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GEOHYDROLOGY OF TEST WELL USW H-1, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 8~~3~~4-4032

Prepared in cooperation with the

U.S. DEPARTMENT OF ENERGY

United States Department of the Interior

GEOLOGICAL SURVEY
BOX 25046 M.S. 416
DENVER FEDERAL CENTER
DENVER, COLORADO 80225

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November 14, 1984

Memorandum

To: Distribution

From: Chief, Nuclear Hydrology Program

Subject: PUBLICATIONS--Correction to report number

Please change the report number on the cover and title pages of the following report; it was shown as Water-Resources Investigations Report 83-4032, and should have been shown as 84-4032. →1483

Geohydrology of test well USW H-1, Yucca Mountain, Nye County, Nevada, by F. E. Rush, William Thordarson, and D. G. Pyles.

The report was distributed several months ago.

William E. Wilson

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Denver, Colorado
1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Chief, Nuclear Hydrology Program
Water Resources Division, Central Region
U.S. Geological Survey
Box 25046, Mail Stop 416
Denver Federal Center
Lakewood, Colorado 80225

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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
millimeter (mm)	3.937×10^{-2}	inch
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
millimeter per year (mm/a)	3.281×10^{-3}	feet per year
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	1.076×10^{1}	foot squared per day
milligram per liter (mg/L)	*1	part per million
microgram per liter (µg/L)	*1	part per billion
liter per second (L/s)	1.585×10^{1}	gallon per minute
liter (L)	2.642×10^{-1}	gallon
degree Celsius per kilometer (°C/km)	2.900	degree Fahrenheit per mile
gram per cubic centimeter (gm/cm^3)		
microsiemen		

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

National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level, referred to as sea level in this report.

SYMBOLS LIST

Symbol	Description	Dimension
b	Saturated thickness	Meters.
H	Hydraulic head at time t after injection or removal of "slug"	Meters.
H_0	Hydraulic head inside well at instant of removal of "slug"	Meters.
K	T/b; hydraulic conductivity	Meters per day.
Q	Flow rate	Liters per second.
r_c	Radius of tubing in interval within which water level fluctuates	Centimeters.
r_s	Radius of open hole	Centimeters.
S	Storage coefficient	Dimensionless.
s	Drawdown	Meters.
s'	Residual drawdown	Meters.
T	Transmissivity	Meters squared per day.
t	Time after pumping started	Minutes, seconds.
t'	Time after pumping stopped	Minutes.
t/t'	Ratio of the time after pumping started to the time after pumping stopped	Dimensionless.
$W(\mu)$	$4\pi Ts/Q$; W (well) function of μ	Dimensionless.
μ	$r^2S/4Tt$	Dimensionless.
Δs	Drawdown for one log cycle	Meters.
Ws'	Residual drawdown for one log cycle	Meters.
α	$r_s^2 S/r_c^2$	Dimensionless.

GEOHYDROLOGY OF TEST WELL USW H-1, YUCCA MOUNTAIN, NYE COUNTY, NEVADA

By F. E. Rush, William Thordarson, and D. G. Pyles

ABSTRACT

This report contains the results of hydraulic testing, hydrologic monitoring, and geophysical logging of test well USW H-1, one of several wells drilled in the southwestern part of the Nevada Test Site in cooperation with the U.S. Department of Energy for investigations related to the isolation of high-level radioactive wastes. All rocks penetrated by the well to a total depth of 1,829 meters were of volcanic origin and of Tertiary age.

Hydraulic head in the zone 688 to 741 meters below land surface was 730 meters above sea level and at a depth of 572 meters below land surface. Deeper zones had hydraulic heads of 781 meters above sea level or higher, indicating an upward component of ground-water flow at the site.

The most transmissive zone, with an apparent transmissivity of about 150 meters squared per day, is in the Prow Pass Member of the Crater Flat Tuff in the depth range from 572 to 688 meters below land surface. The remainder of the penetrated rocks in the saturated zone, 688 to 1,829 meters, has an apparent transmissivity of about 1 meter squared per day. The most transmissive part of the lower depth range is in the Bullfrog Member of the Crater Flat Tuff in the depth interval from 736 to 741 meters. The apparent hydraulic conductivity of the rocks in this lower depth interval from 688 to 1,829 meters commonly ranges between 10^{-4} and 10^{-7} meter per day.

Water chemistry is typical of tuffaceous rocks of southern Nevada. The water is a sodium bicarbonate type and has an apparent age of 12,000 to 13,000 years before present, as determined by carbon-14 dating.

INTRODUCTION

The U.S. Geological Survey has been conducting investigations at Yucca Mountain, Nevada, to evaluate the hydrologic and geologic suitability of this site for storing high-level nuclear waste in an underground mined repository. These investigations are part of the Nevada Nuclear Waste Storage Investigations conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802. Test drilling has been a principal method of investigation. This report presents hydrologic information on test well USW H-1, one of several exploratory wells drilled into tuff in or near the southwestern part of the Nevada Test Site.

Purpose and Scope

The primary purpose of this study is to define hydrologic characteristics of tuff in the southwestern part of the Nevada Test Site that may be useful in determining the acceptability of tuffs for storing high-level nuclear wastes. This report presents detailed hydrological data, supporting geological and geophysical information, and hydrological interpretations for the rocks penetrated in drilling the well, one of a series of test wells designed to obtain data principally for the saturated zone.

Location

The well is approximately 140 km northwest of Las Vegas in southern Nevada (fig. 1). The well is in an easterly draining canyon of Yucca Mountain, northwest of Jackass Flats of the Nevada Test Site. The well is approximately 8 km northwest of water-supply well J-13 and is at Nevada State Central Zone Coordinates N 770,254 and E 562,388. Altitude of the land surface at the well site is 1,302.2 m above sea level. A companion exploratory core hole (USW G-1) was drilled 430 m northwest of this well and was completed just before the start of this well.

Drilling Procedures and Well Construction

Drilling of the well started on September 2, 1980; total depth of 1,829 m was reached on November 22, 1980. The rotary-drilling fluid was air foam that consisted of air, detergent, and water obtained from supply well J-13. Drilling was completed without much difficulty; however, circulation was lost between a depth of 86 and 97 m. The well did not deviate more than 3° from the vertical; the bottom of the well is 30 m southwest (S. 68° W.) of the starting point at land surface.

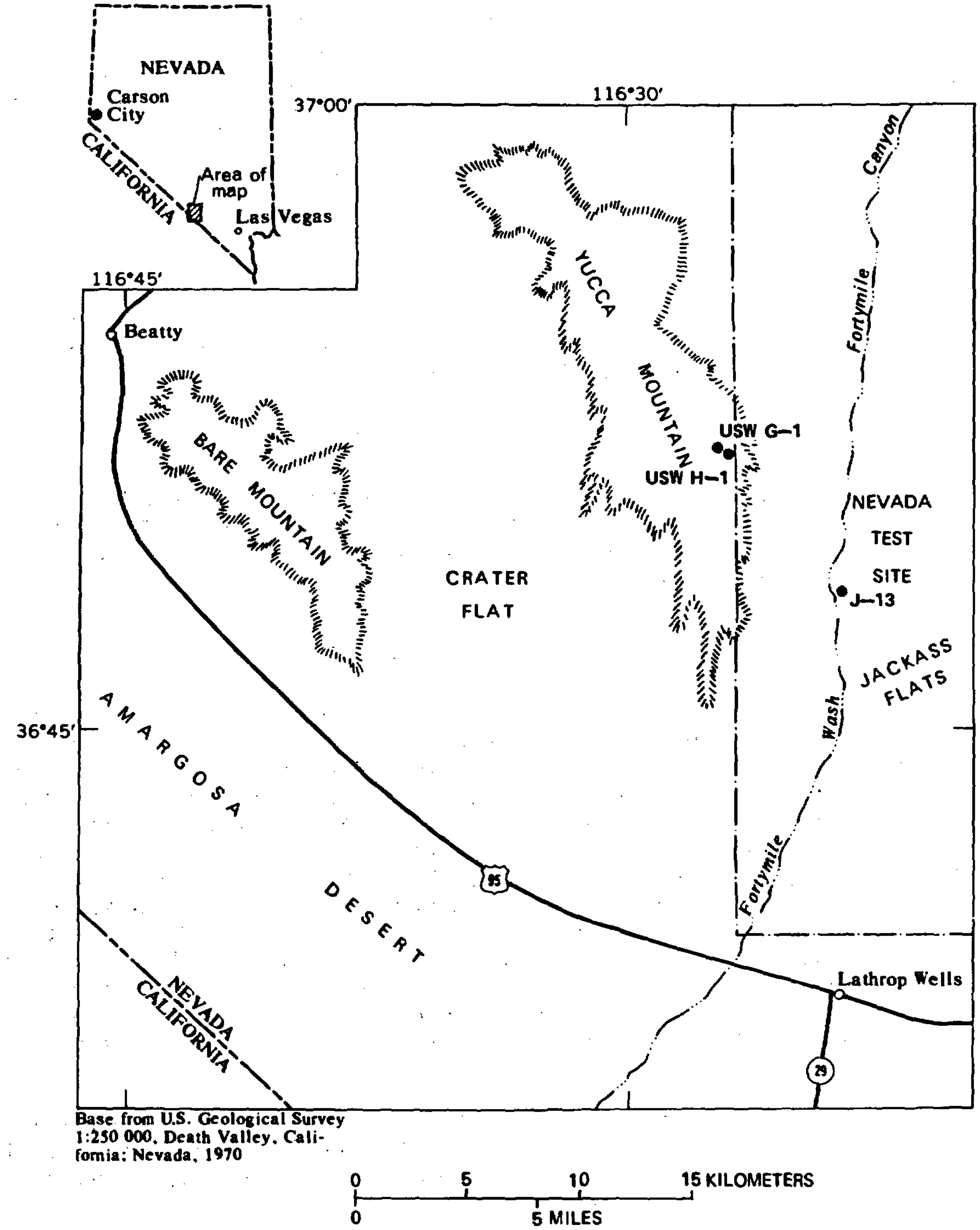

Figure 1.--Location of test well USW H-1 and nearby geographic features in southern Nevada.

