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

By David H. Lobmeyer

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METRIC CONVERSION TABLE

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

Metric unit	*Multiply by*	*To obtain inch-pound unit*
centimeter (cm)	3.937×10^{-1}	inch
kilometer (km)	6.214×10^{-1}	mile
meter (m)	3.281	foot
degree Celsius (°C)	1.8°C + 32	degree Fahrenheit (°F)
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	1.076	foot squared per day
milligram per liter (mg/L)	[1]1.0	part per million
microgram per liter (μg/L)	[1]1.0	part per billion
liter per second (L/s)	15.85	gallon per minute
liter (L)	0.2642	gallon
millimeter (mm)	3.937×10^{-2}	inch

[1] Approximate.

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ABSTRACT

Test well USW G-4 was drilled to a depth of 915 meters on the eastern flank of Yucca Mountain, near the southwestern part of the Nevada Test Site. Yucca Mountain is being evaluated by the U.S. Department of Energy to determine its suitability for a mined geologic repository for storage of high-level nuclear wastes. The wellsite is near the site proposed for an exploratory shaft that would aid site-characterization efforts. Hydrologic tests were conducted on the saturated part of the section, which is entirely within the Miocene Crater Flat Tuff. Two pumping tests were run. Transmissivity for the entire saturated section is about 600 meters squared per day. A flow survey conducted during the second pumping test indicated that most of the water came from a zone about 10 meters thick below a depth of 892 meters. Packer-injection tests indicated that the transmissivity of the interval above 850 meters was about 7 meters squared per day. A sample collected during the first pumping test was sodium bicarbonate type water, typical of the Yucca Mountain area. Radiocarbon dating gave an apparent age of 12,160 years before present. The water level at the end of testing was 540.3 meters below land surface.

INTRODUCTION

The U.S. Geological Survey has been conducting investigations at Yucca Mountain, Nevada, to assist the U.S. Department of Energy in their evaluation of the hydrologic and geologic suitability of this site for potential storage of 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 has been a principal method of investigation. This report, together with one by Bentley (1984), presents hydrologic information for test well USW G-4, one of several exploratory wells drilled into saturated tuff in or near the southwestern part of the Nevada Test Site. The geology penetrated by test well USW G-4 is presented in Spengler and Chornak (1984).

Purpose and Scope

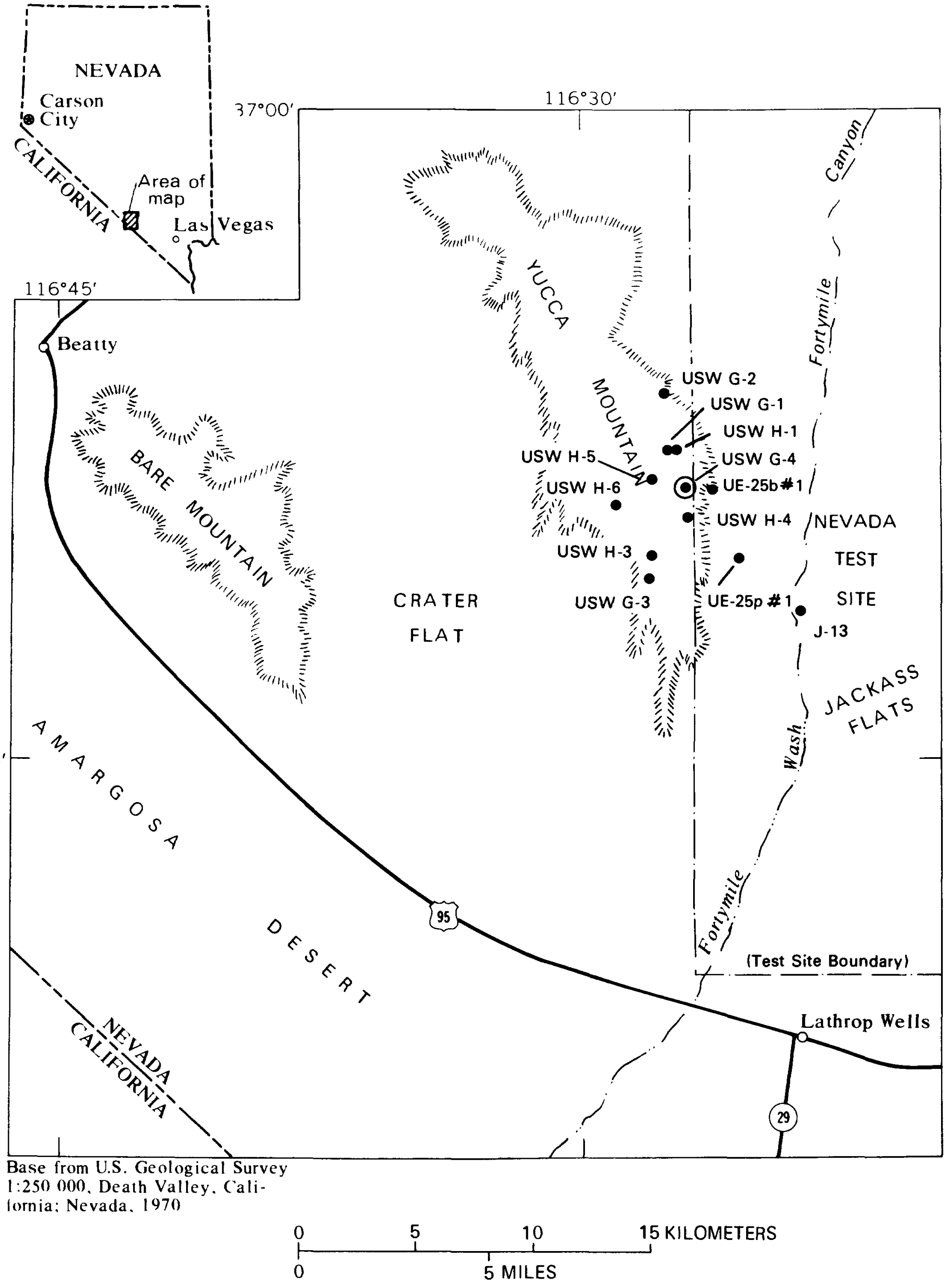
The primary purpose of this study is to evaluate hydrologic characteristics of tuff at Yucca Mountain near the southwestern part of the Nevada Test Site; this may be useful to the U.S. Department of Energy in determining the acceptability of Yucca Mountain as a potential repository for storing high-level nuclear wastes. This report is limited to detailed hydrologic information for the saturated zone, supporting geological and geophysical information, and hydrological interpretations for the rocks penetrated below the water table in test well USW G-4. Test well USW G-4 was designed primarily to evaluate the geology of a proposed exploratory-shaft site, which will aid site-characterization efforts of the U.S. Department of Energy to determine the suitablilty of Yucca Mountain as a site for a mined repository. After completion of coring, the hole was enlarged to allow hydrologic testing of the saturated zone.

Location

Test well USW G-4 is about 140 km northwest of Las Vegas in southern Nevada (fig. 1) and is about 7 km northwest of water-supply well J-13. Location of the site is Nevada coordinate system, central zone, N 765,808, E 563,082, which is at lat. 36°51'14" N., long. 116°27'04" W. The land-surface altitude is 1269.6 m above sea level. The proposed exploratory-shaft site is 91 m northeast of test well USW G-4.

Geohydrologic Setting

Rocks exposed in the vicinity of the Nevada Test Site principally consist of various 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). Rocks of Precambrian and Paleozoic ages have a total thickness of about 11,000 m; they predominantly are limestone and dolomite, but include marble, quartzite, argillite, shale, and conglomerate. Rocks of Paleozoic age have been intruded by granitic stocks of Mesozoic and Tertiary age, and by basalt dikes of Tertiary and Quarternary age. Rocks of Tertiary age primarily consist of welded, vitric, and zeolitic tuff, and rhyolite flows of Miocene and Pliocene age, that were extruded from the Timber Mountain-Oasis Valley caldera complex, centered about 25 km north of the test well. However, the southern boundary of the caldera complex may be as close as 5 km to the north and west of test well USW G-4, and one segment probably is southwest of test well USW G-4. The source for the tuffaceous beds of Calico Hills was about 10 km to the northeast in the northwestern Calico Hills (Carr, 1982; Maldonado and Koether, 1983). The alluvium principally consists of detritus deposited in the intermontane basins, much of it as fan deposits.



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

Figure 1.--Location of test well USW G-4 and nearby test wells in southern Nevada.

Tuff underlies Yucca Mountain from land surface to some undetermined depth in excess of the depth of well USW G-4. The pre-Tertiary lithology is unknown, but it probably is either granite or, as penetrated in test well UE-25p#1, sedimentary rocks of Paleozoic age (Craig and Johnson, 1984).

Well USW G-4 is in a wash on the east side of Yucca Mountain. The drainage is toward Fortymile Wash, which is tributary to the Amargosa Desert. The region is arid; 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). Yucca Mountain probably receives more precipitation (150 mm per year, Montazer and Wilson, 1984), because of its higher altitude. Most of the precipitation occurs in winter and spring, when frontal storms move across the area from the west. During the summer, widely-scattered, intense thunder showers are common.

Infrequent runoff resulting from rapid snowmelt or from summer showers flows off the mountain in ephemeral streams along the washes. Commonly, the beds of the washes are a mix of sand, gravel, and boulders; thus, they have the ability to rapidly absorb the infrequent flows. Most water is returned to the atmosphere shortly after runoff ceases, but a very small quantity percolates to depths beyond which evaporation and transpiration are effective. This water ultimately recharges to the ground-water system. The recharge flux on Yucca Mountain is estimated to be no more than a few millimeters per year (Montazer and Wilson, 1984, p. 42). A much larger part of the water in the ground-water flow system recharges from precipitation about 50 km northwest of the Yucca Mountain area 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). Flow of ground water from Yucca Mountain probably is eastward or southeastward toward the general area of well J-13, based on the configuration of the potentiometric surface (Robison, 1984).

DRILLING AND TESTING OPERATIONS

A drilling rig was moved onto the site of test well USW G-4 on August 22, 1982. After drilling a large-diameter hole to below the base of the alluvium, surface casing was set to 12 m and cemented in place. Coring operations began September 2, 1982. An attempt was made to cut a continuous 64-mm diameter core for the remainder of the depth. Except for the drilled interval from 138 m to 143 m, and a few other minor exceptions, the entire section below the surface hole was cored to a depth of 915 m.

Coring operations were completed on November 7, 1982. The hole was enlarged to a diameter large enough to allow hydrologic testing (fig. 2). On December 2 and 3, 1982, a 140-mm diameter submersible pump was set, with the intake at 602 m, 62 m below the standing water level and a 41-mm inside diameter tube to 615 m. The pump was tested for about 2 hours, and the water-level drawdown was less than 3 m. The small drawdown indicated that the pump was set deeper than necessary. On December 5, 1982, the pump assembly was raised, so that the lower set of perforations of the casing could be checked for entrance of water during a flow survey while pumping. The pump intake was reset to 569 m with the end of the water-level monitoring line at 582 m, and the first of the two pumping tests was started. A water sample for chemical analysis was collected on December 9, 1982, during the later part of the 5,740-minute-long test. Water-level recovery was monitored for 120 minutes after the pump was turned off.

The second pumping test was run from January 4, to January 5, 1983. A flow survey was run during this 1,680-minute-long test. The water level was monitored for 120 minutes after the pump was shut off.

Packer-injection (slug) tests were run on the interval below the casing between January 7, and January 11, 1983. A closed-end tubing for monitoring temperature for heat-flow determination was installed to a depth of 914 m and filled with water on January 12, 1983. An open-ended tubing for monitoring the water level was installed to a depth of 575 m. The test well was left in the condition shown on the construction diagram (fig. 2), when the rig was moved off on January 13, 1983.

GEOPHYSICAL LOGGING

A suite of geophysical logs was run during interruptions in drilling and at the end of drilling; a complete listing of logs is shown in Bentley (1984). None of the geophysical logs shows anomalous conditions for the Yucca Mountain area (Spengler and Chornak, 1984). At the end of geophysical logging, a gyroscopic survey was run to a depth of 906.8 m to determine direction and magnitude of borehole deviation. This subsurface survey indicated a deviation of 42.8 m south and 66.3 m west or 78.9 m south-southwest of the surface location (Spengler and Chornak, 1984). This deviation makes it necessary to subtract 1.53 m from static water-level measurements to make them equivalent to measurements in a vertical hole. This correction is needed when comparing measurements in this hole with other measurements in the Yucca Mountain area.

