H-1. Values of matrix hydraulic conductivity of core samples from test well USW H-1 (about 3.3 km northeast of test well

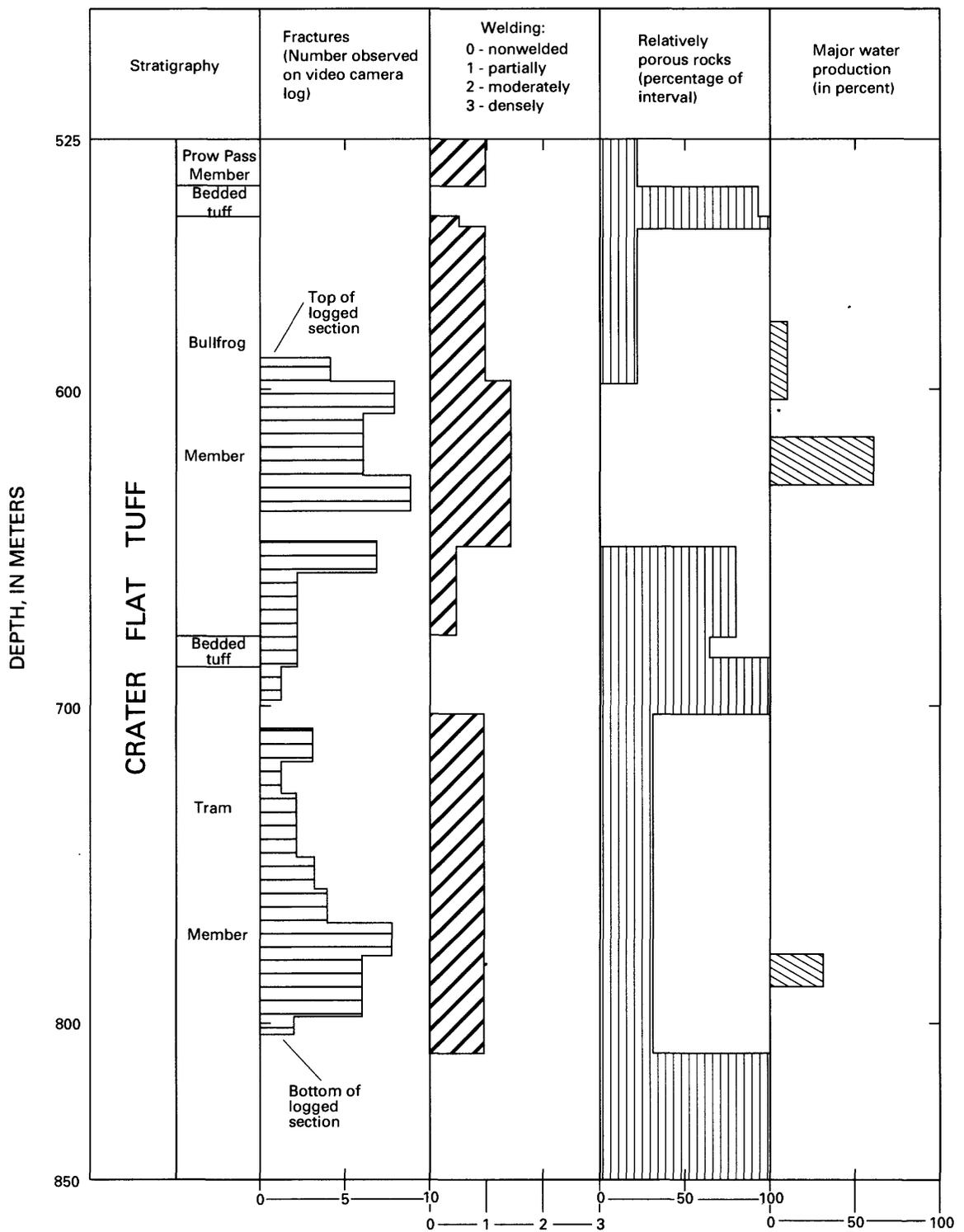


Figure 27.--Relation between stratigraphy, fractures, welding, relatively porous rocks, and major water production.

USW H-6) were about 1×10^{-4} to 5×10^{-5} m/d (Rush and others, 1983, p. 9). Core samples were collected from the same stratigraphic units as penetrated in test well USW H-6. In addition, packer-injection tests in test well USW H-6 confirmed the general magnitude of matrix hydraulic conductivity (see section on "Packer-Injection Tests"). Values of matrix hydraulic conductivity of the indicated magnitude could not have supported the quantity of water produced in test well USW H-6 (see section on "Pumping and Recovery Tests, and Borehole-Flow Survey").

CONCEPTUAL MODEL OF GROUND-WATER FLOW

The accuracy of determining hydraulic characteristics of an aquifer depends to a large degree on applying the correct, or most nearly correct, model to the system under study. Porous-media models are well-known to hydrologists; systems in which heterogeneity is acknowledged are less well known. In a summary of methods for interpreting flow tests in fissured formations, Gringarten (1982, p. 237) stated that mechanisms of fluid flow in heterogeneous formations are still the subject of much debate.

The conceptual model chosen for this study is a dual-porosity model. Barenblatt and others (1960) first introduced the concept of a dual-porosity medium to represent a fractured aquifer. Later studies (Warren and Root, 1963; Odeh, 1965; Kazemi and others, 1969; de Swaan, 1976) investigated variations of the dual-porosity model.