Bit and casing data for the well is listed in the following table:

Drilled interval (meters)	Bit diameter (centimeters)	Cased interval (meters)	Casing inside diameter (centimeters)
0-3	122	-----	--
3-12	118	0-12	76
12-102	51	0-102	41
102-117	38	-----	--
117-530	34	-----	--
530-688	31	0-687	23
688-1,829	22	([1])	--

[1]No casing set below a depth of 687 meters.

After the well was drilled to a depth of 688 meters, geophysical logs and hydraulic tests were made. Then the well was cased to a depth of 687 meters and cemented at its base. Following this, the well was drilled to total depth and again logged and tested in the uncased part of the hole.

Geohydrologic Setting

The rocks exposed in the vicinity of the Nevada Test Site consist principally 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). The rocks of Precambrian and Paleozoic age have a total thickness of approximately 11,000 m; they are predominantly limestone and dolomite, but include marble, quartzite, argillite, shale, and conglomerate. The rocks of Paleozoic age have been intruded by granitic stocks of Mesozoic and Tertiary ages and by basalt dikes of Tertiary and Quaternary age. Most of the rocks of Tertiary age consist of welded, vitric, and zeolitic tuffs and rhyolite flows of Miocene and Pliocene age that were extruded from the Timber Mountain-Oasis Valley caldera complex, several kilometers north of the test well. The alluvium consists principally of detritus deposited in the intermontane basins, much of it as fan deposits.

Tuffs underlie Yucca Mountain from land surface to some undetermined depth in excess of the depth of the well. The pre-Tertiary lithology is unknown, but it is most likely either granite or sedimentary rocks of Paleozoic age.

The well is along a wash locally known as Drill Hole Wash, in a canyon on the east side of Yucca Mountain. The drainage is toward Fortymile Wash, which is tributary to the Amargosa Desert. The region is desert; Jackass Flats (fig. 1), at an altitude of about 1,000 m above sea level, receives an average annual precipitation of about 100 mm (Hunt and others, 1966, p. B5-B7). The mountain receives more precipitation because of its higher altitude; winter and spring are the seasons with the greatest precipitation, when frontal storms move across the area from the west. During the summer, widely scattered, intense thundershowers are common in the region.

Infrequent runoff that results from rapid snowmelt or from summer showers flows into 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 infiltrated water is returned to the atmosphere by evaporation and transpiration shortly after runoff ceases, but small quantities percolate to depths beyond which evaporation and transpiration is effective. This water ultimately recharges the ground-water system. A much larger proportion of the water in the ground-water flow system is recharged from precipitation 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). Migration of ground water from the area is probably eastward or southeastward toward the general area of well J-13.

Sass and Lachenbruch (1982, p. 16-25) have concluded that water percolates with a downward component of flow through the unsaturated and saturated zones, based on geothermal data from this well and other wells on Yucca Mountain. They also have concluded from calculated heat flows that the downward volumetric flow rate in the saturated zone may be about 1 to 10 mm/a, and the average water-particle velocity may be about 40 mm/a, assuming a porosity of 20 percent. Using an empirical method, Rush (1970, p. 15) used a precipitation-recharge rate for Yucca Mountain (computed from data for Jackass Flats, table 3 of his report) of less than 5 mm/a. Rates of flow for the horizontal component were not estimated.

LITHOLOGY

The lithology penetrated by the well is mostly ash-flow tuff with various degress of welding (table 1) as determined from bit cuttings and from geophysical-log correlations with well USW G-1. The principal exception in the tuff sequence is the flow breccia from depths of 1,116 to 1,227 m. Other exceptions are the thin, relatively unlithified, bedded or reworked tuffs at the bases of most stratigraphic units. Other thin bedded or reworked tuffs are within two stratigraphic units, the Tram Member of the Crater Flat Tuff and the older tuffs.

Table 1.--*Generalized lithologic log for the well*

[Modified from Richard Spengler, U.S. Geological Survey, written commun, 1981]

Depth (meters)	Thick-ness (meters)	Strati-graphic unit	Lithology
		Paintbrush Tuff	
0-27	27	Tiva Canyon Member	Tuff, ash-flow, brown, partially welded to nonwelded; pumice and glass shards.
27-29	2	-----do----------	Tuff, bedded, light gray to white, vitric.
29-49	20	Yucca Mountain Member	Tuff, ash-flow, light gray and light brown, partially welded to nonwelded,vitric; glass shards.
49-58	9	-----do----------	Tuff, bedded, vitric.
58-85	27	Pah Canyon Member	Tuff, ash-flow, pale-brown, nonwelded, vitric; pumice.
85-454	369	Topopah Spring Member	Tuff, ash-flow, light brown and red, moderately to densely welded and devitrified; lithophysae and devitrified pumice.
454-459	5	-----do----------	Tuff, bedded.
		Rhyolite lavas, and tuffs of Calico Hills (undivided)	
459-549	90	Tuffaceous beds of Calico Hills	Tuff, ash-flow, pink, nonwelded and zeolitized, pumice and volcanic lithic fragments common.
549-566	17	-----do----------	Tuff, bedded, pink, slightly indurated, zeolitized.
		Crater Flat Tuff	
566-701	135	Prow Pass Member	Tuff, ash-flow, various colors, partially welded and devitrified; devitrified pumice throughout, mud-stone lithic fragments common.
701-707	6	-----do----------	Tuff, bedded, zeolitized.
707-820	113	Bullfrog Member	Tuff, ash-flow, various colors, nonwelded to moder-ately welded, devitrified pumice and mudstone and volcanic, lithic fragments common.
820-832	12	-----do----------	Tuff, bedded, zeolitized; pumice and biotite.
832-1,103	271	Tram Member	Tuff, ash-flow, upper part devitrified, lower part zeolitized mostly gray, nonwelded to partially welded, pumice and volcanic, lithic fragments throughout unit.
1,103-1,116	13	-----do----------	Tuff, bedded.
1,116-1,227	111	Lava flow and flow breccia:	Flow breccia; gray, devitrified, autoclastic; abundant hornblende.
1,227-1,235	8	-----do----------	Tuff, bedded, air-fall, moderately indurated, zeolitized.
1,235-1,500	265	Lithic Ridge Tuff	Tuff, ash-flow, gray and green, partially welded, zeolitized; pumice and volcanic, lithic fragments.
1,500-1,509	9	------do---------	Tuff, bedded, pink, zeolitized.
1,509-1,829	320	Older tuffs	Tuff, ash-flow, and bedded, gray, partially to moder-ately welded, devitrified, zeolitized; sparse rhyo-litic and intermediate lithic fragments.

Welding is greatest in the Topopah Spring Member of the Paintbrush Tuff, which is characterized as having mostly moderate to dense welding. The least welded tuffs are the Pah Canyon Member of the Paintbrush Tuff, the tuffaceous beds of Calico Hills of the rhyolite lava, and tuffs of Calico Hills (undivided), and the upper one-half of the Bullfrog Member of the Crater Flat Tuff, which are nonwelded. Most other ash-flow tuffs are intermediate in degree of welding; the bedded tuffs are nonwelded and slightly indurated. Welding and induration characteristics of the penetrated rock are summarized in figure 2.

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

CORE ANALYSES

During the drilling of the well, 100-mm diameter vertical cores were cut using a core barrel. Laboratory analyses of core samples were made for rock from both unsaturated and saturated zones by Holmes & Narver, Inc., Mercury, Nev. (a contractor of the U.S. Department of Energy). Forty-eight samples were analysed for density, matrix porosity, pore saturation, and pore-water content, mostly from the Topopah Spring, Bullfrog and Tram Members. In addition, horizontal and vertical hydraulic conductivities were measured in the laboratory for the samples from the saturated zone. The measurements were made using distilled water and a constant-head technique, with no application of overburden or pore pressures. Results of these analyses are presented in tables 2 and 3; values in these tables were rounded to one or two significant figures after all calculations were made.

Results of core-sample analyses for the unsaturated zone can be characterized as follows:

1. Matrix porosity is much less in the Topopah Spring Member than in the other units and generally decreases with depth within the unit. Porosity decreases with depth within the unit from about 20 to about 10 percent.

2. Pore saturation shows an irregular increase with depth within the unsaturated zone from about 50 percent to near saturation.