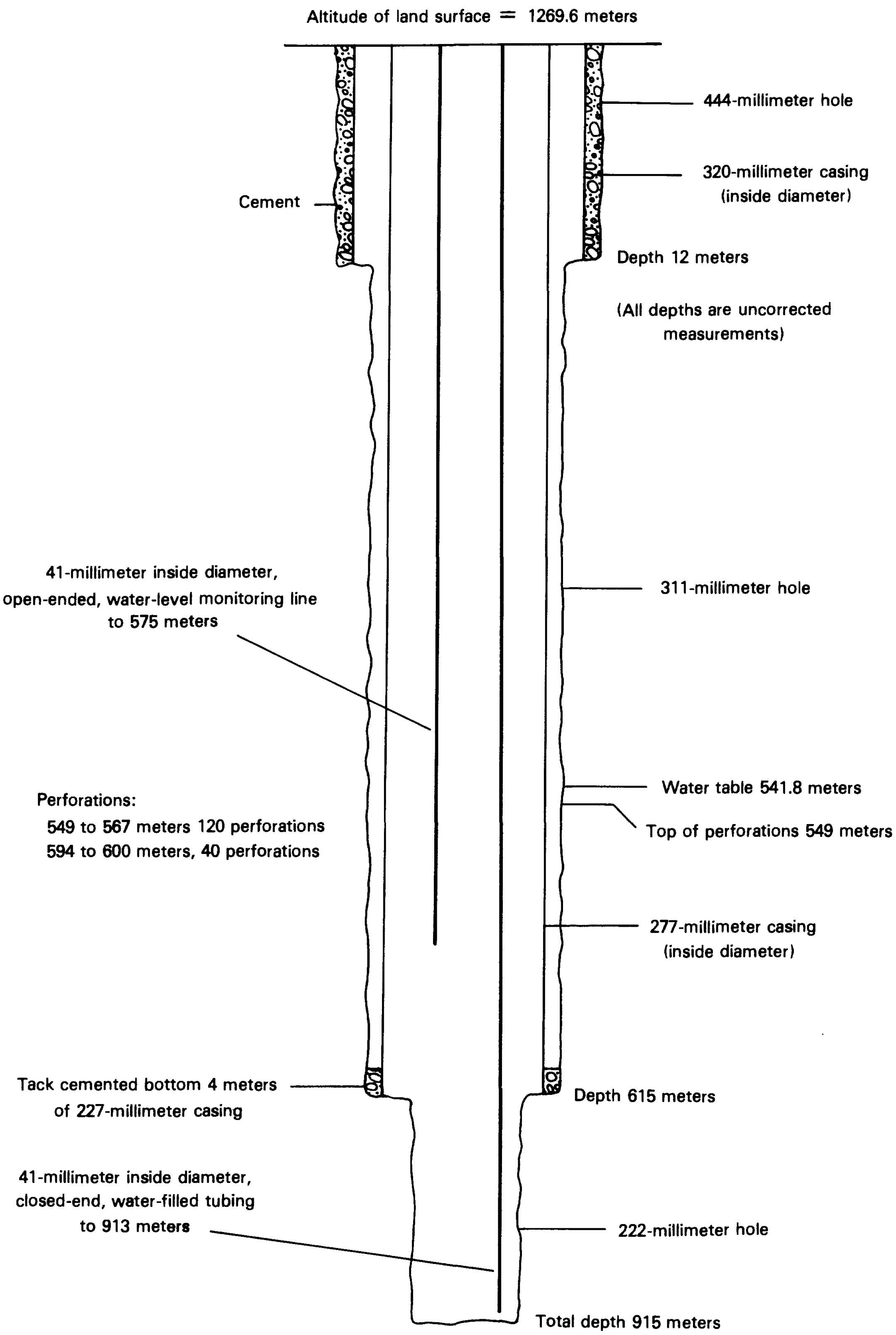


Figure 2.--Construction of test well USW G-4 at the end of hydrologic testing.

STRATIGRAPHY AND LITHOLOGY

Lithologic units penetrated at USW G-4 were a thin interval of alluvium, composed of volcanic-tuff fragments, and more than 900 m of welded and nonwelded tuff, with thin, bedded-tuff intervals (Bentley, 1984). Stratigraphy and lithology of the saturated part of the section are summarized in table 1. Lithologic-unit descriptions are based on core descriptions, supplemented with information from geophysical logs (Spengler and Chornak, 1984). A more complete description of the units penetrated is presented in table 1 of Bentley (1984).

Table 1.--*Lithologic log of part of test well USW G-4*

[Modified from Spengler and Chornak, 1984. Color descriptions, descriptions of lithic inclusions and descriptions of phenocrysts have been deleted; m, meter; cm, centimeter; mm, millimeter]

Stratigraphic and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)
Crater Flat Tuff (Miocene)		
Prow Pass Member		
Tuff, ash-flow, nonwelded, zeolitic	0.3	537.2
Tuff, ash-flow, intensely altered to zeolites	0.6	537.8
Tuff, ash-flow, nonwelded, moderately to mostly zeolitic (contains montmorillonite), alteration decreases downward (argillic parting at lower contact), (static water level near the base of this subunit).	4.0	541.8
Tuff, ash-flow, nonwelded, devitrified [slightly zeolitic(?) and argillic]	2.8	544.6
Tuff, ash-flow, nonwelded, slightly to moderately argillic (increase in alteration relative to unit above).	1.7	546.3
Tuff, ash-flow, nonwelded, vapor-phase crystallization; possible shear fracture at 546.5 m.	1.1	547.4

Table 1.--*Lithologic log of part of test well USW G-4*--Continued

Stratigraphic and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)
Crater Flat Tuff (Miocene)--Continued		
Prow Pass Member--Continued		
Tuff, ash-flow, partially welded, vapor-phase crystallization; shear fracture with slickensides at 547.7 m, steep-angle fractures with iron oxide(?) staining cut core from 564.5 to 565.9 m; lower contact gradational.	22.7	570.1
Tuff, ash-flow, partially welded (slight increase in welding), devitrified; vapor-phase crystallization common in upper 7.3 m and decreases downward; shear fractures present at 577.4 to 578.5 m and 582.3 to 582.7 m; fault-plane cuts core from 585.5 to 586.9 m; slickensides observed along segments of fault.	17.7	587.8
Tuff, ash-flow, stained near fractures (593.4 to 594.2 m and 594.7 to 595.6 m), partially welded, devitrified [slightly argillic(?)], increase in degree of alteration relative to unit above; alteration progressively increases downward to base of unit; shear fractures present at 589.5 m, 591.3 to 595.6 m; abrupt contact with lower unit, but no apparent ash-fall parting.	8.0	595.8
Tuff, ash-flow, nonwelded to partially welded, moderately to mostly zeolitic (clinoptilolite/mordenite); thin clay parting at 603.02 m; shear fracture present at 596.2 to 596.5 m; fault with breccia along plane at 606.6 to 607.2 m; abruptly gradational contact, but no ash-fall parting present.	29.1	624.9
Tuff, ash-flow, partially welded, devitrified, mostly zeolitic (clinoptilolite/mordenite), slightly to moderately silicified; moderately to mostly indurated from 630.5 to 640.5 m, 640.8 to 643.7 m, 646.6 to 649.2 m.	43.4	668.3
Tuff, ash-flow, nonwelded, mostly zeolitic (clinoptilolite/mordenite).	7.3	675.6
Tuff, ash-flow, nonwelded, mostly zeolitic (clinoptilolite/mordenite), and slightly argillic, intensity of alteration increases downward to base of unit.	6.4	682.0

Table 1.--*Lithologic log of part of test well USW G-4*--Continued

Stratigraphic and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)
Bedded tuff (unnamed unit)		
Tuff, bedded, ash-fall, reworked, upper 0.5 m consists of tuffaceous siltstone and very fine tuffaceous sandstone, lower 1.4 m consists of ash-fall and reworked tuff slightly to moderately zeolitic; thickness of bedding ranges from a few centimeters to 1.0 m; base of unit marked by a fault.	2.0	684.0
Crater Flat Tuff--Continued		
Bullfrog Member		
Tuff, ash-flow, partially welded, devitrified; fault zone from 684.0 to 685.2 m, truncation of pumice fragments along fracture, interval moderately altered, fault plane dips at 73° relative to axis of core; shear fractures present at 685.8 and 686.3 m; lower contact gradational.	6.8	690.8
Tuff, ash-flow, partially welded, devitrified; shear fractures occur at 694.4 and 694.7 m; lower contact gradational.	8.1	698.9
Tuff, ash-flow partially welded, devitrified (vapor-phase crystallization); conspicuous, almost vertical shear fracture extending along core from 713.8 to 715.0 m, in places aperture along fracture is as wide as 0.5 cm; lower contact gradational.	23.5	722.4
Tuff, ash-flow, moderately welded, devitrified (some vapor-phase crystallization); lower contact abruptly gradational.	8.4	730.8
Tuff, ash-flow, partially welded, devitrified (vapor-phase crystalization); almost vertical shear fractures occur from 743.3 to 744.5 m and from 745.3 to 745.7 m.	39.9	770.7
Tuff, ash-fall interbedded with ash-flow(?), well indurated, devitrified; pumice fragments, poorly sorted; noticeably foliated; foliation either due to welding or compaction; well sorted, thin (1 to 1.5 cm) ash-fall beds occur at 770.67 m and 770.78 m.	1.7	772.4
Tuff, ash-flow, nonwelded, devitrified; lower contact gradational.	7.6	780.0

Table 1.--*Lithologic log of part of test well USW G-4*--Continued

Stratigraphic and lithologic description	Thickness of interval (meters)	Depth to bottom of interval (meters)
Crater Flat Tuff--Continued		
Bullfrog Member--Continued		
Tuff, ash-flow, partially welded, devitrified; prominent, almost-vertical shear fracture occurs from 781.2 to 783.8 m; lower contact gradational.	6.9	786.9
Tuff, ash-flow, moderately to densely welded, devitrified; shear fracture present from 809.0 to 809.6; 2 slight-angle, manganese-oxide-coated fractures with 0.3 to 1.1 cm separation mark base of interval.	30.1	817.0
Tuff, ash-flow, partially welded, slightly indurated, moderately argillic (montmorillonite and illite); lower contact gradational.	4.6	821.6
Tuff, ash-flow, partially welded, devitrified, moderately zeolitic (mordenite), mostly indurated; lower contact gradational.	9.5	831.1
Tuff, ash-flow, nonwelded, devitrified (slightly zeolitic).	2.0	833.1
Bedded tuff (unnamed unit)		
Tuff, ash-fall, reworked, moderately indurated, in places slightly argillic and slightly zeolitic (mordenite/clinoptilolite); individual beds range in thickness from a few centimeters to 0.61 m, most contacts gradational, thin clay parting occurs at 839.7 m and at base of interval.	6.8	839.9
Crater Flat Tuff--Continued		
Tram Member		
Tuff, ash-flow, nonwelded, devitrified.	1.6	841.5
Tuff, ash-flow, partially welded, devitrified; base of interval marked by 3 cm of ash-fall tuff(?).	0.5	842.0
Tuff, ash-flow, nonwelded to partially welded, devitrified, moderately zeolitic (mordenite/clinoptilolite).	24.0	866.0
Tuff, ash-flow, devitrified; prominent shear fractures occur at 885.3 m, 887.9 m, 889.9 to 891.3 m, 893.0 to 893.6 m, 894.0 to 894.4 m, and 909.9 to 911.2 m.	48.0	914.0
Tuff, ash-flow, moderately welded, devitrified; prominent shear fracture occurs at 914.4 m.	0.7	914.7
	TOTAL DEPTH	914.7

HYDROLOGY

Water Levels

Measurements shortly after coring to 915 m indicated that the fluid level was at 541 m, very similar to the water level at the end of hydrologic testing. No consistent difference in hydraulic head with depth could be detected (table 3 of Bentley, 1984). Water levels appeared to be varying about 0.3 m every 24 hours but no consistent trend was detectable during testing. Measurements from nearby well USW H-4, where closely spaced measurements for several months are available, indicated variations in water level that are about the same magnitude. These variations probably are related to earth-tide effects (R.W. Craig, U.S. Geological Survey, oral commun., 1985). The variation in water level is unusually large for earth tides; however, the combination of substantial hydraulic conductivity and minimum porosity could cause larger than ordinary tidal effects (Bredehoeft, 1967). Because trend measurements under nonpumping conditions are not available, interpretation of the data from aquifer tests is limited to the first few hours of the tests.

Flow Survey

On January 4, 1983, a flow survey was conducted in the borehole while pumping at a rate of 13.4 L/s (fig. 3). The flow-survey and temperature logs run during the survey indicate that about 75 percent of the water was produced from a zone less than 10 m thick (between 890 and 900 m) near the bottom of the well. About 98 percent of the water was from below 850 m.