The conceptual model used in this study has the following elements:

1. Both primary and secondary porosity are present.
2. Primary porosity is in the matrix; secondary porosity is controlled by fractures.
3. Both primary and secondary porosity may be decreased by mineral deposition.
4. Flow to the well is through fractures only; flow occurs between the matrix and fractures. Mineral deposition (fracture skin) at the matrix-fracture surface, if present, probably decreases such flow.
5. Hydraulic conductivity of fractures is several orders of magnitude greater than hydraulic conductivity of the matrix.
6. Volume of water stored in the fractures is small relative to the volume stored in the matrix.
7. Distances between fractures are small in comparison with dimensions of the ground-water system under study.

The natural flow system is assumed to be represented by slab-shaped blocks, bounded by major water-producing fracture zones. These fracture zones are envisioned to be markedly more conductive than other interconnected fractures that may be present in the natural system. The conceptual model likely oversimplifies a complex natural system.

Data supporting the use of the conceptual model are:

1. Production was associated with observed fractures.
2. Production was not detected in intervals without fractures.
3. Values of matrix hydraulic conductivity determined by packer-injection testing were small (about 1×10^{-4} m/d, see section on "Packer-Injection Tests").
4. Pumping tests indicated that transmissivity was much larger than could be accounted for by matrix hydraulic conductivity alone (see section on "Pumping and Recovery Tests, and Borehole-Flow Survey").

The conceptual model is inconsistent with the following available information:

1. Only two major zones of water entry, spaced 150 m apart, exist.
2. Late-time drawdown data do not reflect typical dual-porosity characteristics.

Based on the dual-porosity model, homogeneous porous-medium solutions can be used to define general ground-water flow properties using late-time data (Odeh, 1965, p. 63; Kazemi, 1969, p. 458; Kazemi and others, 1969, p. 467; Najurieta, 1980, p. 1247; and Gringarten, 1982, p. 251). Gringarten (1982, p. 251) further stated that, at early time, water is primarily released from the fracture system, with flow from the matrix being virtually zero. At intermediate times, a transition occurs from fracture storage to a combined storage from fractures and matrix. At late time, the transition is complete and the response is like that of a homogeneous porous medium. Average values for hydraulic characteristics then can be determined for the combined system. Alternative models considered were one that assumed a homogeneous porous medium and one that assumed the presence of a recharge hydraulic boundary. A discussion of results using these models, as well as the dual-porosity model, is included in the section on "Pumping and Recovery Tests, and Borehole-Flow Survey."

The degree to which the dual-porosity model describes the actual system in the vicinity of test well USW H-6 is not entirely known. One measure of the suitability of the model is the fit of the test data to the response predicted by the model as well as the reasonableness of the calculated properties. A good fit does not entirely rule out other models, but it does indicate that the conceptual model may adequately describe the system under study.

Pumping and recovery tests conducted in test well USW H-6 were evaluated in terms of the conceptual model, and the following elements deriving from that model:

1. A semilogarithmic data plot should show a straight-line segment in both early and late time. Transition- or intermediate-time data also should plot on a straight line of less slope. The existence of a straight line on any segment of the data plot depends on whether sufficient time had elapsed for the straight line to manifest itself. If "fracture skin" is present, the transition-time data may develop a slope that is less than one-half that of the late-time slope, resulting in a response that is similar to that of a water-table aquifer.

2. The previous element is dependent on late time having been reached and early-time data not having been distorted by factors such as wellbore skin effect and well storage.

According to the conceptual model, if a pumping test does not reach late time, a semilogarithmic plot will have (at most) only two straight-line segments. A similar type of drawdown-time response also could be the result of a hydraulic boundary with increased transmissivity that would appear the same as the response during the transition period of a dual-porosity model.

SUMMARY AND CONCLUSIONS

Rocks penetrated by test well USW H-6 below 9 m of alluvium were primarily ash-flow tuff with interspersed bedded tuff, both of Tertiary age. The lone exception was dacitic(?) lava in the depth interval from 877 to 1,126 m. The bedded tuffs are nonwelded; the ash-flow tuffs vary from nonwelded to densely welded.

The top of the saturated zone in test well USW H-6 is at a depth of 526 m (776 m above sea level) in the Prow Pass Member of the Crater Flat Tuff. The hydraulic head of the bottom 33 m of the well is about 2 m higher than composite head for the remainder of the well.

A borehole-flow survey indicated that major water production is restricted to two zones in Crater Flat Tuff. The depth interval from 616 to 631 m in the Bullfrog Member yielded 60 percent of production while pumping, and the depth interval from 777 to 788 m in the Tram Member yielded 32 percent of production. The remaining production was above a depth of 616 m. Based on the borehole-flow survey, it was concluded that no producing fractures occur in the depth intervals from 631 to 777 m, and from 803 to 1,220 m.

From analysis of two pumping tests based on the transitional part of a dual-porosity solution, calculated transmissivity is about $240 \text{ m}^2/\text{d}$. However, a large degree of uncertainty is associated with this solution. Analysis of two additional pumping tests of isolated intervals generally confirmed previous test results. Maximum estimated transmissivity probably is about $480 \text{ m}^2/\text{d}$, based on a recharge-boundary model.

Packer-injection tests indicated two intervals with apparent values of transmissivity greater than about $5 \text{ m}^2/\text{d}$. These intervals corresponded to intervals of primary production detected during the borehole-flow survey. Calculated values of apparent transmissivity for the remaining intervals ranged from 3×10^{-3} to $3 \times 10^{-1} \text{ m}^2/\text{d}$, with one interval having a transmissivity value too small to be determined by the testing method used. Values of hydraulic conductivity for intervals with no detected fracture flow ranged from about 1×10^{-3} to $1 \times 10^{-5} \text{ m/d}$; these values probably are representative of matrix hydraulic conductivity near the borehole.

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