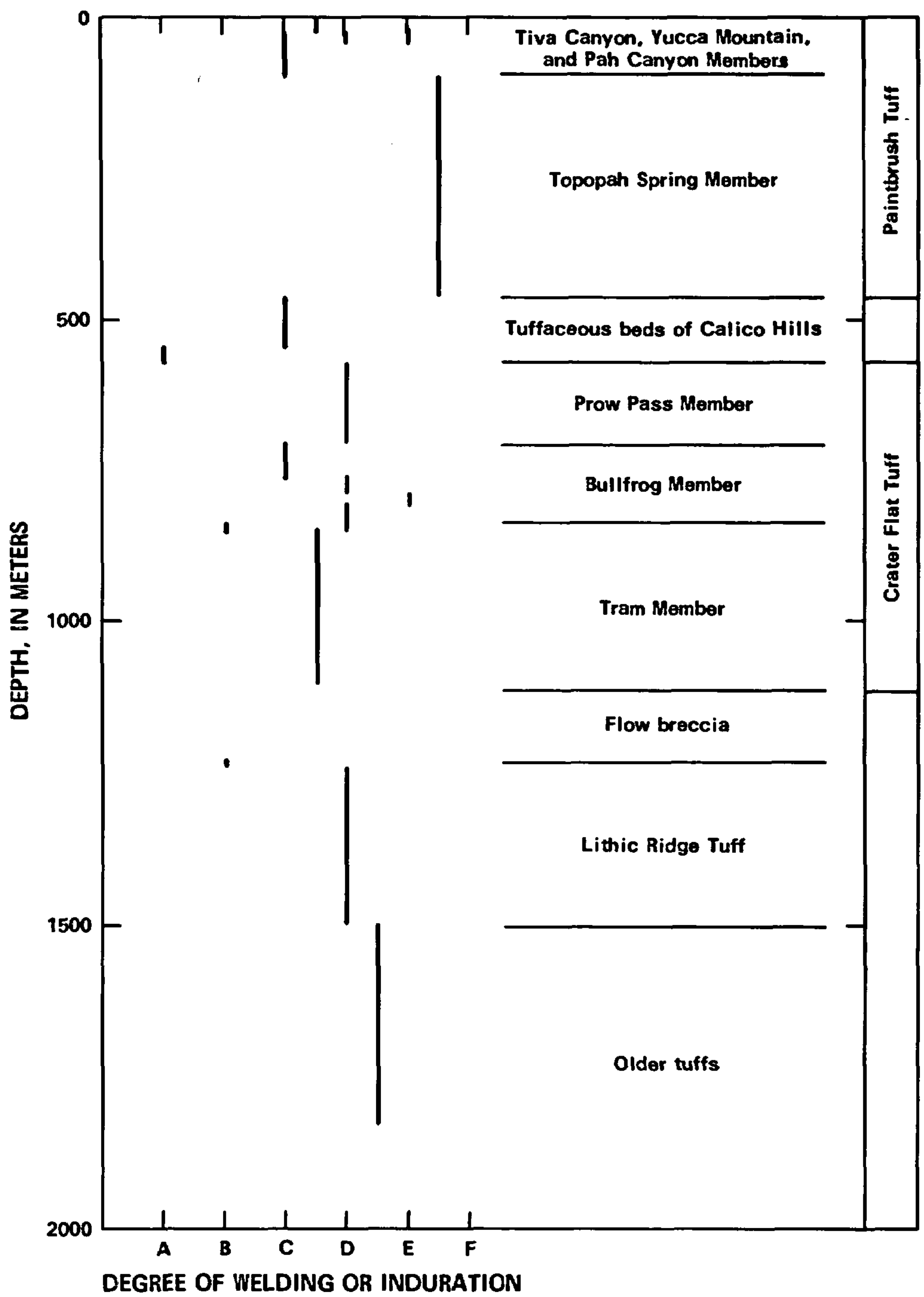

Figure 2.--Generalized distribution of welding and induration in rocks penetrated by the well (Induration: A, slightly; B, moderately. Welding: C, nonwelded; D, partially; E, moderately; F, densely).

Table 2.--*Results of laboratory analyses of physical and hydraulic properties of core samples from the unsaturated zone for the well*

[Analyses by Holmes & Narver, Inc.]

Depth (meters)	Density (grams per cubic centimeter)			Matrix porosity (percent)		Pore saturation (percent)	Natural-state pore-water content (percent)	
	Natural state	Dry bulk	Grain	From dry bulk and grain densities	From helium pycnometer		Weight	Volume
				YUCCA MOUNTAIN MEMBER				
33.5	1.6	1.3	2.4	45	42	49	14	22
34.1	1.6	1.4	2.4	43	--	55	14	23
				PAH CANYON MEMBER				
76.9	1.4	1.3	2.4	48	--	34	11	--
				TOPOPAH SPRING MEMBER				
128	2.1	2.0	2.6	22	20	45	4.5	10
129	2.1	2.0	2.6	24	19	49	5.4	11
135	2.1	2.0	2.6	21	20	44	4.3	9.3
137	2.2	2.1	2.6	19	17	57	4.8	11
140	2.2	2.2	2.6	16	--	58	4.2	10
141	2.2	2.2	2.6	17	--	57	4.2	9.4
142	2.2	2.2	2.6	17	15	54	4.0	9.0
143	2.3	2.2	2.6	15	13	57	3.8	8.5
219	2.2	2.1	2.6	17	15	73	5.7	13
221	2.0	1.8	2.6	28	17	42	6.0	12
222	2.2	2.1	2.6	18	13	68	5.4	12
226	2.2	2.0	---	--	16	--	5.3	12
390	2.3	2.2	2.6	16	15	70	4.9	11
391	2.3	2.2	2.6	16	13	74	5.0	11
398	2.3	2.2	2.6	14	11	72	4.4	10
399	2.4	2.3	2.6	10	10	80	3.4	8.2
405	2.4	2.3	2.6	12	12	82	4.4	10
406	2.4	2.3	2.6	11	7.9	76	3.5	8.4
				TUFFACEOUS BEDS OF CALICO HILLS				
531	1.7	1.3	2.4	47	43	96	27	46
533	1.8	1.4	2.4	44	37	96	24	42

Table 3.--*Results of laboratory analyses of physical and hydraulic properties of core samples from the saturated zone for the well*

[Analyses by Holmes & Narver, Inc.]

Depth (meters)	Density (grams per cubic centimeter)			Matrix porosity (percent)		Pore saturation (percent)	Natural-state pore-water content (percent)		Matrix hydraulic conductivity, *K* (meters per day)	
	Natural state	Dry bulk	Grain	From dry bulk and grain densities	From helium pycnometer		Weight	Volume	Horizontal	Vertical
				PROW PASS MEMBER						
640	2.0	1.7	2.5	33	28	97	16	32	$1x10^{-4}$	$7x10^{-5}$
641	2.0	1.7	2.5	31	29	96	15	30	$7x10^{-5}$	$5x10^{-5}$
641	2.0	1.7	2.5	32	29	95	16	31	$6x10^{-5}$	$5x10^{-5}$
				BULLFROG MEMBER						
709	2.0	1.6	2.5	33	27	92	16	31	$3x10^{-5}$	$2x10^{-5}$
709	2.0	1.6	2.5	33	32	95	16	32	$3x10^{-4}$	$2x10^{-4}$
710	1.9	1.6	2.5	38	34	92	18	35	$8x10^{-4}$	$4x10^{-4}$
713	2.3	2.1	2.6	19	20	82	6.8	15	$1x10^{-4}$	$4x10^{-5}$
764	2.1	1.9	2.6	28	--	87	11	24	$1x10^{-3}$	$3x10^{-4}$
772	2.2	2.0	2.6	25	25	94	10	23	$6x10^{-4}$	$2x10^{-4}$
790	2.3	2.1	2.6	19	19	89	7.5	17	$4x10^{-5}$	$4x10^{-5}$
791	2.3	2.1	2.6	19	20	84	6.9	16	$6x10^{-5}$	$8x10^{-5}$
792	2.2	2.1	2.6	21	22	89	8.4	19	$7x10^{-5}$	$3x10^{-5}$
830	2.1	1.8	2.6	27	25	91	12	25	$4x10^{-5}$	$3x10^{-5}$
				TRAM MEMBER						
833	2.1	1.8	2.6	28	26	94	12	26	$1x10^{-4}$	$1x10^{-4}$
840	2.1	1.8	2.5	26	26	93	11	24	$2x10^{-5}$	$8x10^{-6}$
844	2.2	2.0	2.6	24	21	90	10	22	$4x10^{-6}$	$2x10^{-6}$
1,031	2.2	2.0	2.6	25	21	87	9.9	22	$4x10^{-4}$	$5x10^{-4}$
1,031	2.2	2.0	2.6	23	23	75	7.8	17	$3x10^{-4}$	$2x10^{-4}$
1,032	2.2	2.0	2.6	26	22	79	9.4	20	$2x10^{-4}$	$3x10^{-4}$
1,039	2.4	2.2	2.7	18	18	79	5.9	14	$1x10^{-4}$	$1x10^{-4}$
1,039	2.3	2.1	2.6	19	18	81	6.6	15	$2x10^{-4}$	$7x10^{-5}$
1,040	2.2	2.1	2.6	22	21	83	8.1	18	$5x10^{-5}$	$1x10^{-5}$
				FLOW BRECCIA						
1,201	2.6	2.5	2.7	7	7.3	77	2.2	5.5	$8x10^{-7}$	$8x10^{-7}$
				OLDER ASH-FLOW AND BEDDED TUFF						
1,569	2.3	2.2	2.6	16	17	50	3.6	8.2	$6x10^{-5}$	$2x10^{-5}$
1,820	2.5	2.4	2.7	10	8.8	87	3.3	8.3	$3x10^{-4}$	$4x10^{-4}$

Results of core-sample analyses for the saturated zone can be characterized as follows:

1. Within both the Bullfrog and Tram Members, matrix porosity decreases with depth and with very irregular patterns. For the depth interval, average matrix porosity generally decreases with depth.

2. All samples from below the water table were expected to be saturated. The unsaturated condition of the core samples probably resulted from drying during sampling, processing, or testing activities.

3. For the Bullfrog Member, the matrix hydraulic conductivity, measured in the horizontal direction, averages 3.0×10^{-4} m/d and is about twice the magnitude of the average in the vertical direction, averaging 1.3×10^{-4} m/d. Both horizontal and vertical matrix hydraulic conductivities for the Tram Member average similarly to the vertical conductivities for the Bullfrog Member, which is 1.3×10^{-4} m/d. The smallest matrix value was determined from the single core sample from the flow breccia, 8×10^{-7} m/d for both vertical and horizontal measurements.

4. Characteristics of the core sample from bedded tuff, depth 830 m, are very similar to those of the overlying Bullfrog Member and the underlying ash-flow tuffs of the Tram Member.

Average horizontal hydraulic conductivity for the 25 core samples listed in table 3 is 2×10^{-4} m/d. If this value approximated the average for the entire saturated zone, then the transmissivity attributable to the matrix can be computed. Using a saturated thickness penetrated by the well of 1,257 m, the computed value of transmissivity attributed to the matrix is 2.5×10^{-1} m^2/d, a very small value. Transmissivity of the saturated zone has been evaluated by pumping and packer tests. Results of the tests are discussed in later sections of the report.

GEOPHYSICAL-LOG INTERPRETATIONS

Geophysical well logs were run in the well for a variety of purposes, including (1) defining lithology; (2) correlating with logs for other nearby wells; (3) obtaining data for porosity, fractures, and permeability; (4) locating fluid level, casing perforations, and casing cement; and (5) gaging the diameter of the open-hole part of the well. Some of these uses are not discussed here, because they do not directly contribute to characterization of the geohydrology of the penetrated stratigraphic units. However, they were useful in designing the hydraulic tests and sampling programs for the well. A summary of the geophysical logs run in the well is given in table 4.