Aquifer Tests

Testing methods and methods used to analyze the results are based on the assumption of a homogeneous, isotropic, porous medium. Most test interpretations require that enough of the aquifer be sampled to average the variations caused by the lack of homogeneity in the aquifer (Warren and Root, 1963; Odeh, 1965; Kazemi, 1969; Kazemi and others, 1969; Wang and others, 1977; and Najurieta, 1980). Initial early time data is affected by wellbore storage and skin effects (Earlougher, 1977). Jenkins and Prentice (1982) proposed a method of analysis based on linear flow through a fracture system draining a less permeable matrix. Moench (1984) proposed a method based on a double porosity system with the matrix separated from the fracture system by a skin of less permeable material. Witherspoon and others (1980) stated that the coefficients derived from tests of fractured rocks can be regarded as slightly different forms of coefficients derived from tests of homogeneous rocks. In this report, an attempt is made to judge the applicability of coefficients derived from aquifer tests of test well USW G-4.

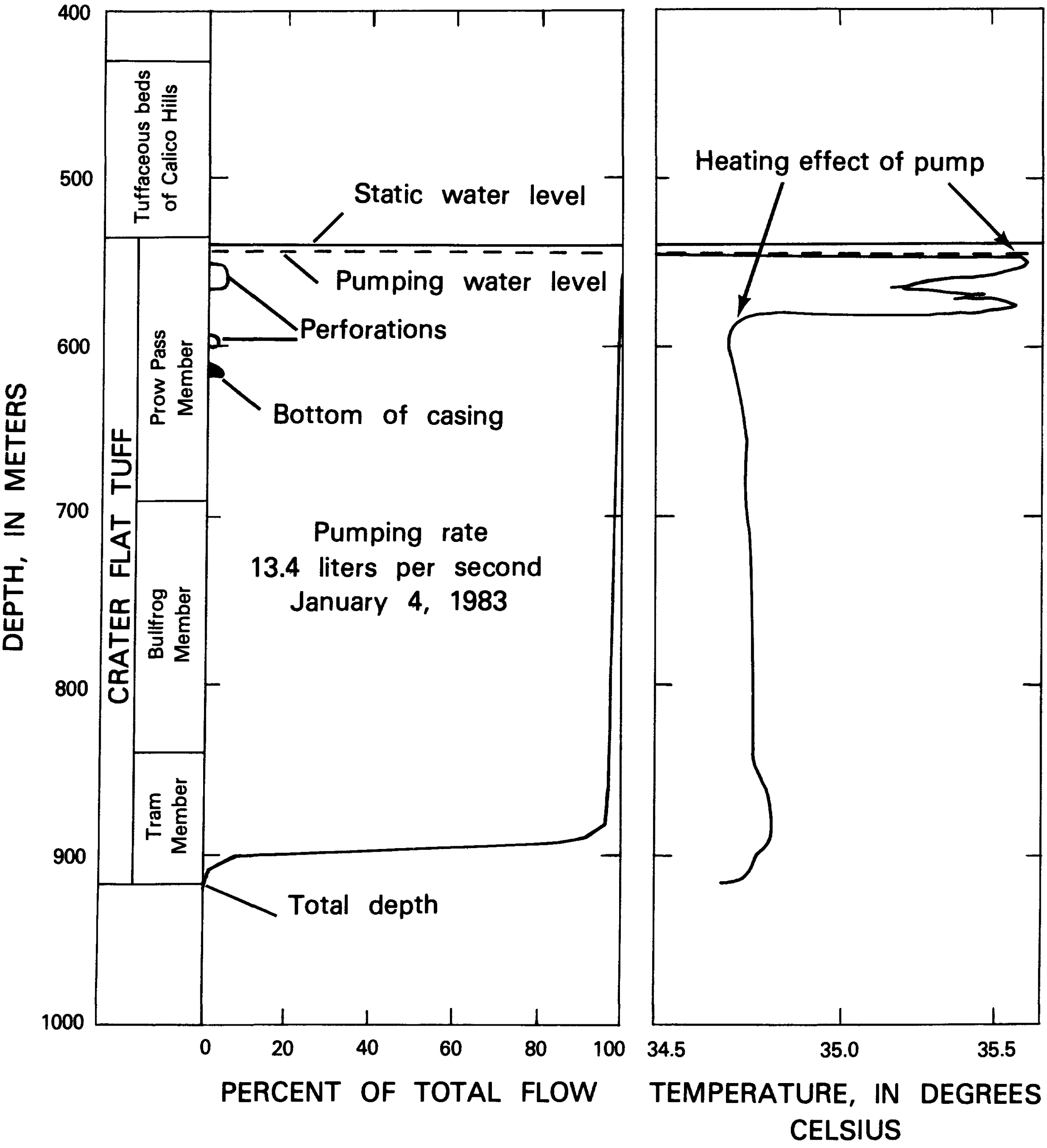


Figure 3.--Borehole flow survey in test well USW G-4.

Pumping Tests

The well was pumped for about 4 days begining December 5, 1982, and for slightly more than 1 day beginning on January 21, 1983. Drawdown during pumping and residual drawdown (recovery) were monitored using a pressure transducer suspended below the water level in a small-diameter access tubing. Recovery after pumping was monitored for 2 hours after each of the tests.

Drawdown during the tests was relatively small. After about 100 minutes, the rate of drawdown decreased so that the effects of pumping could not be distinguished from undefined background trends. Thus, only the segment of the tests before 100 minutes appeared to be analyzable.

The method used to analyze the drawdown part of the tests was the method of Papadopulos and Cooper (1967) for analysis of drawdown in a well of large diameter. The recovery part was analyzed using the Theis recovery method (Ferris and others, 1962). Test data and analyses are shown in figures 4 through 7, and the results of the tests are summarized in table 2.

Table 2.--*Summary of pumping tests in test well USW G-4*

[All tests include the total saturated thickness from about 541 to 915 meters; only Crater Flat Tuff tested.]

Date	Transmissivity (meters squared per day)	Hydraulic conductivity (meters per day)	Test duration (minutes)	Remarks
12/05/82	622	1.2	5,740	Pumped 5,400,000 liters.
12/09/82	490	1.3	120	Recovery after pumping.
01/04/83	675	1.4	1,680	Pumped 1,300,000 liters.
01/05/83	570	1.5	120	Recovery after pumping.

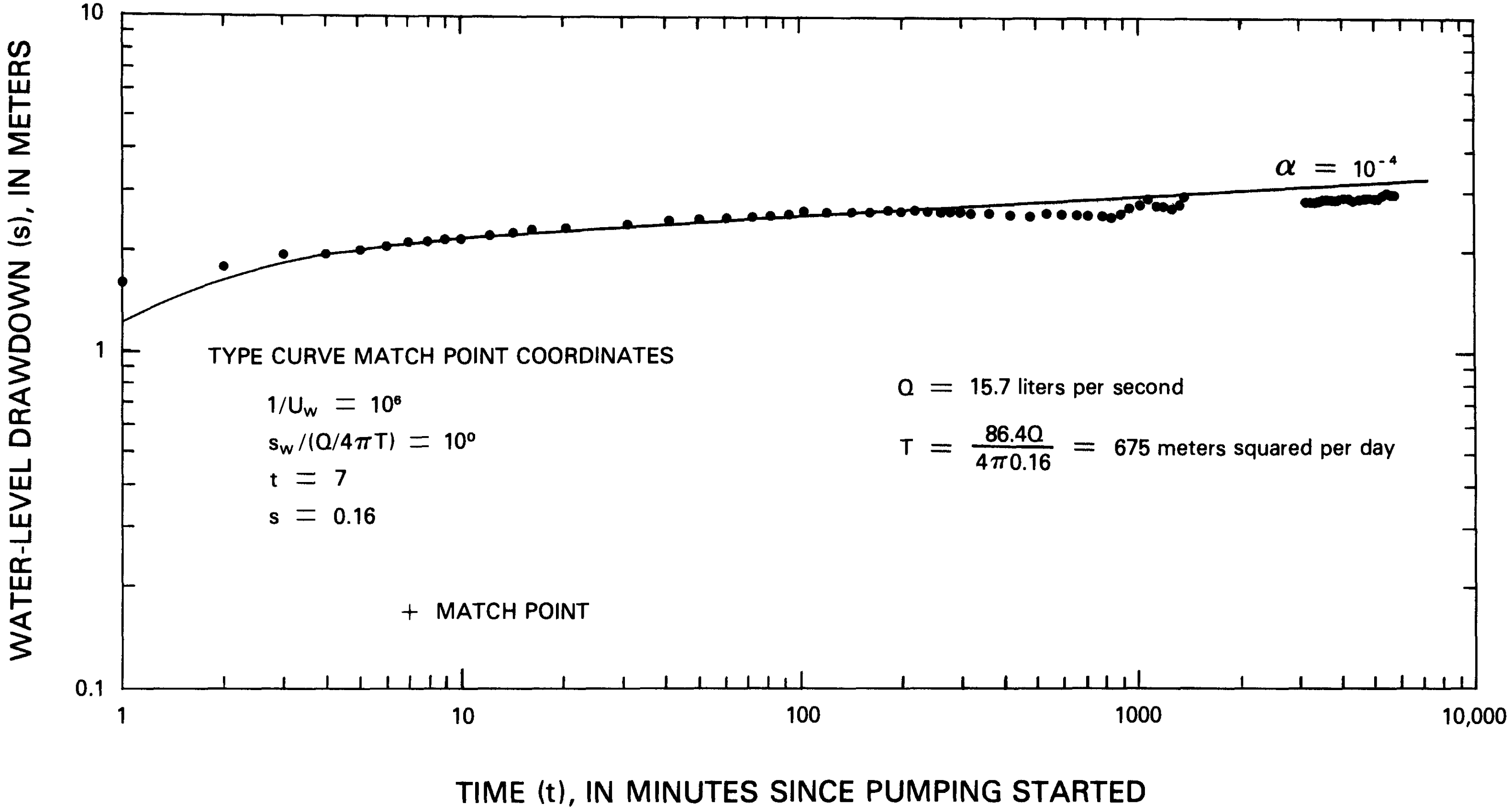


Figure 4.--Water-level drawdown in test well USW G-4 during pumping test 1.

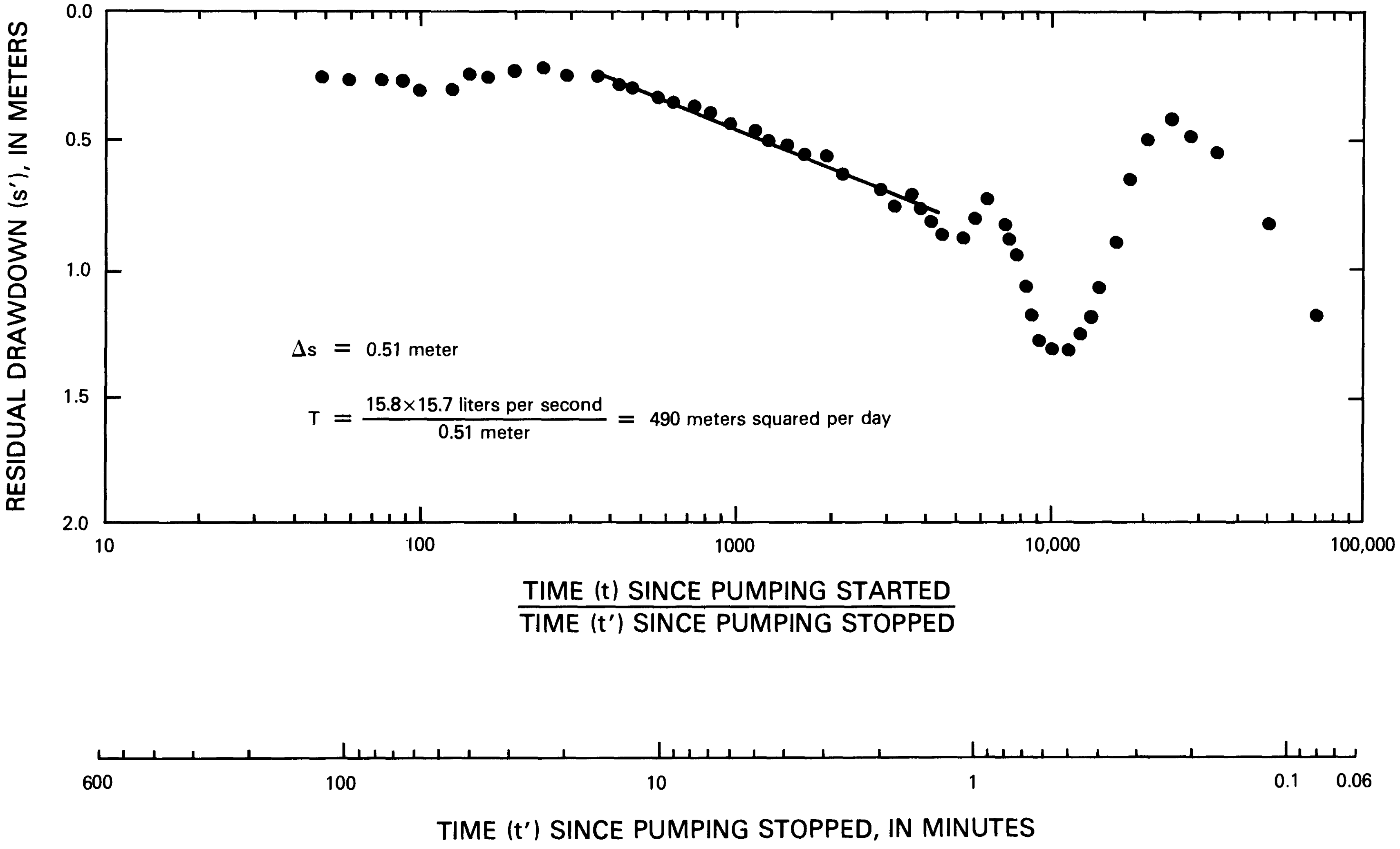


Figure 5.--Residual drawdown in test well USW G-4 after pumping test 1.

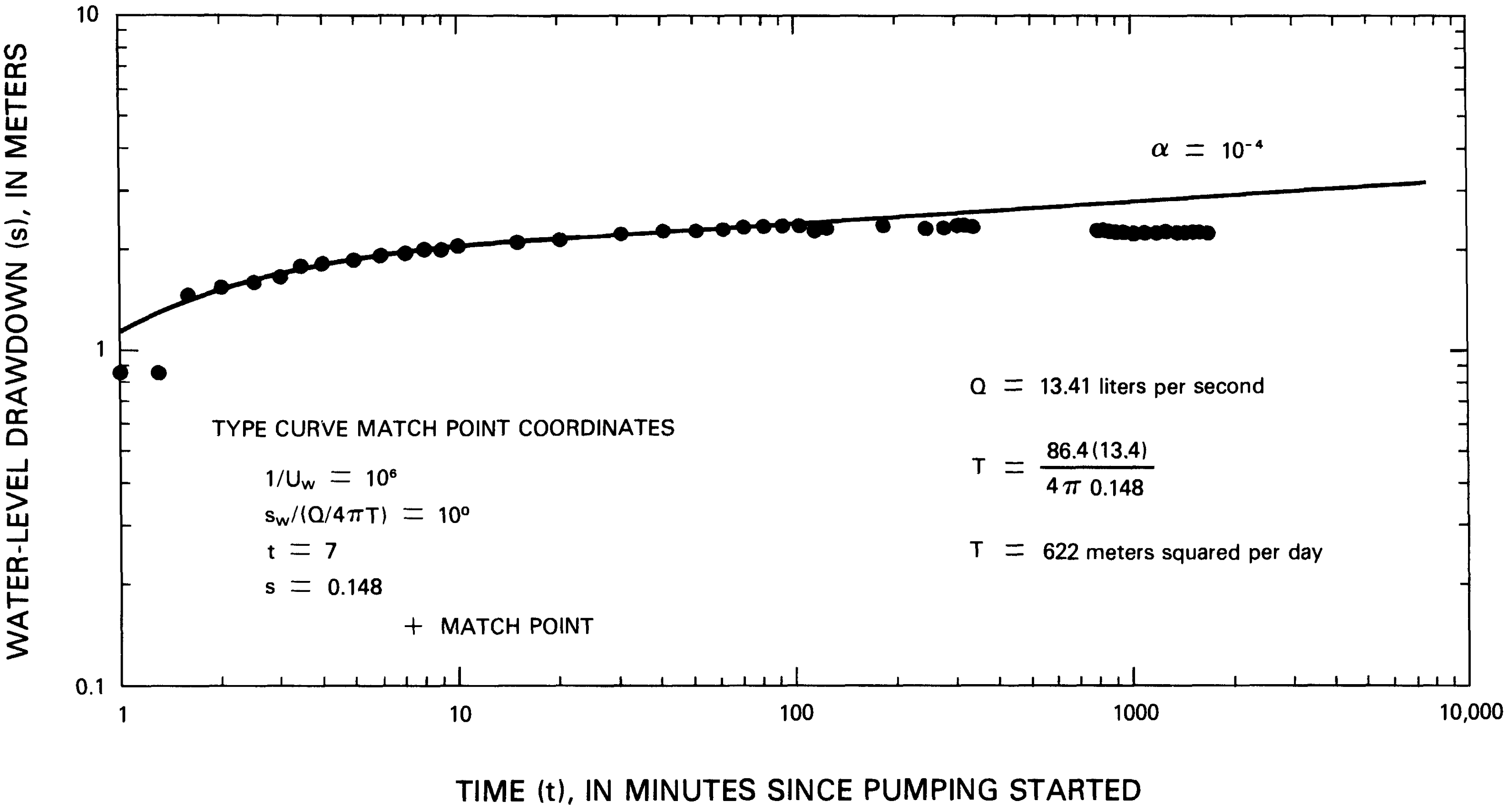


Figure 6.--Water-level drawdown in test well USW G-4 during pumping test 2.

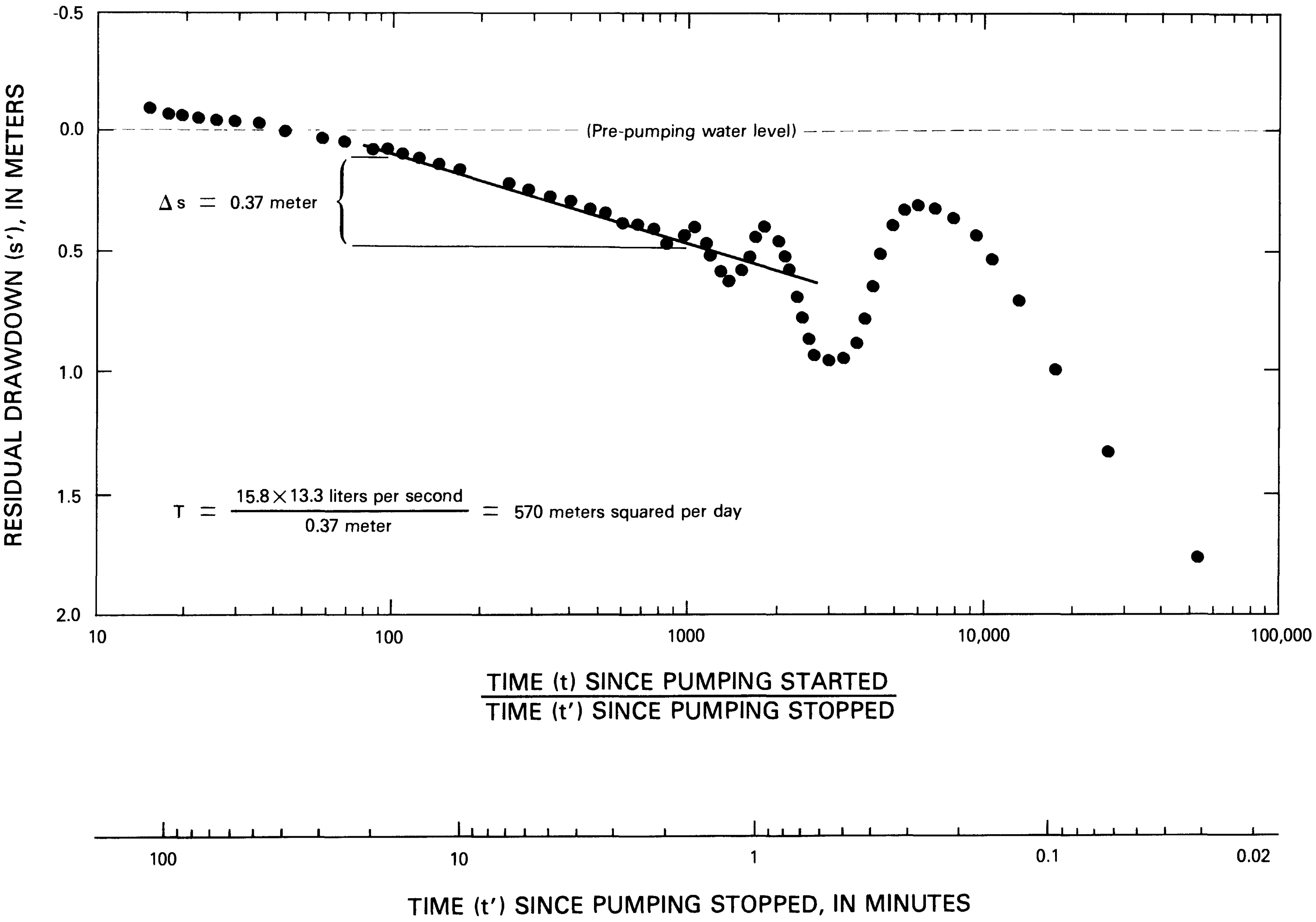


Figure 7.--Residual drawdown in test well USW G-4 after pumping test 2.

For analysis of the drawdown while pumping, drawdown (s), in meters, was plotted against time (t), in minutes, on logrithmic coordinate paper. The proper curve for matching to the data was selected by using the formula:

$$\alpha = \frac{r_w^2}{r_e^2} S$$

where r_w is the diameter of the wellbore in millimeters;

r_e is the diameter of the well in which the water level varies in millimeters; and

S is the estimated storage coefficient.

An estimated storage coefficient of 1×10^{-5} was used to select the type curve designated $\alpha = 10^{-4}$.

The transmissivity was estimated by matching the curve for $\alpha = 10^{-4}$ to the drawdown curve and using the value at $s_w/(Q/4\ T)$ in the modified formula:

$$T = \frac{86.4\ Q}{4\ \pi\ S_w}$$

where T is the transmissivity, in meters squared per day;

86.4 is the factor to convert liters per second to cubic meters per day;

Q is the average discharge, in liters per second; and

s_w is the value for s at the selected match point.

Average hydraulic conductivity, K, was calculated using:

$$K = \frac{T}{b}$$

where b is thickness of the aquifer, in meters.

Recovery after pumping was analyzed by plotting s'; residual drawdown against the log of t/t', where t is the time since pumping started and t' is the time since pumping stopped. The formula becomes

$$T = \frac{15.8\ Q}{\Delta s'}$$

where Q is the average discharge rate, in liters per second for the pumping period; and

$\Delta s'$ is the change in residual drawdown over one log cycle. Results were affected by water-level trends after about 30 minutes.

Time since pumping stopped t' is shown along the top of the graph of each recovery plot.

After each of the tests when the pump was shut off, the water level oscillated on a frequency of about one-half minute per cycle. These fluctuations appear to be underdamped responses to sudden changes in water level as analyzed by Van Der Camp (1976). The period of the fluctuations is related to the effective length of the water column and the damping of the fluctuations is related to the transmissivity and storage coefficient of the formation. The relatively long period of the fluctuations indicates that the effective length of the water column is relatively long and the damping of the oscillations appears to be about as expected from the transmissivity calculated from pumping tests and the inferred relatively small storage coefficient. Information presented by Van Der Camp (1976) indicates that analysis of these fluctuations would give an estimate of transmissivity somewhat larger than that estimated from pumping tests but still within the same order of magnitude. The short period of measurement for such analyses would mean that the part of the aquifer sampled is very close to the wellbore. Other sudden changes in water level produced similar but less noticeable oscillations. Most of the departure from the type curve during the first minute of both pumping tests may be related to such oscillations and for those slug tests that were run on very transmissive zones, oscillations with an amplitude of a few centimeters could be detected about 4 minutes after the shut-in value was opened.

The second pumping test, which began on January 4, 1983, yielded less water than the first test, because a drain-back valve missing from the pump caused some of the water to recirculate within the well before being pumped out. The missing valve also allowed water to drain from the pump column when the pump was shut off. The effect of this drainage appears to be limited to a slight change in damping of the sinusoidal wave pattern of the variation in water level in the first few minutes after pumping stopped.

The rounded average of these four tests, 600 m^2/d, was used to estimate permeabilities of the parts of the productive zone defined by the flow survey. Drawdown in test well USW G-4 during the first 100 minutes of pumping and recovery during the first 30 minutes after the pump was shut off probably was affected by crowding of flow lines near the well, and, therefore, transmissivity calculated using such early data is likely to be too small. However, the 600 m^2/d probably is within the right order of magnitude for the aquifer within 100 m of test well USW G-4.