Table 4.--*Geophysical logs run in the well*

Geophysical log	Depth interval (meters)
Acoustic televiewer	570-1,783
Caliper	0-99 85-688 91-685
Density	6-102
Density, borehole-compensated	12-196 91-688 683-1,829
Downhill seismic survey	107-685 686-1,227 1,227-1,821
Dual induction, focused	102-512
Electric	67-1,829 366-511 584-688
Epithermal neutron porosity	6-102 90-688 101-688
Fluid density for fluid location	76-102 306-393 [1]566-578 174-189 189-204 152-167 152-169 549-565 552-582 [2]564-579 [3]522-583 381-439
Formation density	0-102
Gamma ray	0-102
Gamma ray-neutron	[1]91-688 671-1,829
Gyroscopic	0-1,783
Induction	12-101 91-687
Magnetometer	104-688
Neutron	253-511 570-1,829
Neutron-neutron	[1]0-511 0-1,829
Neutron, borehole-compensated	683-1,829
Nuclear annulus investigation	572-686
Radioactive-tracer survey	102-688 687-1,829
Spectral	0-1,829
Television-camera videotape	0-570 351-427 546-594 564-576
Temperature	0-688 6-1,829
3-D sonic velocity	[1]310-510 [1]563-687

[1]Two logs run in this interval.
[2]Five logs run in this interval.
[3]Six logs run in this interval.

Density, neutron, and 3-D velocity logs were used to determine the distribution of rock porosity based on techniques described by Schlumberger Limited (1972, p. 37-55) and Birdwell Division (1973, p. OF90-OF188). The 3-D velocity log responds to matrix porosity. Borehole-compensated density and neutron logs respond to both matrix and fracture porosity. For the purpose of defining the general distribution of rock with greater than average porosity, that is, rock having porosity greater than the middle of the range indicated by the logs, the penetrated-rock sequence was divided into 60 equal depth intervals, each about 30 m thick. Using the three types of logs, each depth interval was evaluated for percent of relatively porous rock; that is, rock having porosity greater than the average for the rocks penetrated by the well. The 3-D velocity and the density logs produced results that were very similar throughout most of the penetrated sequence. Because these empirical-log interpretations are affected by personal judgment, the three interpretations were combined into a single generalized graph of porous-rock distribution (fig. 3). The following conclusions are made from the graph: (1) The Topopah Spring Member and overlying stratigraphic units contain abundant porous rock, except for the depth interval from 300 to 360 m, which has much less porous rock; (2) the tuffaceous beds of Calico Hills, the Lithic Ridge Tuff, the Prow Pass, Bullfrog, and Tram Members, have similar patterns (porous rock at the contacts and much less porous rock within each of the five units); (3) the flow breccia is relatively porous, with only one 30-m zone having a relatively small thickness of porous rock; and (4) the older tuffs have relatively porous rock near the middle of the penetrated part of the unit.

Porosity at shallow depths probably represents both matrix porosity and fractures. However, the volume of fracture porosity at greater depths probably is much less because of greater overburden pressure; therefore, the porosity represented there is largely or entirely matrix porosity.

The occurrence of relatively significant porosity at or near the stratigraphic contact may be related to three features: (1) The relatively unlithified bedding or reworked tuff at the base of most units probably is more porous than the ash-flow tuffs; (2) the upper part of each stratigraphic unit may have fractures related to rapid cooling; and (3) weathering of the rock while it was exposed to the atmosphere may have increased porosity near the upper contacts of stratigraphic units.

The neutron log also can be used to determine the water table and to identify any perched zones of ground water. Based on log interpretations, the following conclusions are made: (1) The top of the saturated zone is at a depth of about 572 m; and (2) the rock is at or near saturation in the interval from 448 to 572 m, possibly indicating a perched ground-water zone above the regional water table. This perched zone probably includes the lower part of the Topopah Spring Member, a 6-m-thick interval of saturated, moderately to densely welded ash-flow tuff above a 5-m interval of bedded tuff. The tuffaceous beds of Calico Hills and the upper 6 m of the Prow Pass Member probably are not saturated, but are close to saturated.

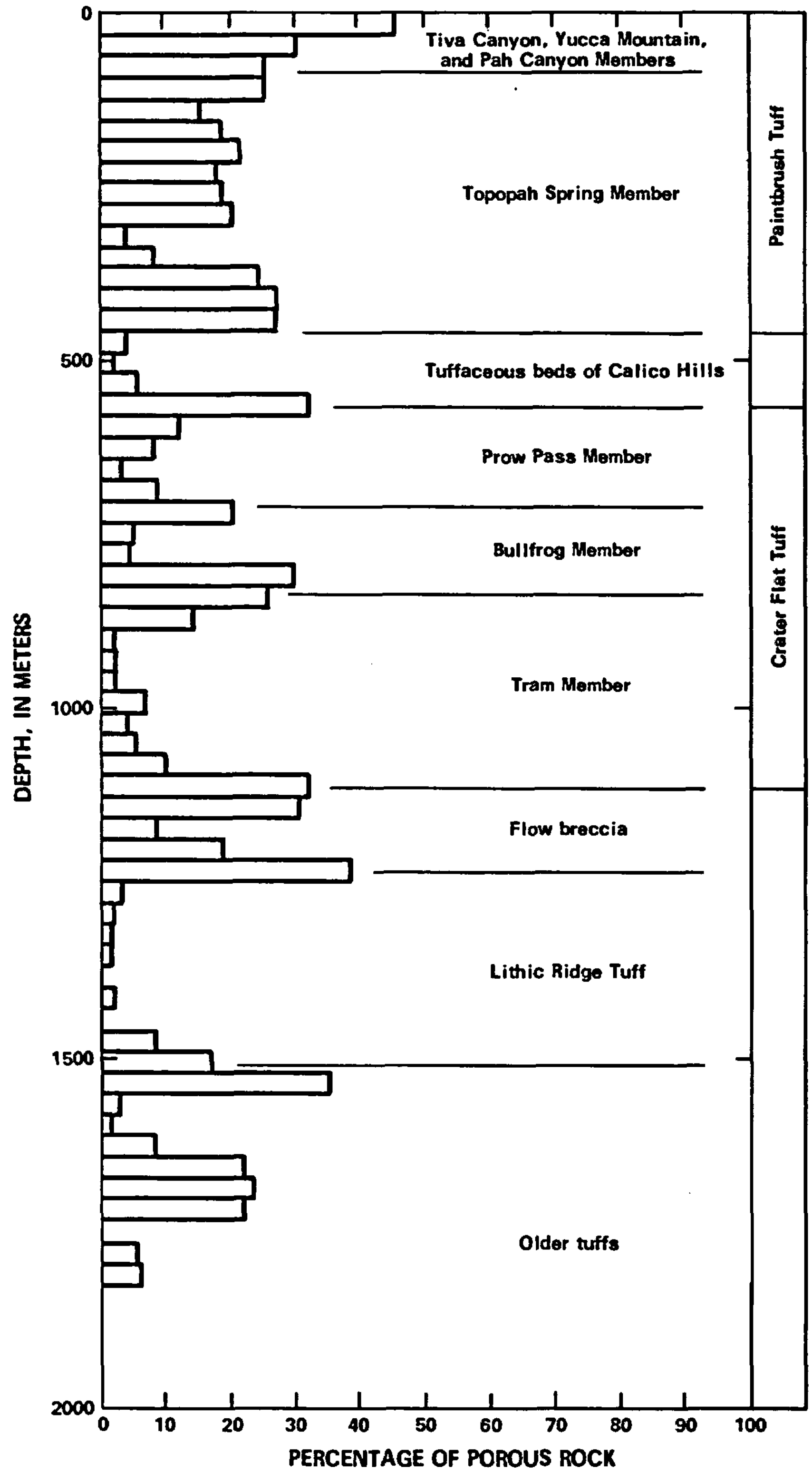

Figure 3.--Distribution of porous rock penetrated by the well, as determined from geophysical logs.

Four days after the well reached total depth, on November 26, 1980, a temperature log was made in the well under static conditions but probably not under equilibrium conditions; that is, no stresses were being applied to the well or the penetrated rock during the logging period, but effects of past drilling stresses probably still remained. A summary follows of some of the thermal conditions logged or estimated from the log: (1) The estimated average ambient land-surface temperature at the well site was 19.7°C, and the bottom-hole temperature at a depth of 1,829 m was 62.9°C; (2) temperature reversals in the geothermal temperature gradient were recorded at depth intervals 100-114 m, 197-206 m, 372-405 m, and 436-439 m in the Topopah Spring Member; and (3) the average geothermal temperature gradient for the stratigraphic sequence penetrated by the well was 24°C/km. Depth intervals that greatly exceeded this average were 38-48 m (89.5°C/km, Yucca Mountain Member), 296-298 m and 429-436 m (246°C/km and 171°C/km, respectively; both in the Topopah Spring Member), 560-572 m (69°C/km extending from the water table up into the tuffaceous beds of Calico Hills), and 1,470-1,474 m (76°C/km, Lithic Ridge Tuff). The large gradient at the water table is associated with and may be related to near-saturated conditions. Other hydrologic conditions that might be related to the summarized geothermal conditions have not been identified for this report.

The acoustic televiewer log, an acoustic travel-time log, was made to record borehole-wall texture in the liquid-filled part of the hole (table 4). Such features as fractures, bedding planes, and lithophysae were detected below the water table. Because the log is directionally oriented, direction of dip of inclined lineations was identified. Horizontal or nearly horizontal linear features were identified from the logs; they probably are either bedding planes or fractures. The steeply inclined linear features are more likely to be fractures. All water-saturated stratigraphic units, except the Lithic Ridge Tuff, had lineations.

Westward-dipping lineations at depths of 580 and 608 m probably represent open fractures able to transmit ground water at relatively large rates. Both of these lineations are in the upper part of the Prow Pass Member (table 5). The other lineations were either of questionable nature or, if fractures, appeared to be nearly closed. The quality of the log was not good.

Caliper logs were made to determine the open-hole diameter distribution with well depth. Erosion due to drilling activity is the cause of the enlargement in well diameter. Erosion probably is caused by slight lithification, abundant fractures, and perhaps other unknown factors.

A summary of hole gage is presented in table 6. Out-of-gage is defined for this report as a diameter 100 mm greater than the diameter of the bit used to drill the interval. Thick out-of-gage intervals commonly cannot be tested by use of inflatable packers because of the difficulty of seating packers or because overinflation results in packer rupture. In the upper part of the Bullfrog Member a thick zone was out of gage from a depth of 708 to 764 m. Elsewhere in the penetrated stratigraphic sequence packer seats commonly were available.