Packer-Injection Tests

Packer-injection slug tests using inflatable straddle packers were attempted on 12 separate zones, representing all of the part of the borehole below the cased interval (figs. 8 through 16, and table 3). Only those tests that could be used to estimate transmissivity are illustrated. The data for all the tests attempted is shown in Bentley (1984). One of the tests failed to yield any usable data, apparently because the packer did not seat properly; three of the tests near the bottom of the hole yielded only water-level data. The formation below 850 m is so permeable, that natural hydraulic responses occurred more quickly than restrictions of the equipment would allow the water level to respond.

The leveling of time-drawdown curves late in the tests and in the case of pumping test 2, the actual recovery during pumping, probably are caused by a combination of two effects. Some undefined change in the flow system near test well USW G-4 took place at about 200 minutes after the start of pumping and water-level changes independent of pumping combined to cause a variable drawdown pattern near the end of the pumping tests. The change in the flow system could be caused by the presence of a very permeable zone near the borehole or it could be caused by a double porosity effect, possibly from production of water from the fine-grained matrix of the welded tuff, but more likely from fractures intersected by the fractures that intersected the borehole. Another possibility is that the leveling of the drawdown curves indicates the end of the effect of crowding of flow lines near the borehole. Thus, the actual transmissivity might be somewhat larger than the estimates based on the pumping tests.

Equipment for running the packer-injection tests consisted of 2 sets of double packers separated by 24 or 46 m of straddle with a valve system. Inflation of packers, the interval tested, and opening or closing of a shut-in valve were controlled by movement of the 63-mm inside diameter tubing used to lower the packers into place. Instrumentation provided by the contractor conducting the tests consisted of three mechanical pressure recorders and three magnetic-tape pressure recorders. The recorders were placed, one of each type, above, within and below the packed-off interval. Data from recorders were used to determine whether the packers were properly seated during the tests, but also could be used to determine aquifer parameters if the time required for the water level to return to static water level was more than 15 minutes after injection time. The pressure sensor used to determine water levels during the tests was a transducer suspended by a cable at about 550 m inside the 63-mm-diameter tubing. The cable was connected to a recorder at the land surface that printed the output of the transducer at selected time intervals.

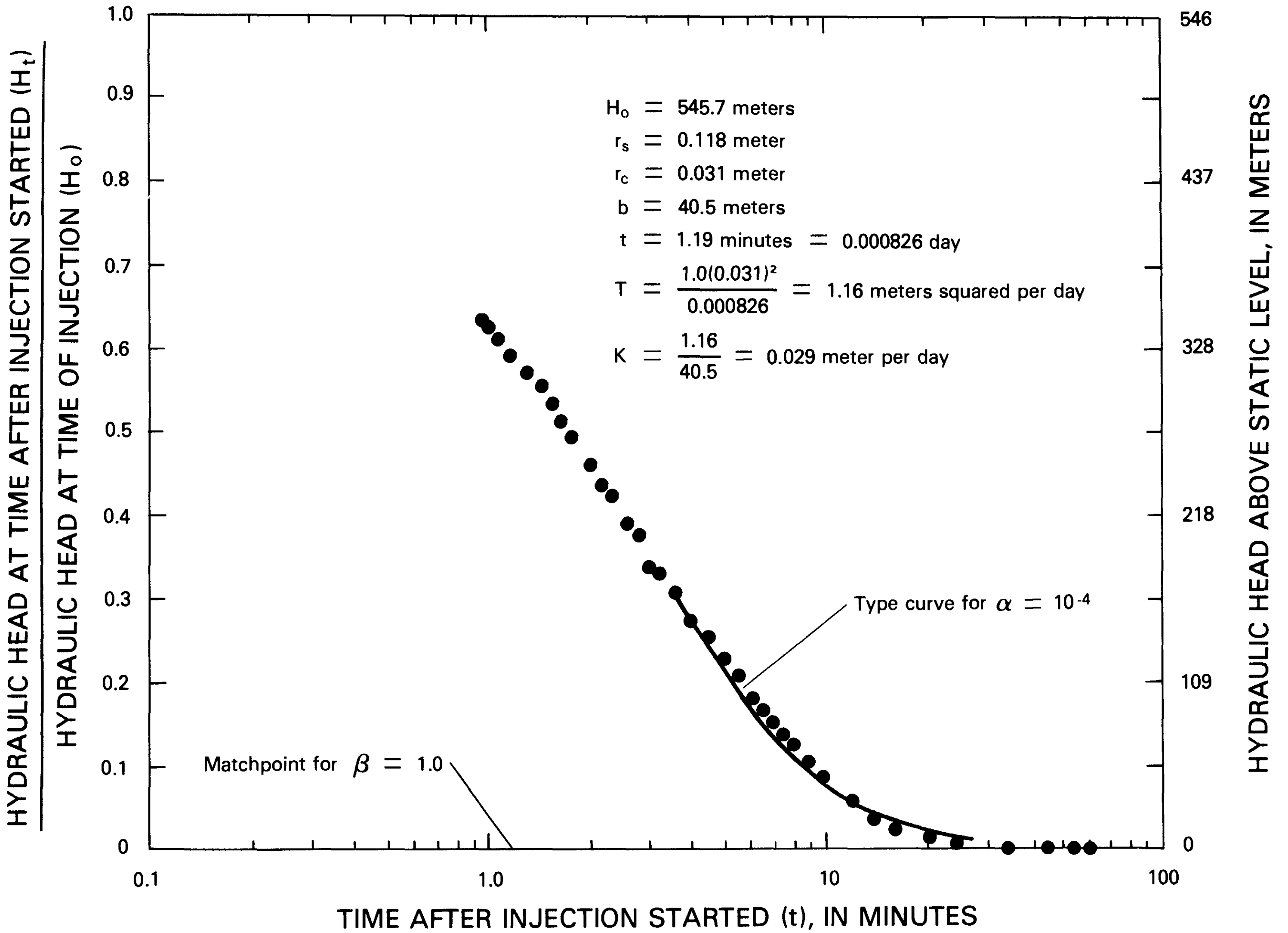


Figure 8.--Packer-injection test in test well USW G-4 for interval 615 to 655 meters.

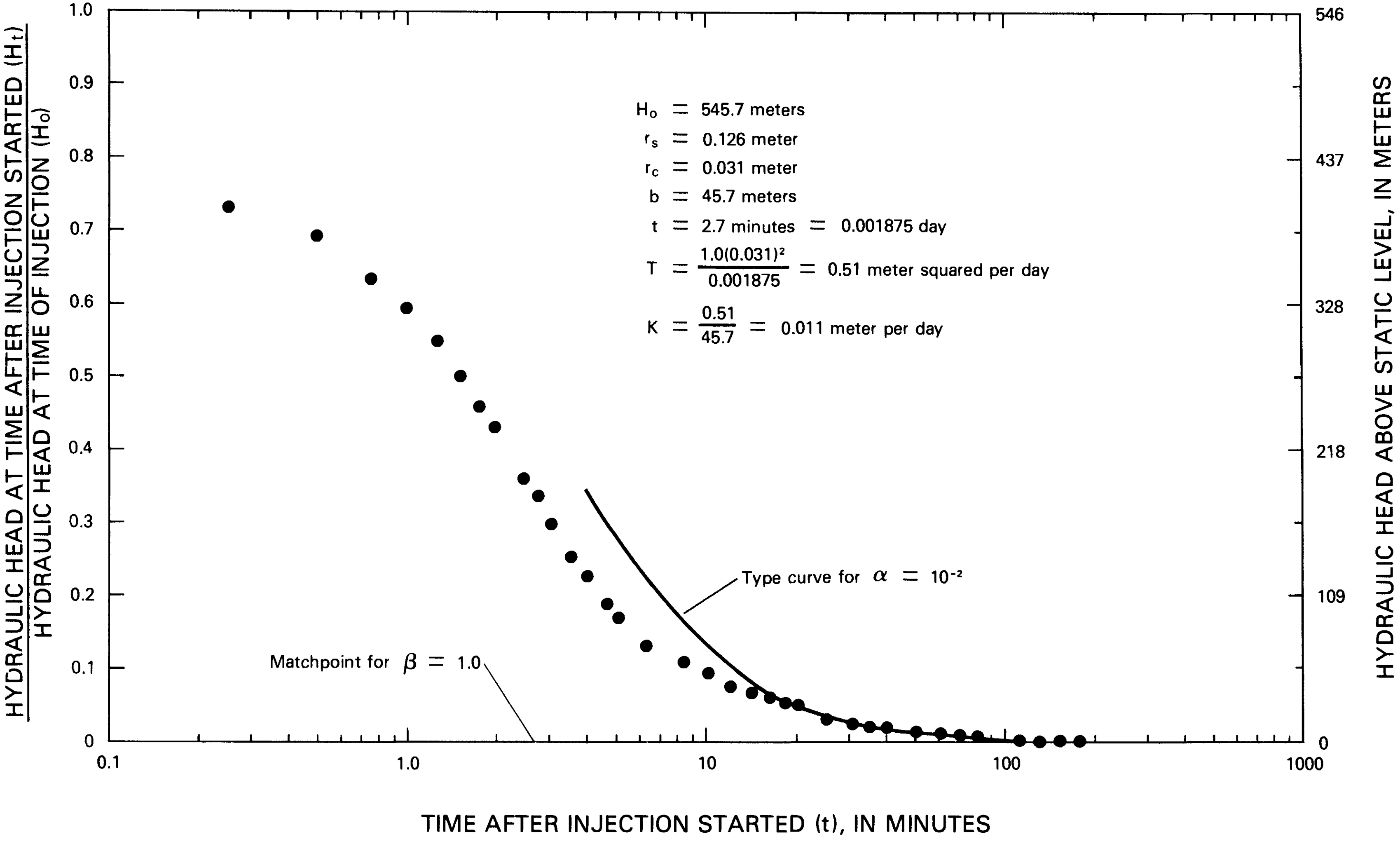


Figure 9.--Packer-injection test in test well USW G-4 for interval 655 to 701 meters.

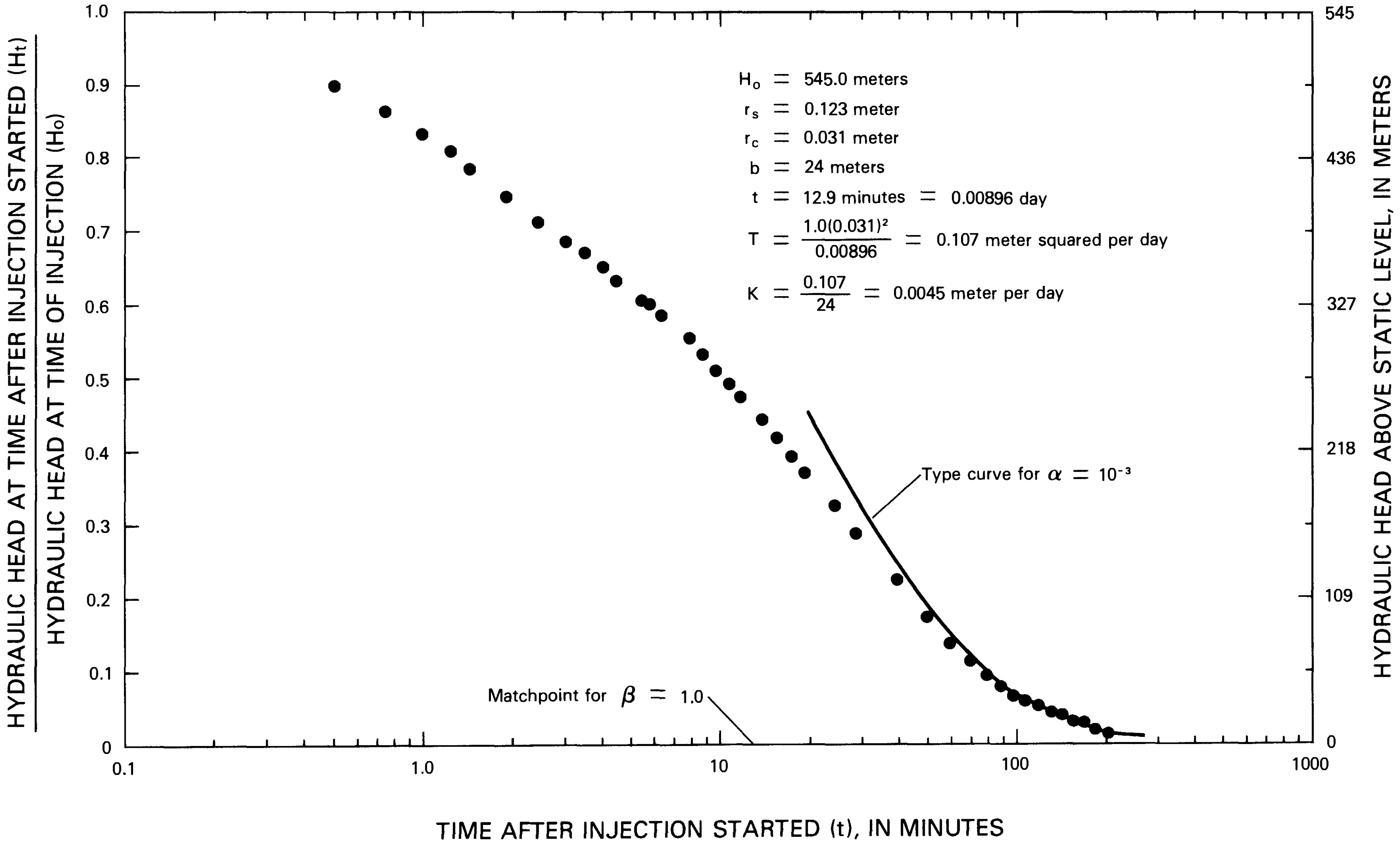


Figure 10.--Packer-injection test in test well USW G-4 for interval 698 to 722 meters.

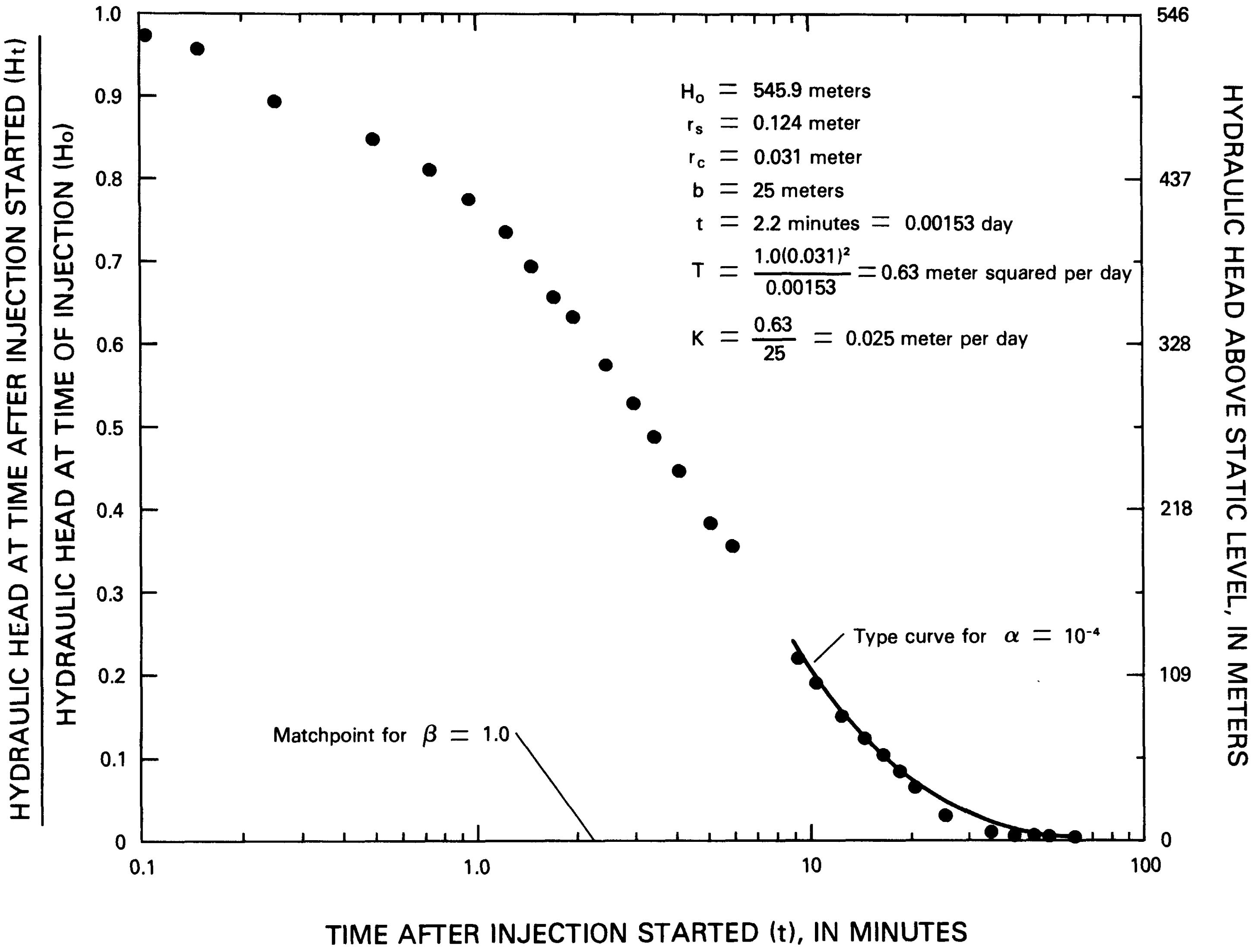


Figure 11.--Packer-injection test in test well USW G-4 for interval 722 to 747 meters.

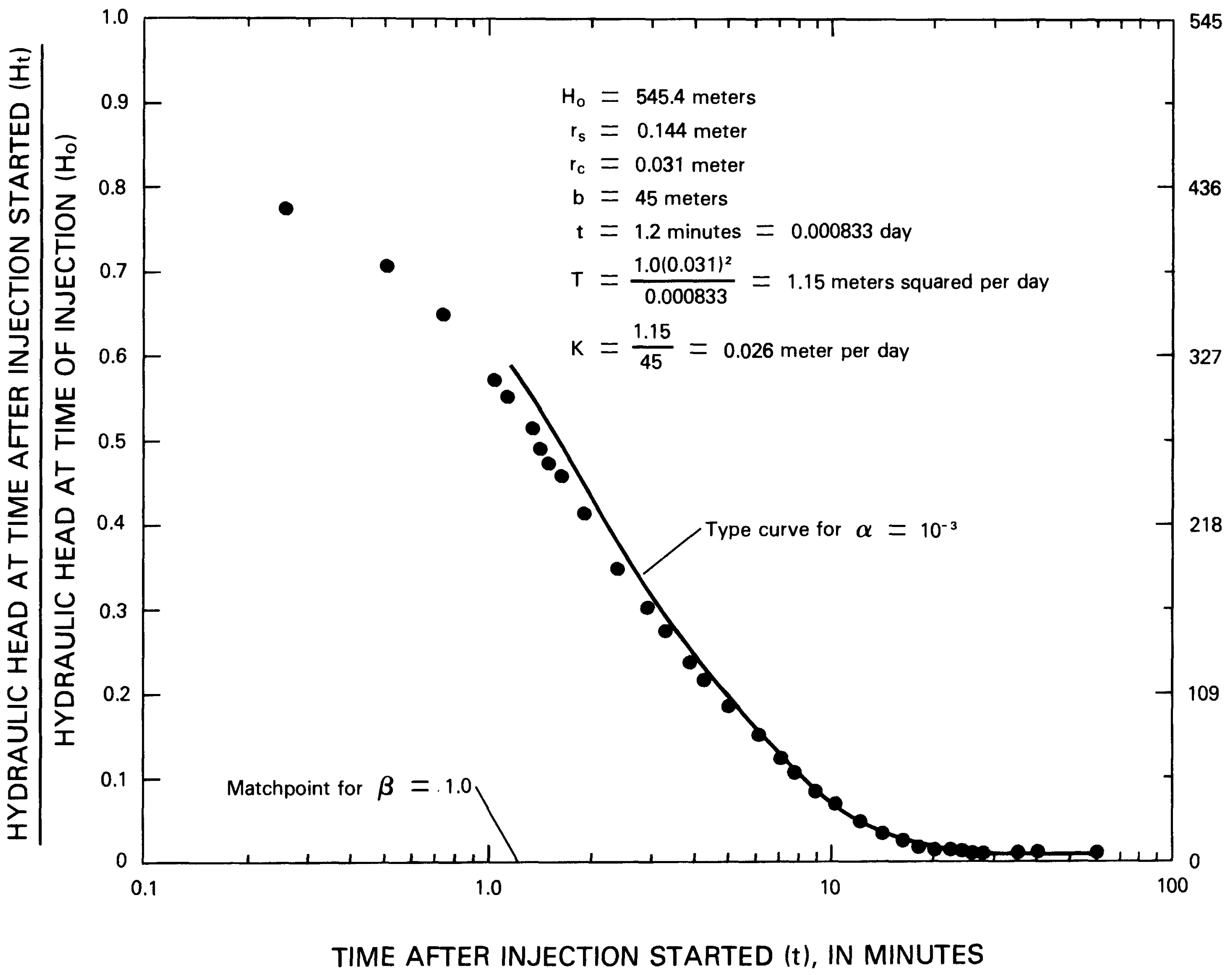


Figure 12.--Packer-injection test in test well USW G-4 for interval 747 to 792 meters.

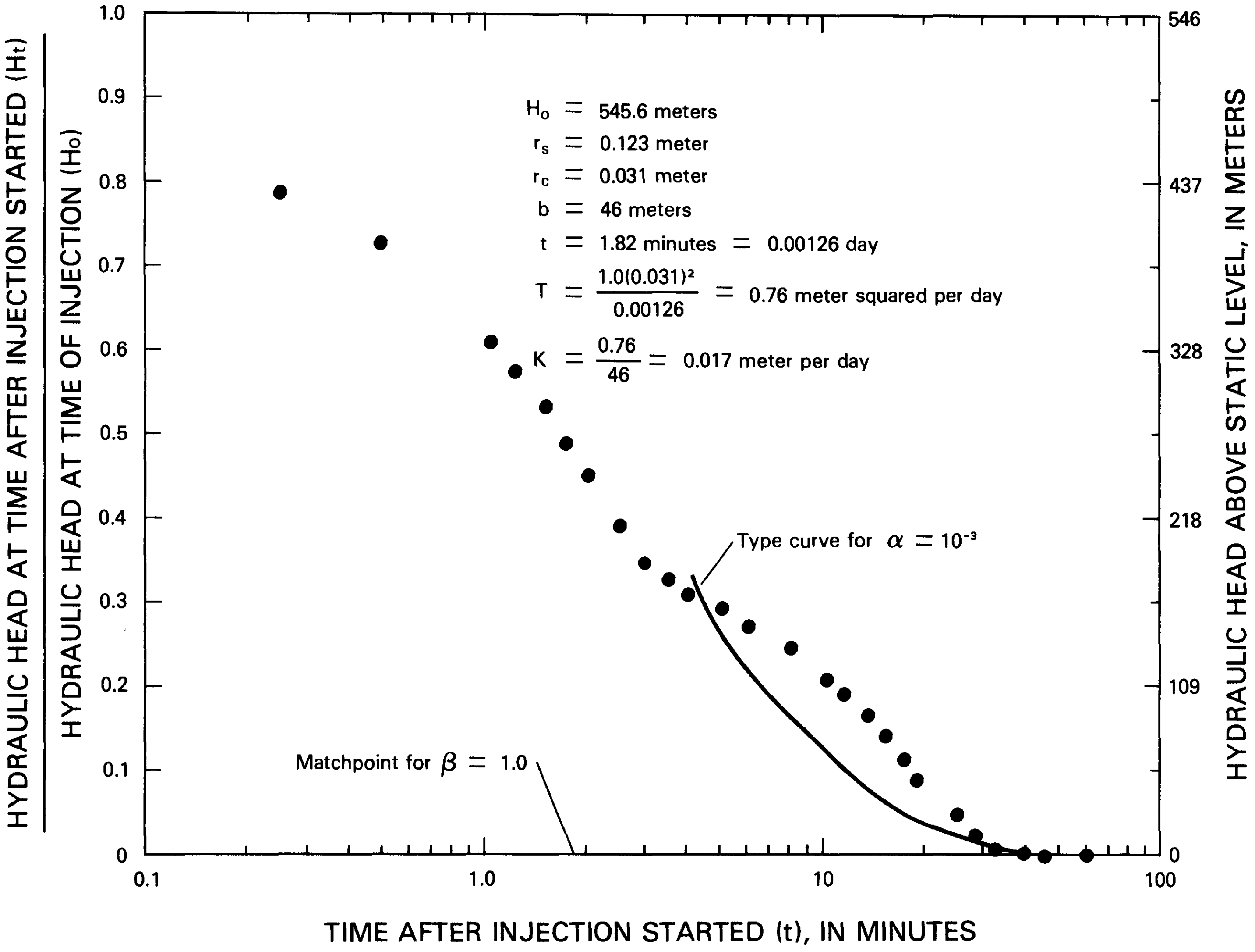


Figure 13.--Packer-injection test in test well USW G-4 for interval 792 to 838 meters.