Table 5.--*Lineations observed on acoustic-televiewer log in the well*

[Log made in water-filled part of hole]

Stratigraphic unit (see table 1 for rank and affiliated rock unit)	Remarks for stratigraphic unit	Depth below land surface (meters)	Orientation
Prow Pass Member--	Lineations present throughout unit.	580	Dipping steeply westward.
		608	Dipping westward about 75°.
		635	Horizontal.
		657	Do.
		676	Do.
		688	Dipping westward.
Bullfrog Member---	----------------------------	825	Horizontal.
		827	Do.
		831	Do.
Tram Member-------	Lineations only in upper part of unit.	874	Horizontal.
		877	Dipping westward. about 75°.
		919	Horizontal.
Flow breccia------	Lineations only in upper part of unit.	1,137	Dipping southeast about 80°.
Older tuffs-------	----------------------------	1,635	Horizontal.
		1,636	Do.
		1,665	Do.

Table 6.--*Distribution of out-of-gage hole in the well*

Stratigraphic unit (see table 1 for rank and affiliated rock unit)	Part of unit out of gage (percent)	Location within stratigraphic unit
Tiva Canyon Member[1]	39	In lower part of interval.
Yucca Mountain Member	26	Mostly near base of unit.
Pah Canyon Member	42	Throughout unit.
Topopah Spring Member	16	Do.
Tuffaceous beds of Calico Hills	13	Near base of unit.
Prow Pass Member	19	In upper one-half of unit.
Bullfrog Member	44	Do.
Tram Member	0.1	Near base of unit.
Flow breccia	7	Do.
Lithic Ridge Tuff	2	In lower part of unit.
Older tuffs	4	At center of unit.
Average for well	10	

[1]Below a depth of 12 meters.

Enlarged borehole zones that are possibly fracture controlled are listed in table 7. These zones were identified from caliper logs as zones with irregular enlargement, but not necessarily as enlarged as the out-of-gage zones discussed above. The principal fracture-controlled zones are: (1) Two thick intervals in the Topopah Spring Member; and (2) one thick interval in the upper one-half of the Bullfrog Member.

The Topopah Spring Member, compared to other units penetrated by the well, has the greatest aggregate thickness of fractured rock, based on hole gage. The tuffaceous beds of Calico Hills, the Tram Member, and the Lithic Ridge Tuff have no identified fractures based on hole gages.

A television-camera log was made in the well before casing the well to a depth of 687 m. Open-hole conditions were logged from a depth of 102 m to the water level in the well at 572 m. Features observed were fractures, hole enlargement, lithologic features, and water seeps. The latter were observed at many depths; they are summarized in table 8. All seeps appeared small; however, larger seeps were from the tuffaceous beds of Calico Hills and the Prow Pass Member. It could not be determined whether the seeping water was drilling fluid or perched water.

In comparing information in tables 7 and 8, the fractures in the Topopah Spring Member observed with the television camera occur within intervals of enlarged borehole, possibly caused by fracturing as determined from caliper logs. The few fractures observed in the depth interval 541-549 m in the tuffaceous beds of Calico Hills apparently did not produce significant borehole enlargement.

Table 7.--*Enlarged bore-hole intervals possibly caused by fracturing*

[Based on caliper-log interpretations]

Stratigraphic unit (see table 1 for rank and affiliated rock unit)	Remarks for stratigraphic unit	Depth interval (meters)	Interval thickness (meters)
Tiva Canyon Member-----	Interval continues into underlying unit.	[1]12-29	22
Yucca Mountain Member--	Lower interval continues into underlying unit.	29-34	
		[2]44-58	30
Pah Canyon Member------	Lower interval continues into underlying unit.	58-74	
		78-85	13
Topopah Spring Member--	----------------------------	85-91	
		123-139	16
		150-327	177
		332-406	74
Tuffaceous beds of Calico Hills.	No intervals identified in stratigraphic unit.	-----------	---
Prow Pass Member-------	Ten zones having a combined thickness of 28 meters occur in the unit.	-----------	28
Bullfrog Member--------	Interval is upper one-half of stratigraphic unit.	707-762	55
Tram Member------------	No intervals identified in stratigraphic unit.	-----------	---
Flow breccia-----------	Interval near top of stratigraphic unit.	1,116-1,120	4
Lithic Ridge Tuff------	No intervals identified in stratigraphic unit.	-----------	---
Older tuffs------------	Enlargement may be the result of slight lithification.	1,519-1,557	38
		1,647-1,653	6
		1,682-1,696	14
		1,796-1,798	2
		1,805-1,806	1

[1]Well cased to 12 meters.
[2]Interval includes a thin interval of bedded and reworked tuff.

Table 8.--*Descriptions of water seeps above the zone of saturation in the well observed with a down-hole television camera*

[Well cased to 102 meters]

Depth (meters)	Description
	TOPOPAH SPRING MEMBER
183	Rough walls; a few drops of water.
261	Vertical fracture seeping water.
343-344	Densely fractured, may be fault; hole enlarged; water present.
351-358	Fracture seeping water; hole enlarged.
	TUFFACEOUS BEDS OF CALICO HILLS
472-488	Tuff with many lithic fragments dripping small stream of water.
488-495	Tuff with many lithic fragments yielding water running down side of hole.
500-511	Stratiform beds dripping water.
511-526	Tuff with many lithic fragments dripping water.
526-533	Tuff with many lithic fragments yielding small stream of water.
541-549	A few fractures; dripping water.
549-564	Water on side of hole.
564-566	Hole enlarged; dripping water.
	PROW PASS MEMBER
566-570	Dripping water.
570	Large stream of water on side of hole.

RADIOACTIVE-TRACER SURVEYS

Radioactive-tracer surveys (Blankennagel, 1967, p. 15-26) were used to measure vertical flow rates in the well while water was pumped from the well. From this information, the zones through which the water flowed into the well and estimated flow rates for the zones were identified. Surveys were made: (1) While the well was at a depth of 688 m, testing only the Prow Pass Member; and (2) after the well had been cased to a depth of 687 m and had a total depth of 1,829 m, testing the lower 20 m of the Prow Pass Member and the penetrated underlying units (figs. 4 and 5).

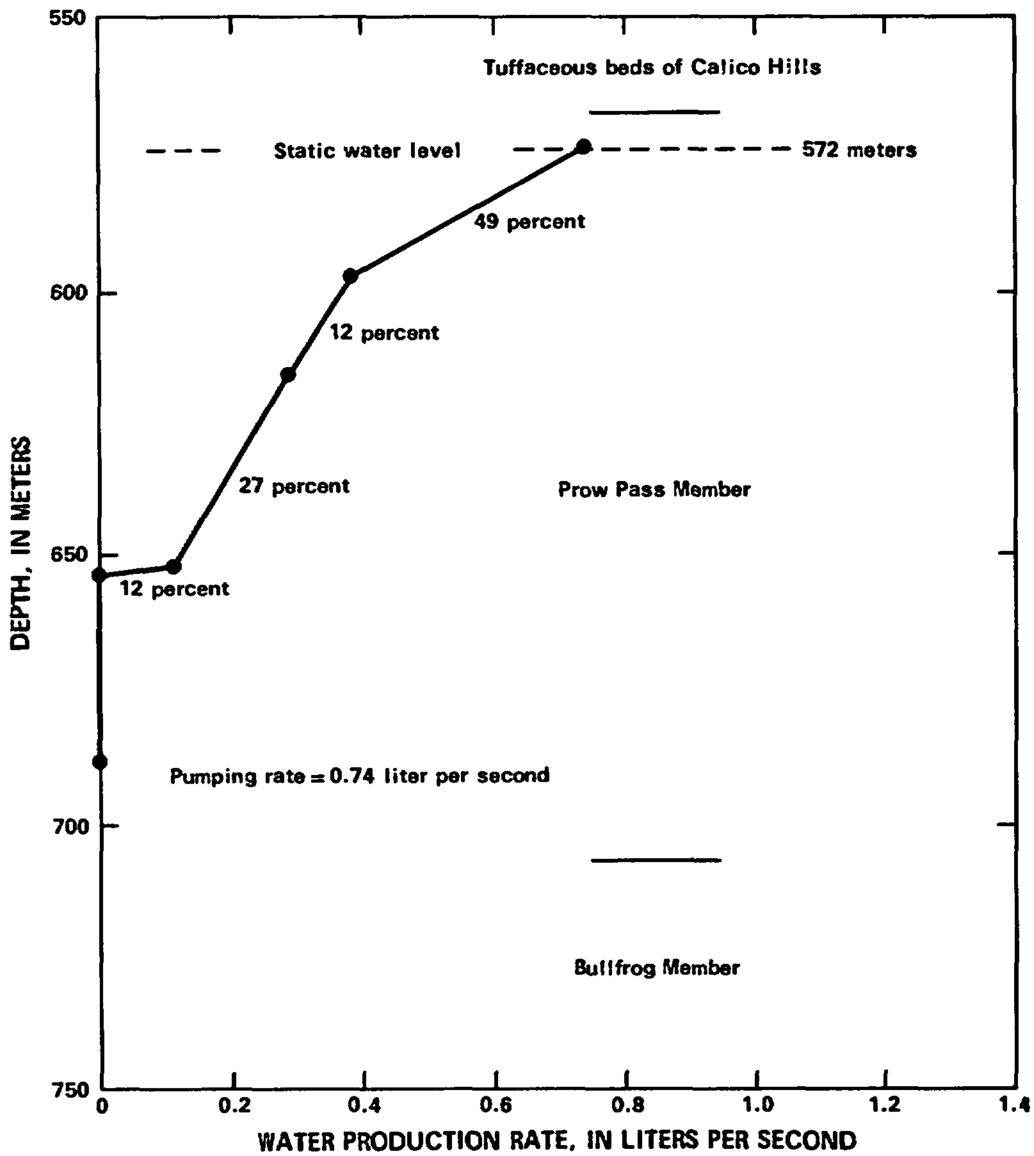

Figure 4.--Radioactive-tracer survey for depth 572 to 688 meters in the well, showing percentage of pumping rate produced by intervals.

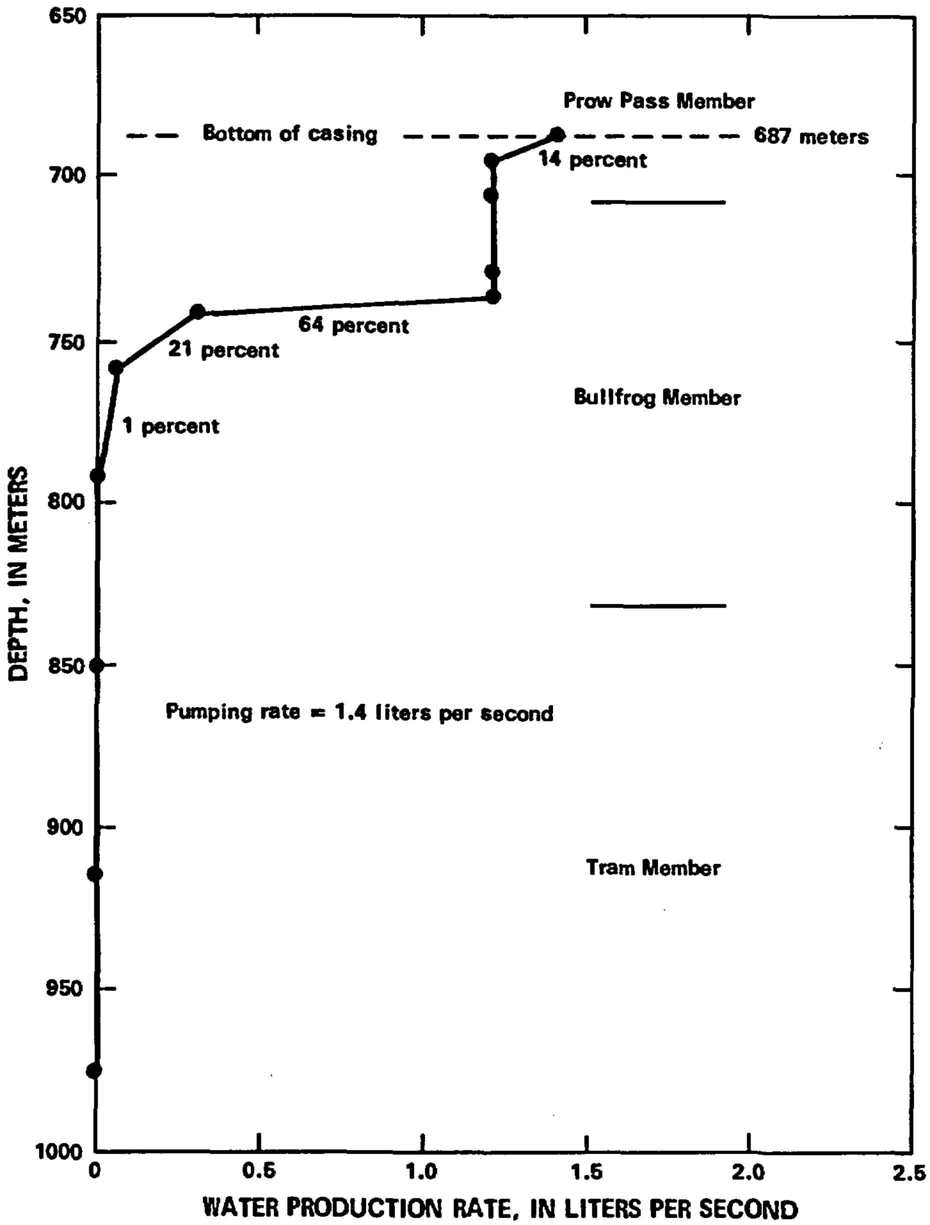

Figure 5.--Radioactive-tracer survey for depth 687 to 1,829 meters in the well, showing percentage of pumping rate by intervals.

Conclusions from the surveys assume no significant hydraulic-head loss in the well bore:

1. The 1-m zone from 652 to 653 m has the most productive rock included in the first test; the interval from 572 to 597 m is more productive than the zone from 597 to 652 m; both zones produced water. The zone from 653 to 688 m produced no detectable flow of water.

2. The interval from 736 to 792 m, in the middle part of the Bullfrog Member, is more productive than the interval from 687 to 694 m, in the lower part of the Prow Pass Member. Within the productive zone in the Bullfrog Member, the interval from 736 to 741 m has the greatest productivity. The interval from 792 to 1,829 m produced no detectable flow of water as did the no-flow zone from 694 to 736 m.

In a later section of this report, these survey results are used in conjunction with the associated drawdown and recovery pumping tests to assign values of transmissivity and hydraulic conductivity to 11 intervals within the zone of saturation.

HYDROLOGIC MONITORING AND TESTING

This section of the report includes discussions of water-level monitoring during the time the well was being drilled and after drilling was completed, the volume of drilling fluid needed to drill the well, and pumping- and injection-test results. These activities and their hydrologic results are discussed separately in subsequent sections of the report.

According to Bredehoeft and Miani (1981, p. 293-294) definition of ground-water flow and the factors that control flow through typical porous media--sand, gravel, sandstone--are well understood. In contrast, flow through a fractured-rock mass, such as tuffs beneath Yucca Mountain, is much less understood. Neither the theory nor the field technology required to measure the flow characteristics of a ground-water system in a fractured medium is very advanced; thus, the uncertainties in the predictions are significant in both time and space. As a result, a conceptual model of the ground-water system beneath Yucca Mountain is presented, and a solution to the theory and field-technology dilemma is presented in the following paragraphs.

In order to define ground-water characteristics for the flow system at this well site, a conceptual model is required. The principal elements of the model are:

1. The rock containing the primary matrix porosity is homogeneous and isotropic. The primary porosity is intergranular and controlled principally by deposition and lithification.

2. Secondary porosity is controlled by fractures. The fractures generally are vertical or steep angle in the saturated zone and are the result of tensional failure during mechanical deformation. The volume of water stored in fractures is relatively small in comparison to that stored in the matrix porosity. On a small scale, the fracture permeability is anisotropic.

3. Both primary and secondary porosity may be decreased by precipitation of mineral matter.

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

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

6. On a large scale, orientation of fractures may be assumed random so that the system appears isotropic.

Based on the conceptual model of this dual-porosity system, homogeneous porous-media solutions can be used to define general ground-water parameters and ground-water flow in fractured media, using late-time test data (Warren and Root, 1963; Odeh, 1965; Kazemi, 1969; Kazemi and Seth, 1969; Wang and others, 1977, p. 104; and Najurieta, 1980, p. 1242). Early-time test data will yield characteristics that apply only to the fractured part of the system. Early hydraulic-head-change data may be dependent partly on nonrepresentative, near-well hydraulics (Wang and others, 1977, p. 103), on well-bore storage, and on skin effects (During pumping, skin effects is the pressure decrease at the wellface in addition to the normal transient pressure decrease in the ground-water resulting from damage or improvement of the rocks ability to transmit water at the wellface, Earlougher, 1977, p. 57). Commonly, the damage or improvement is the result of well drilling). The exact time boundary between early time and late time is not distinct for conditions at this well. However, A. F. Moench (U.S. Geological Survey, written commun., 1983) concluded that data used for computing transmissivity for the three pumping tests (figs. 7-15), pumping periods of 2,880, 3,383, and 90 minutes respectively, probably are in the early time region. His conclusion is based upon the shapes of drawdown and recovery curves; the fact that the earliest drawdown measurements appear to plot on the Theis curve; and estimates of the value of Warren and Root's (1963) λ parameters.

Witherspoon and others (1980, p. 26-28), in their hydrologic work in crystalline rock, have assumed that, in general, a fracture system can be treated as a slightly different form of porous media, measuring equivalent porous-media properties. The porous-media solutions will not yield correct porosity and hydraulic conductivity values for each porosity type in this dual-porosity system beneath Yucca Mountain, but rather average values for the zones tested. As a result, hydraulic conductivity, aperture, and volume of specific fractures or effective pore volume of the matrix are not determined.

The degree of reliability of the conceptual model is related to the degree to which the model approximates the actual fracture-flow, ground-water system beneath Yucca Mountain, for the purposes intended and for the time during which the data are valid. This relationship between model and the actual system is not known precisely enough at this time to assure a significant degree of reliability in the model; however, the departure of test data is a measure of how far conditions are from the ideal (Ferris and others, 1962, p. 102). Departure from ideal for each test has been evaluated and is described in the following sections where the testing results are presented.

Water Levels

Water-level observations and measurements in the well were made during the drilling, as part of hydraulic tests, and after testing was completed. The purposes of these observations and measurements were: (1) To locate any perched-water zones above the water table; (2) to identify at what depth water saturation occurs; (3) to determine the composite hydraulic head in the well; (4) to identify hydraulic heads in various water-bearing zones; and (5) to determine the existence of artesian or water-table conditions.

Water entered the well at a depth of 448 m from a moderately to densely welded ash-flow tuff in the lower part of the Topopah Spring Member (table 9). While the well was at a depth of 458 m, air-lift testing of the well produced a discharge to the land surface of from 1.3 to 1.6 L/s for 45 minutes. This water probably was perched above an underlying 5 m-thick (454 to 459 m) bedded or reworked ash-flow tuff at the base of the member. At a depth of 564 m, the driller reported encountering water; however, this observation was unconfirmed by the hydrologist at the well.

The water level was measured at a depth of 572.3 m (rounded to 572 m in the remainder of the report) while the well was at a depth of 688 m, on October 22, 1980. This depth probably is the top of the principal zone of saturation, that is watertable conditions. It occurs about 6 m below the top of the Prow Pass Member; therefore, 135 m of the Prow Pass are below the water table at this site.