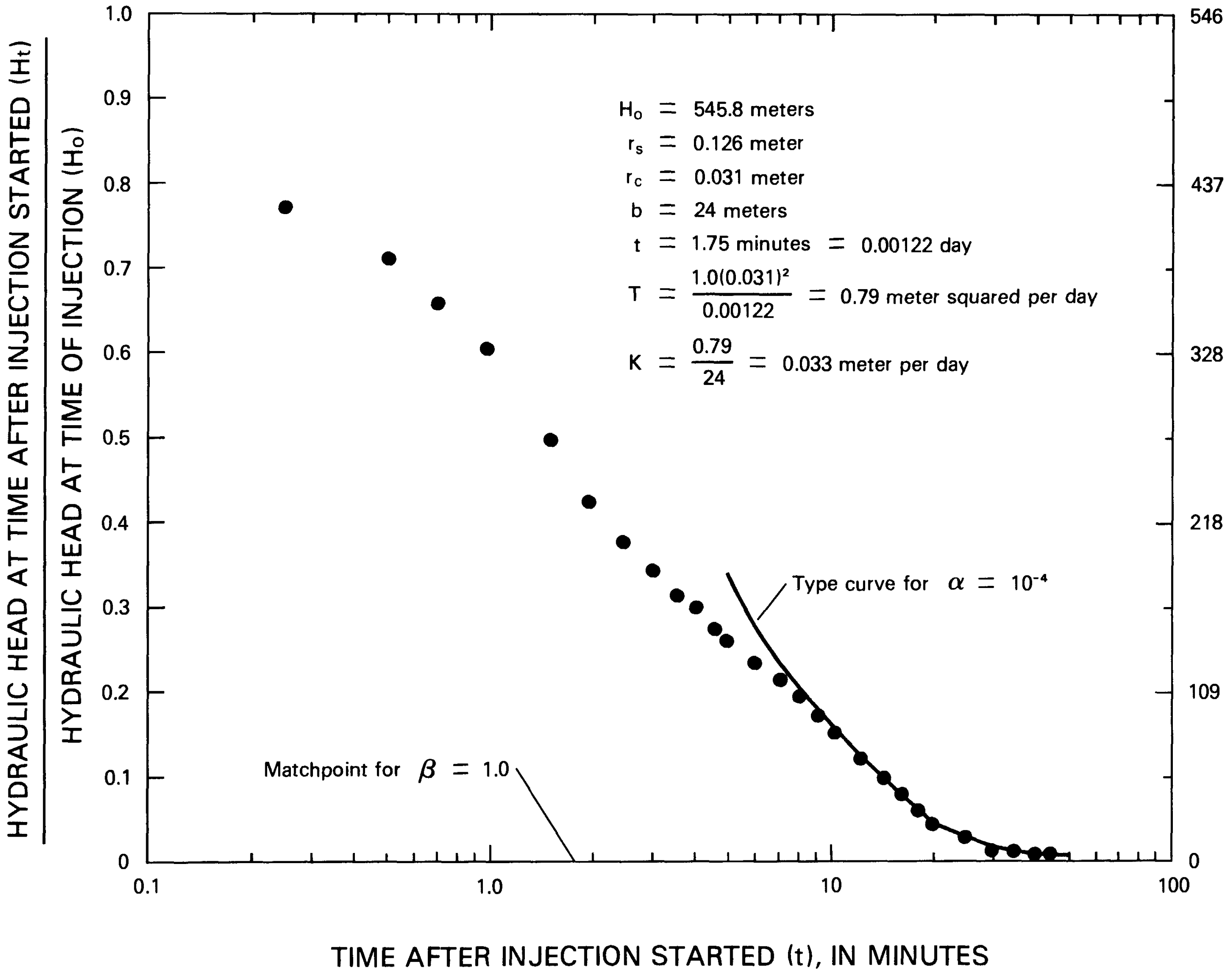


Figure 14.--Packer-injection test in test well USW G-4 for interval 802 to 826 meters.

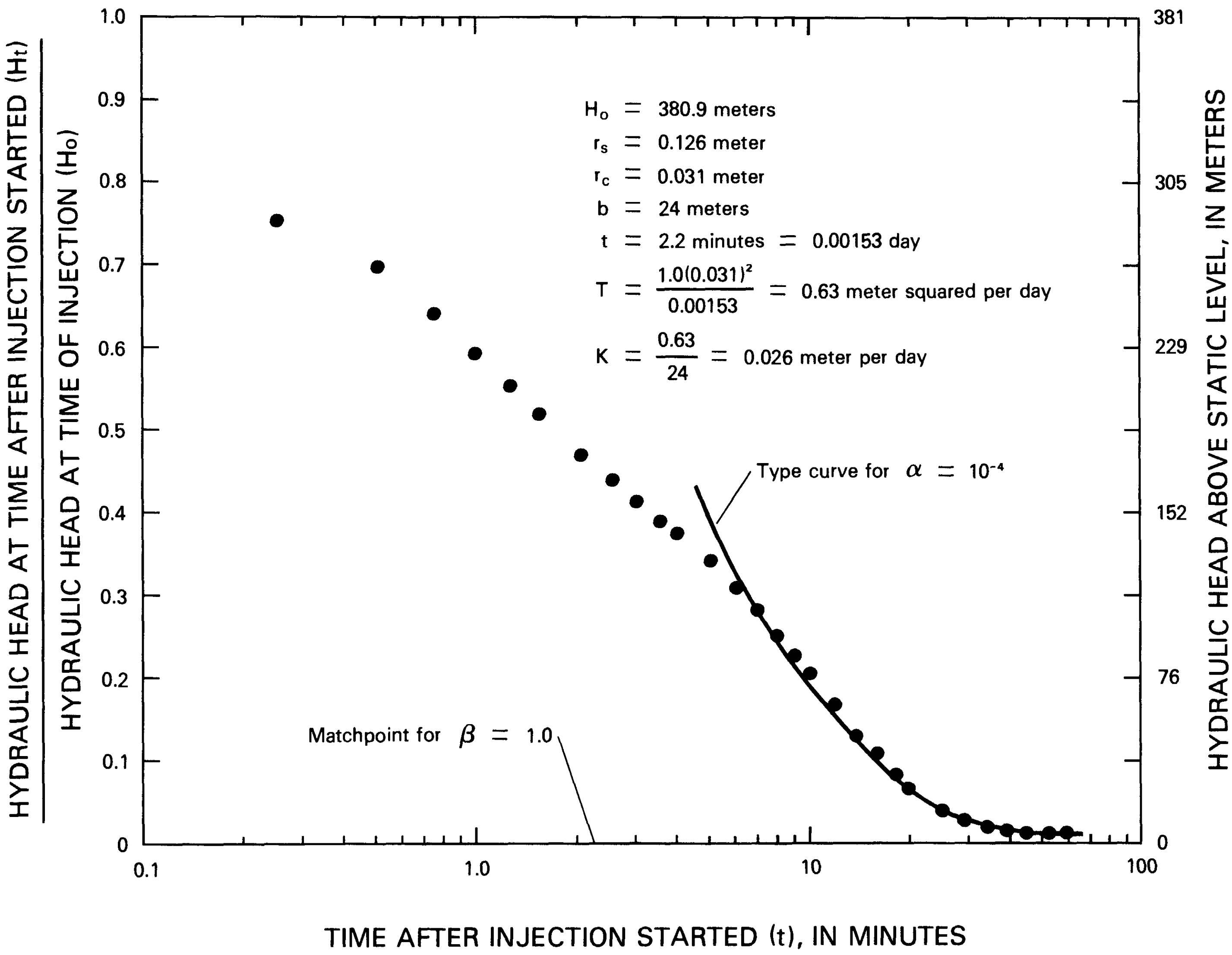


Figure 15.--Packer-injection test in test well USW G-4 for retest of interval 802 to 826 meters.

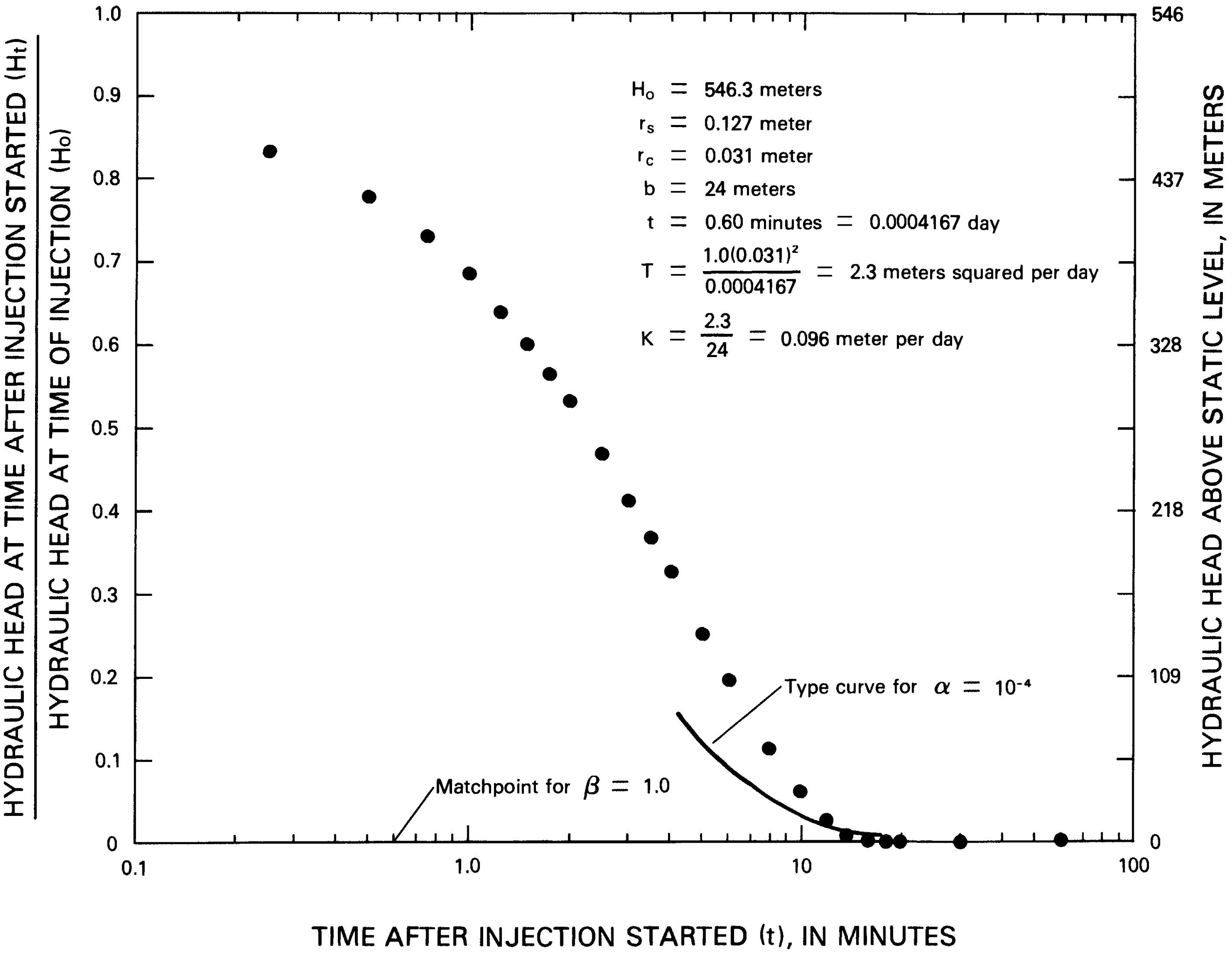


Figure 16.--Packer-injection test in test well USW G-4 for interval 826 to 850 meters.

Table 3.--*Summary of packer-injection tests in test well USW G-4*
[All tests were within the Crater Flat Tuff]

Date	Interval tested (meters)	Geologic unit	Depth to water level (uncorrected) (meters)	Transmissivity (meters squared per day)	Hydraulic conductivity (meters per day)	Test duration (minutes)	Remarks
01/07/83	616-655	Prow Pass Member	541.50	1.16	0.029	60	
01/07/83	655-701	Bedded tuff, Bullfrog Member	541.43	0.51	0.011	140	
01/10/83	698-722	Bullfrog Member	541.6?	0.107	0.0045	200	Water level declining at end of test
01/11/83	722-747	Bullfrog Member	541.78	0.63	0.025	71	
01/08/83	747-792	Bullfrog Member Bedded tuff	541.57	1.15	0.026	60	
01/09/83	792-838	Bullfrog Member Bedded tuff	541.56	0.76	0.017	60	
01/11/83	802-826 (retest)	Bullfrog Member Bedded tuff	541.78	0.63	0.026	60	Overlapped by previous test
01/09/83	826-850	Bullfrog Member Bedded tuff Tram Member	531.60	2.3	0.096	60	Total transmissivity above 850 meters, about 7 meters squared per day
01/10/83	850-875	Tram Member	541.76	--	--	30	Substantial transmissivity
01/11/83	875-899	Tram Member	541.84	--	--	15	
01/10/83	902-915	Tram Member	541.72	--	--	15	

For testing, the packer assembly was lowered into place, straddling the desired interval. The packers were inflated by filling the tubing with water. The shut-in valve was then closed and the tubing below the shut-in valve opened to the interval between the packers. A pressure transducer was lowered inside the open tubing to below the static water level, calibrating the transducer by checking the output at selected depths below the water surface. The shut-in valve was opened by raising the tubing about 0.5 m and the pressure change with time was recorded as the water level declined. The water level was allowed to stablize at the end of each test unless the rate of decline was very slow. At the end of the test, the packers were deflated and moved to the next test interval, or if the 48-hour clocks on the downhole recorders were nearly run out, the packer assembly was pulled to the surface and the recorders serviced before the next series of tests. The lowermost interval from 902 to 915 m was tested by opening the system to below the bottom packer assembly rather than to between the packers.