After the composite water-level measurement on June 24, 1982, piezometers were permanently installed in the well to measure water levels in four zones: (1) Interval 572 to 640 m in the upper part of the Prow Pass Member; (2) interval 738 to 741 m in the upper part of the Bullfrog Member; (3) interval 1,112 to 1,115 m at the base of the Tram Member, and (4) interval 1,803 to 1,806 m in older tuffs. These intervals were selected to obtain relative hydraulic-head information at widely spaced intervals. Since the installation of piezometers, water levels in the two shallowest zones (intervals 572 to 640 m and 738 to 741 m) appear to have stabilized at virtually the same depth as the composite level, between 572 and 573 m. However, the two deeper zones have levels higher than the shallower zones, and were continuing to rise at the date of the measurements, September 24, 1982. The hydraulic-head relations indicate a potential for an upward component of water flow toward the shallow, more transmissive zones near to the water table. Distribution of transmissivity is described in a later section of the report. This would indicate that, at the site of this well, water in the rocks penetrated by the well does not drain downward to any deeper zones.

Water beneath the bedded tuff at a depth of 701-707 m probably is under artesian pressure, because this type bed commonly is only slightly lithified and lacks fracture permeability. Above the bedded tuff, other conditions that have not been identified also may cause artesian conditions.

Table 9.--*Water levels in the well*

[Altitude of land surface at well is 1,302.2 meters; water level in well accurate to ±0.5 meter]

Date	Depth zone (meters)	Water level in well (meters)		Remarks
		Depth to water from land surface	Altitude of water surface above sea level	
10-05-80	448-458	448	854	Air-lifted water at a rate of 1.3 to 1.6 liters per second for 45 minutes when the well was 458 meters deep.
10-07-80	564	564	738	Depth at which first water was reported by driller.
10-22-80	572-688	572.3	729.9	Prow Pass Member, upper part.
1-21-81	687-698	574.7	727.5	Prow Pass Member, lower part.
1-21-81	687-698	574.3	727.9	Prow Pass Member, lower part.
2-26-81	687-1,829	572.4	729.8	------------------------------
5-31-81	687-1,829	572.4	729.8	------------------------------
10-09-81	687-1,829	572.0	730.2	------------------------------
11-10-81	687-1,829	572.4	729.8	------------------------------
12-09-81	687-1,829	572.0	730.2	------------------------------
2-25-82	687-1,829	572.3	729.9	------------------------------
6-24-82	687-1,829	572.0	730.2	------------------------------
9-24-82	572-640	572.5	729.7	Piezometer.
9-24-82	738-741	572.7	729.5	Do.
9-24-82	1,112-1,115	569.7	732.5	Water level continued to rise after installation of peizometer.
9-24-82	1,803-1,806	521.4	780.8	Do.

Drilling-Fluid Use

To minimize the invasion and plugging of fracture and matrix porosity while drilling the well, a drilling fluid of air-foam, consisting of small quantities of detergent and water and large volumes of air was used; about 14,300 L of detergent and 2,200,000 L of water were used during drilling. Additional water entered the well during injection tests.

The use of drilling fluid is shown in figure 6. Variations in fluid use are related mostly to fluid losses into penetrated rock. Because more permeable zones of a given thickness receive more infiltration than less permeable zones, the fluid-use rate was used as an approximate index of permeability.

The horizontal offsets in cumulative fluid use in figure 6, at depths of about 400, 680, and 1,180 m, correspond to either logging, testing, or holiday periods, when no drilling was in progress, rather than to fluid losses into permeable rock. The following general hydrologic conclusions are drawn from the data: (1) The fluid-use rate generally increased to a depth of 780 m, indicating that, in general, the well was penetrating consistently permeable rock as it was gradually deepened to the middle of the Bullfrog Member; (2) the graph steepens at 780 m, indicating less permeability from 780 to 1,200 m, in the lower part of the flow breccia; and (3) an additional steepening of the graph at a depth of 1,200 m indicates a further decrease in permeability.

Pumping Tests

The well was pumped, and the resulting drawdown and recovery of the water level was measured to determine apparent horizontal transmissivity of the tested zones. The well was tested during two periods: (1) While the well was at a depth of 688 m; and (2) after it had been cased to a depth of 687 m and after being drilled to a depth of 1,829 m.

The methods used to analyze the data were either the straight-line method (Cooper and Jacob, 1946; Ferris and others, 1962, p. 100) or the Theis method (Ferris and others, 1962, p. 92). Method assumptions are discussed in the cited references. Test data and analyses are shown in figures 7 through 15; results of the tests are summarized in table 10.

For the straight-line method of analysis of the drawdown in a pumped well, drawdown, s, was plotted against time after pumping started, t, on semilogarithmic coordinate paper. Drawdown was plotted on the arithmetic scale and time on the logarithmic scale. After values of time became sufficiently large, and if testing conditions were met (as described earlier in the report), the measured data plotted along a straight line. The slope of this line for one log cycle, s, was used in the following equation:

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

where T is transmissivity, in meters squared per day;
Q is constant rate of discharge of the well, in liters per second; and
Δs is drawdown for one log cycle, in meters.

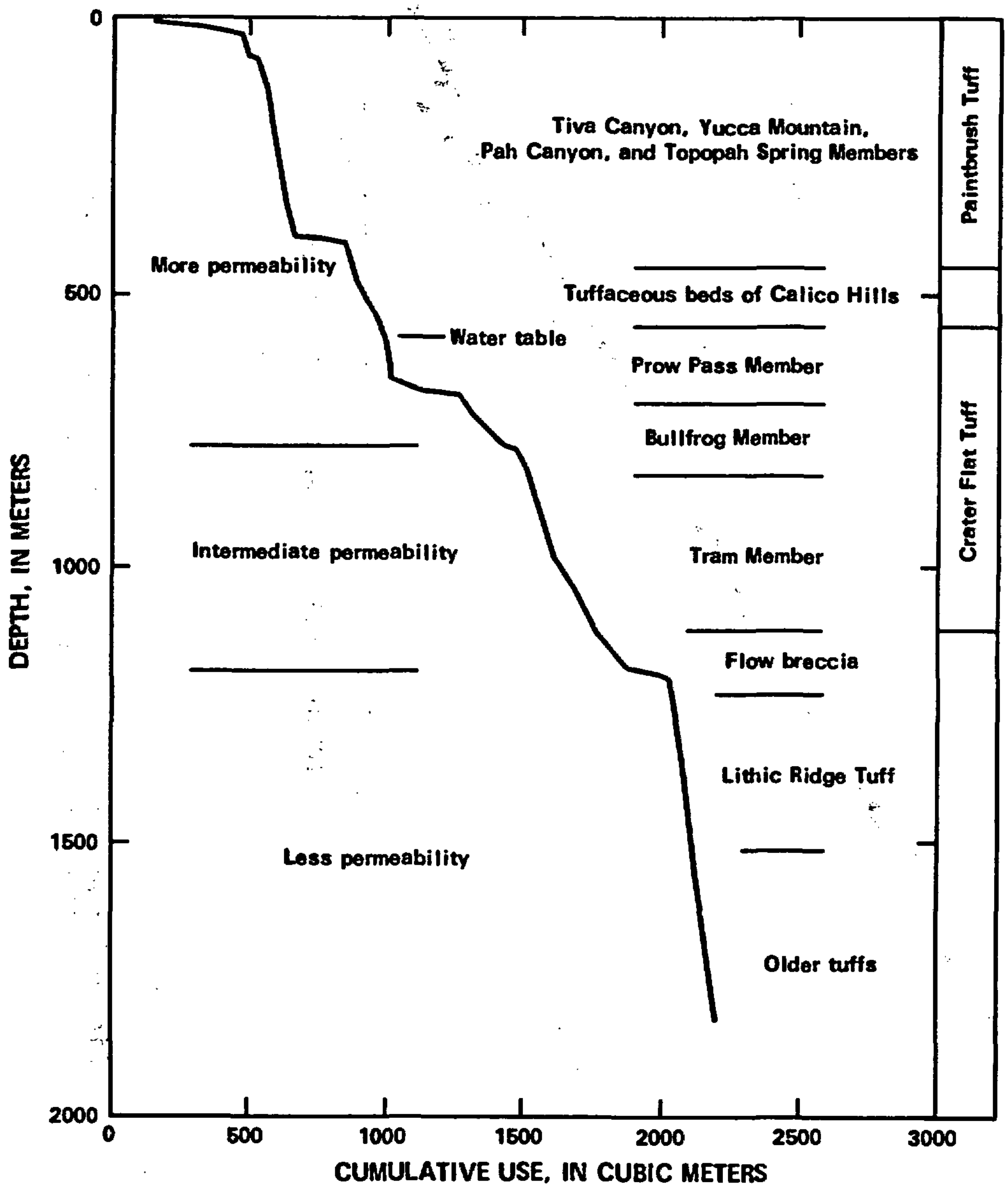

Figure 6.--Drilling-fluid use in the well and estimates of relative permeability.