Packer-injection tests were interpreted using the method of Cooper and others (1967), and Papadopulos and others (1973). As with pumping tests, the early data probably are not indicative of formation conditions. In those tests where transmissivity is substantial, the water level returned to the static water level in about 4 minutes. From this response it was assumed that the first 4 minutes of all the tests were affected by the equipment used, and that, ideally, the later in time the part of the curve interpreted for aquifer parameters, the more likely the interpretation is valid.

The ratio of the hydraulic head to the hydraulic head at time 0, H_t/H_o, was plotted against time after injection started, t, on semilogarithmic coordinate paper. H_t/H_o was plotted on the arithmetic scale; time was plotted on the logarithmic scale. An extended family of type curves based on Papadopulos and others (1973) was used to determine a match point at $\beta=1.0$. The time at the match point was converted to days, and used to determine transmissivity in the equation:

$$T = \frac{1.0 r_c^2}{t} ,$$

where T is transmissivity, in meters squared per day;

r_c is radius of the tubing in meters;

t is the match-point, in days.

Hydraulic conductivity can be calculated from the equation:

$$K = \frac{T}{b}$$

where b is the thickness of the interval tested, in meters.

The storage coefficients can be determined using equation:

$$S = \alpha \frac{r_c^2}{r_s^2},$$

where α is a value determined by the matching curve selected; and
r_s is the radius of the open hole, in meters.

Values that could be determined for storage coefficient are not reliable, because the part of the curves used in the analysis could be matched to curves for several α values. An estimated storage coefficient was used to determine which type curve to match as suggested by Papadopulos and others (1973).

A summary of all the packer-injection tests is given in table 3. The sum of the transmissivities of all the parts of the section above the yielding zone defined by the flow survey is less than 2 percent of the transmissivity determined during the pumping tests. Some relationships between geologic characteristics and hydrologic characteristics can be determined by comparing the results of core analysis and selected geophysical logs with permeabilities determined from hydrologic tests.

The interval between the water level and bottom of the surface casing at 615 m could not be tested using packer-injection tests, because the interval could not be isolated from the unsaturated zone. The flow survey and the temperature survey during pumping did not indicate that an appreciable quantity of water was being produced through the perforations in the casing.

The interval from 698 to 722 m has the least permeability of any interval tested (fig. 12). Comparison with a fracture log (fig. 17) shows that this interval probably is the least fractured interval tested.

All packer-injection tests were conducted by using hydraulic heads at the start of the tests that were high enough to cause fracturing, or momentarily to expand existing fractures near the borehole (Ellis and Swolfs, 1983). This effect is especially evident from the shape of the test curve for the intervals 792 to 738 m (fig. 14), and 802 to 826 m (fig. 15). The interval 802 to 826 m was retested (fig. 16) at a lower hydraulic head, with proportionately less apparent expansion of fractures near the borehole. Alternative explanations for the unusual shape of the curves, such as the change in fracture aperature as in Wang and others (1977) were considered. Comparison of figures 14 and 15 seems to indicate that the changes in slope were pressure related rather than time related. The enlargement of fractures near the borehole by pressure is believed to be the cause of the recovery pattern. The fractures probably closed back to their normal opening as the pressure dissipated.

All packer-injection tests were interpreted by matching the type curves to the part of the test where the water level had nearly reached the static water level. The first 4 minutes of most of the tests probably are the critical flow period (Earlougher, 1977); the shape of the test curves immediately after the first 4 minutes was affected by expansion, or creation of fractures from overpressuring. Permeability under near-static water-level conditions is more important for definition of the hydrologic system than permeability created by hydrofracturing. The valid part of a test probably could be extended by lowering the hydraulic head at the start of the test, thereby decreasing the part of the test during which flow rates are controlled by turbulent flow through the testing tools. A starting hydraulic-head differential of less than 100 m probably would have resulted in a better match with type curves; however, the end point of all but the shortest tests would not have changed appreciably.

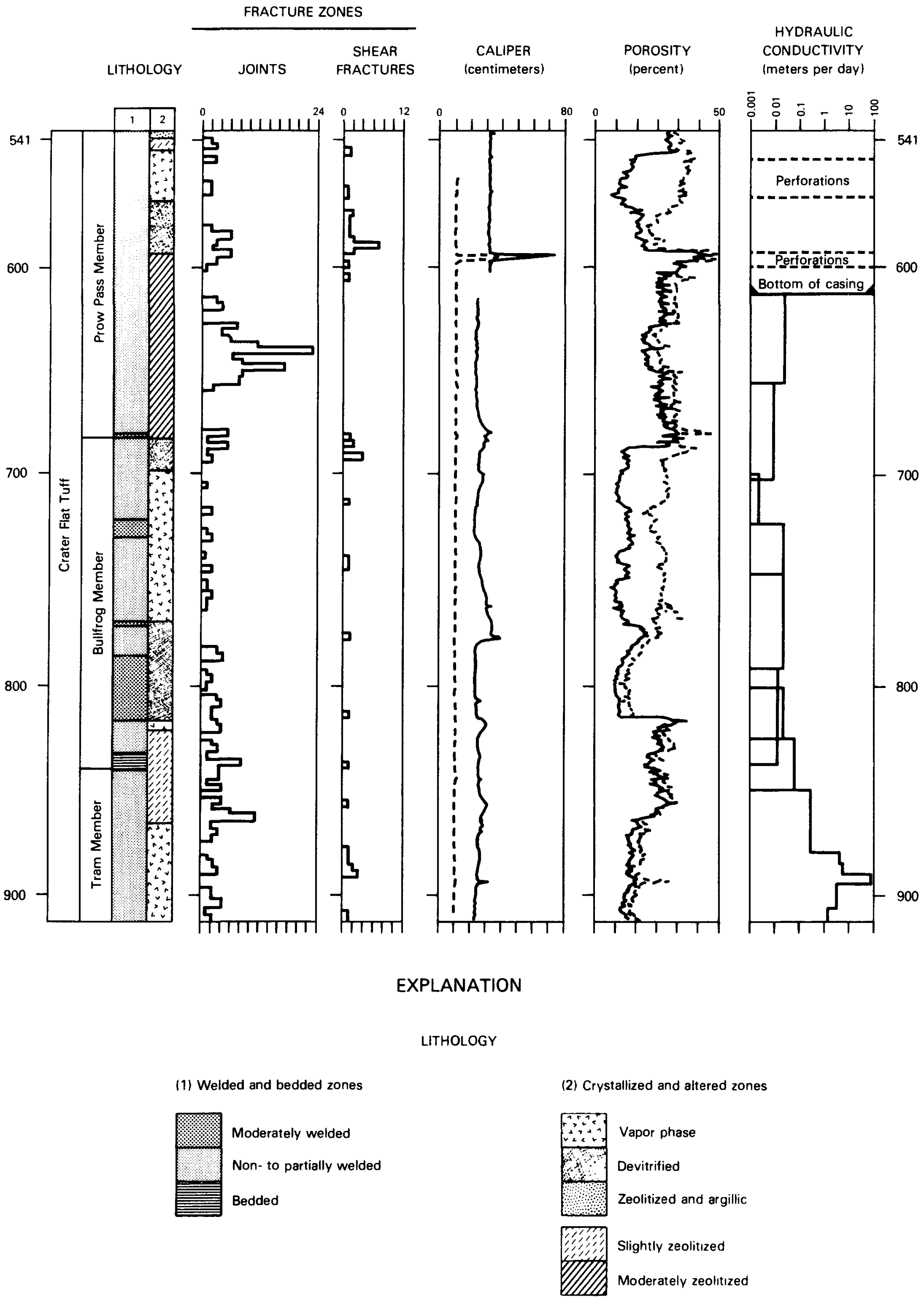
Three tests were made of parts of the interval from 792 to 850 m (table 3 and fig. 17). Results are interpreted as indicating a hydraulic conductivity ranging from about 0.02 m/d at the top of the interval, to about 0.1 m/d at the bottom of the interval.

The most permeable zone, centered around 893 m, probably is a fractured zone, possibly along a fault. Prominent shear fractures near this depth (table 1) indicate possible faulting. Other intervals in the hole with prominent shear fractures have very little permeability.

GROUND-WATER QUALITY

A water sample was collected on December 9, 1982, for analysis by the U.S. Geological Survey. Water temperature and composition, as indicated by analysis of samples for the concentration of lithium, had been stable for several days. About 5 million L of water had been pumped before sampling to ensure that most of the drilling fluid, to which 20 mg/L lithium had been added as a tracer, was flushed from the producing zones.

The analysis (table 4) indicates a water similar to others in the Yucca Mountain area, a soft, sodium bicarbonate type (Benson and others, 1983). Hydrogen and oxygen-isotope analysis indicate that the water is recharged by direct infiltration of precipitation, rather than from surface water that had been concentrated by evaporation (Claassen, 1983). Carbon-14 dating indicated an apparent age of 12,160 years before present. No unusual characteristics are indicated by the analysis of water from test well USW G-4.



NOTE:

Joints represent number of measured joint planes per 3-meter interval

Shear fractures represent number of fracture planes per 3-meter interval along which differential movement was recognized

Figure 17.--Comparison of results of coring, selected geophysical logs, and results of aquifer tests in test well USW G-4.

Table 4.--*Results of chemical analysis of a water sample from test well USW G-4*

[Analysis by U.S. Geological Survey, Denver, Colorado; all dissolved constituents are in milligrams per liter unless otherwise indicated. Date of collection, 12-09-82]

Constituent or property	Concentration or value
Bicarbonate (HCO_3) (laboratory)	143
Bicarbonate (HCO_3) (onsite)	139
Bromide (Br)	0.04
Calcium (Ca)	13
Chloride (Cl)	5.9
Fluoride (F)	2.5
Lithium (Li), in micrograms per liter	67
Magnesium (Mg)	0.20
Potassium (K)	2.1
Silica (SiO_2)	45
Sodium (Na)	57
Strontium (Sr), in micrograms per liter	17
Sulfate (SO_4)	19
Dissolved solids (residue on evaporation)	219
Hardness	33
Temperature, in degrees Celsius	35.6
Specific conductance, onsite, in microsiemens per centimeter at 25° Celsius[1]	312
Specific conductance, laboratory, in microsiemens per centimeter at 25° Celsius[1]	307
pH, onsite, in standard units	7.7
pH, laboratory, in standard units	7.5
Sodium-absorption ratio	4.3
Oxygen-18/oxygen-16 ($\delta^{18}O$)[2]	13.8
Deuterium/hydrogen ($\delta^{2}H$)[3]	103
Carbon-13/carbon-12 ($\delta^{13}C$)[4]	9
Carbon-14, percent of modern standard	22
Apparent age (carbon-14 dating)	12,160 years

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

[2] Deviation of oxygen-18/oxygen-16 ratio of sample from standard mean ocean water (SMOW) relative to SMOW, 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 carbon-13/carbon-12 ratio of sample from PeeDee Belemnite standard (PDB) relative to PDB, in parts per thousand.

SUMMARY AND CONCLUSIONS

Results of hydraulic tests, hydrologic monitoring, and geophysical logs indicated that virtually all permeability measured during tests was from fractures. Transmissivity of the part of the saturated zone penetrated by this well is about 600 m^2/d. Most of the permeability in this well is below the depth of 850 m. About 75 percent of the water produced during the pumping tests was from the interval between 890 and 900 m in the Tram Member of the Miocene Crater Flat Tuff. No vertical hycraulic-head gradient was detected in test well USW G-4. Static water level at the end of testing was 540.3 m below the surface, 729.3 m above sea level.

Water sampled from USW G-4 was sodium bicarbonate type, typical of the Yucca Mountain area. Radiocarbon dating of the water gave an apparent age of 12,160 years before present. Isotope analysis indicated that the water was from precipitation.

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