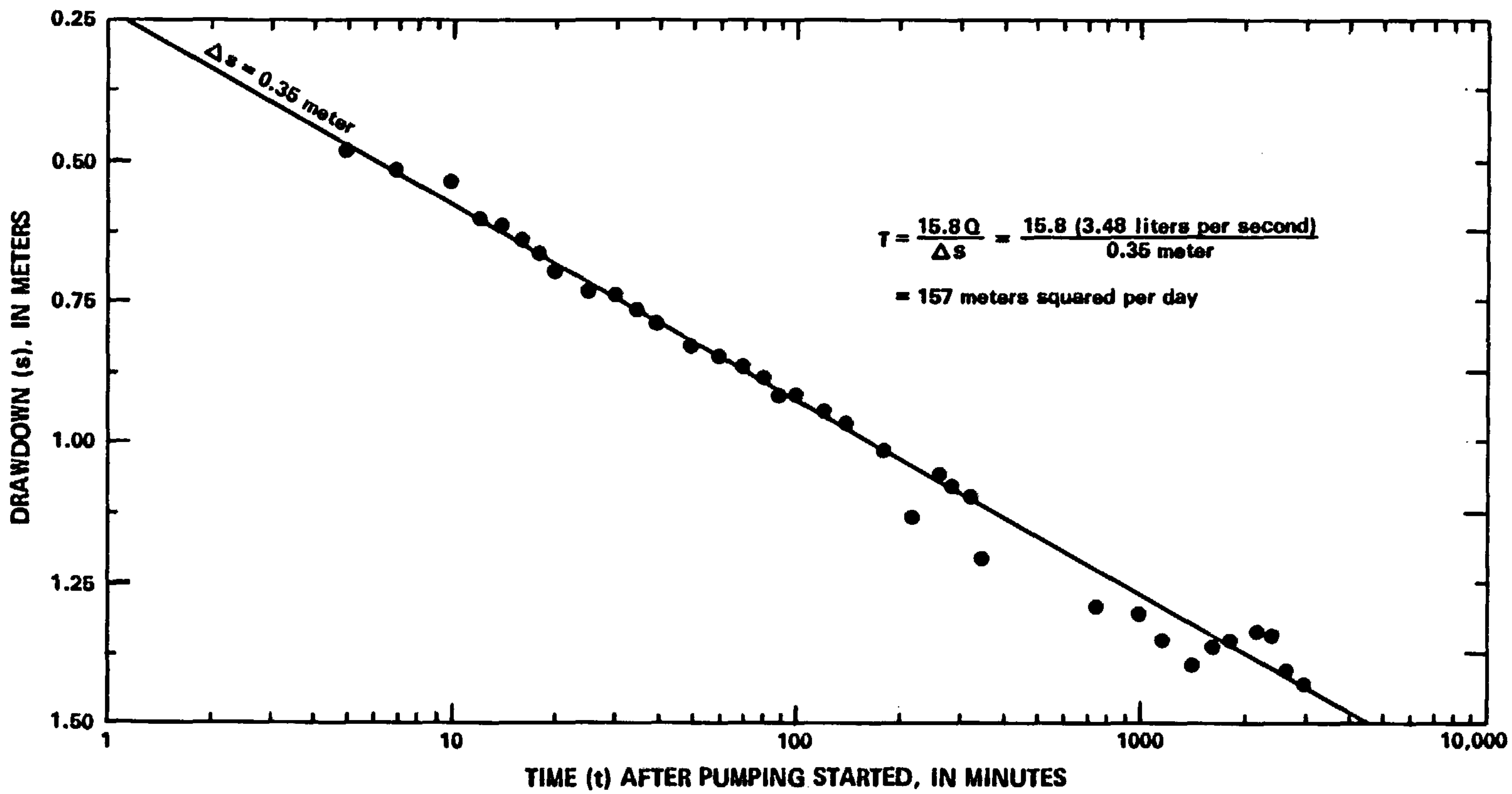

Figure 7.--Analysis of water-level drawdown, pumping test 1, zone from 572 to 688 meters in the well, straight-line solution.

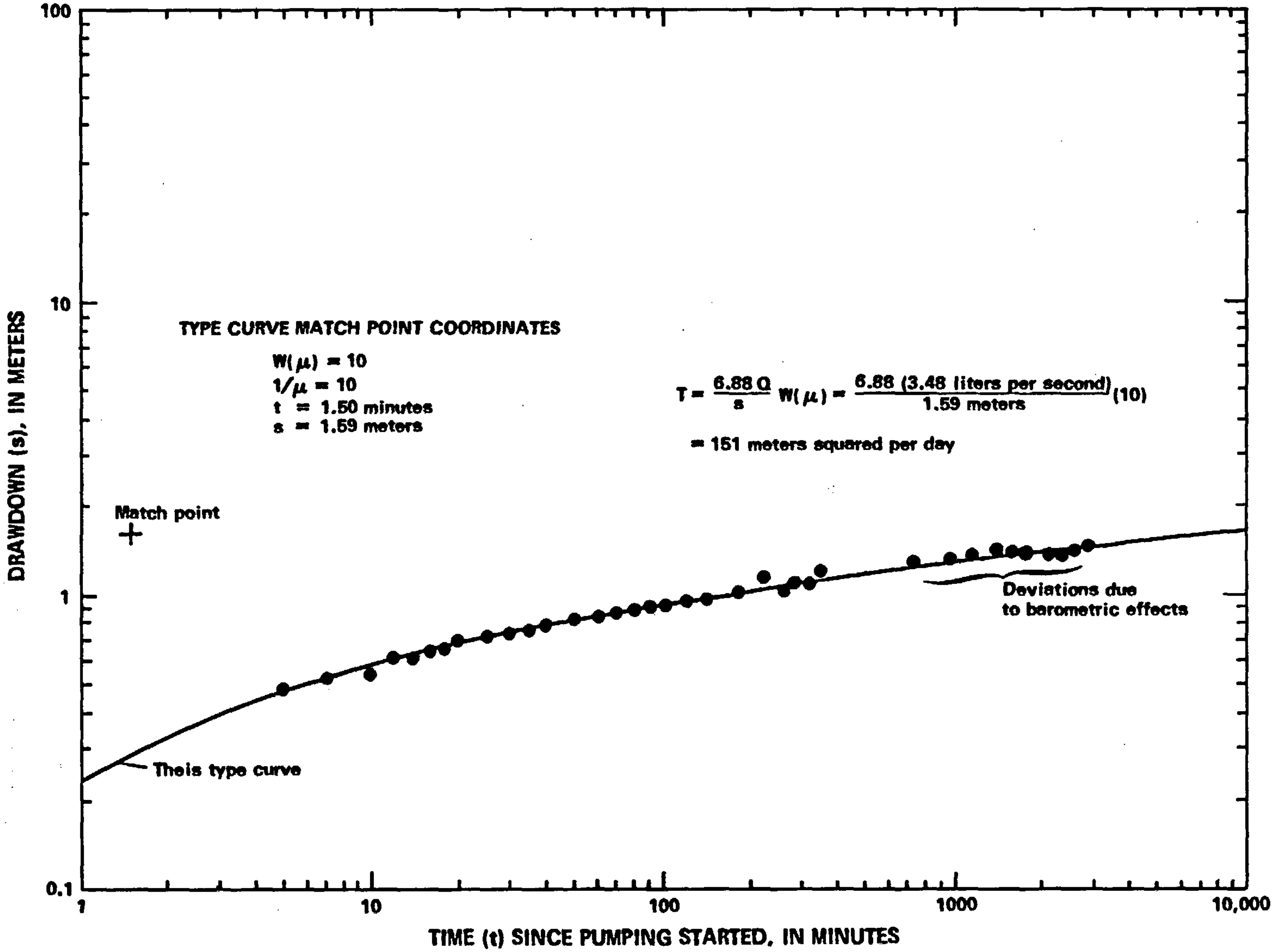

Figure 8.--Analysis of water-level drawdown, pumping test 1, zone from 572 to 688 meters in the well, Theis method.

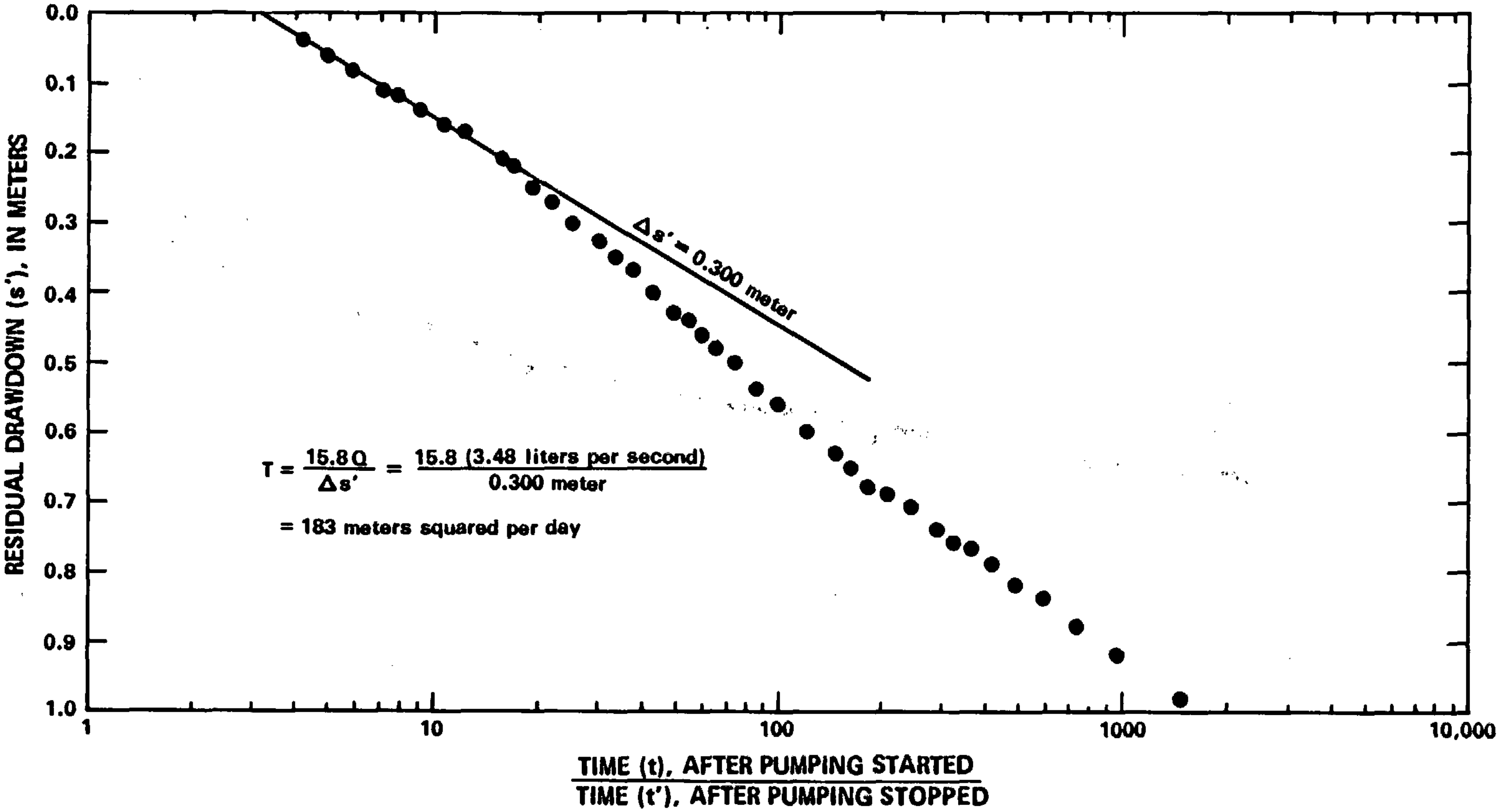

Figure 9.--Analysis of water-level recovery, pumping test 1, zone from 572 to 688 meters in the well, straight-line solution.

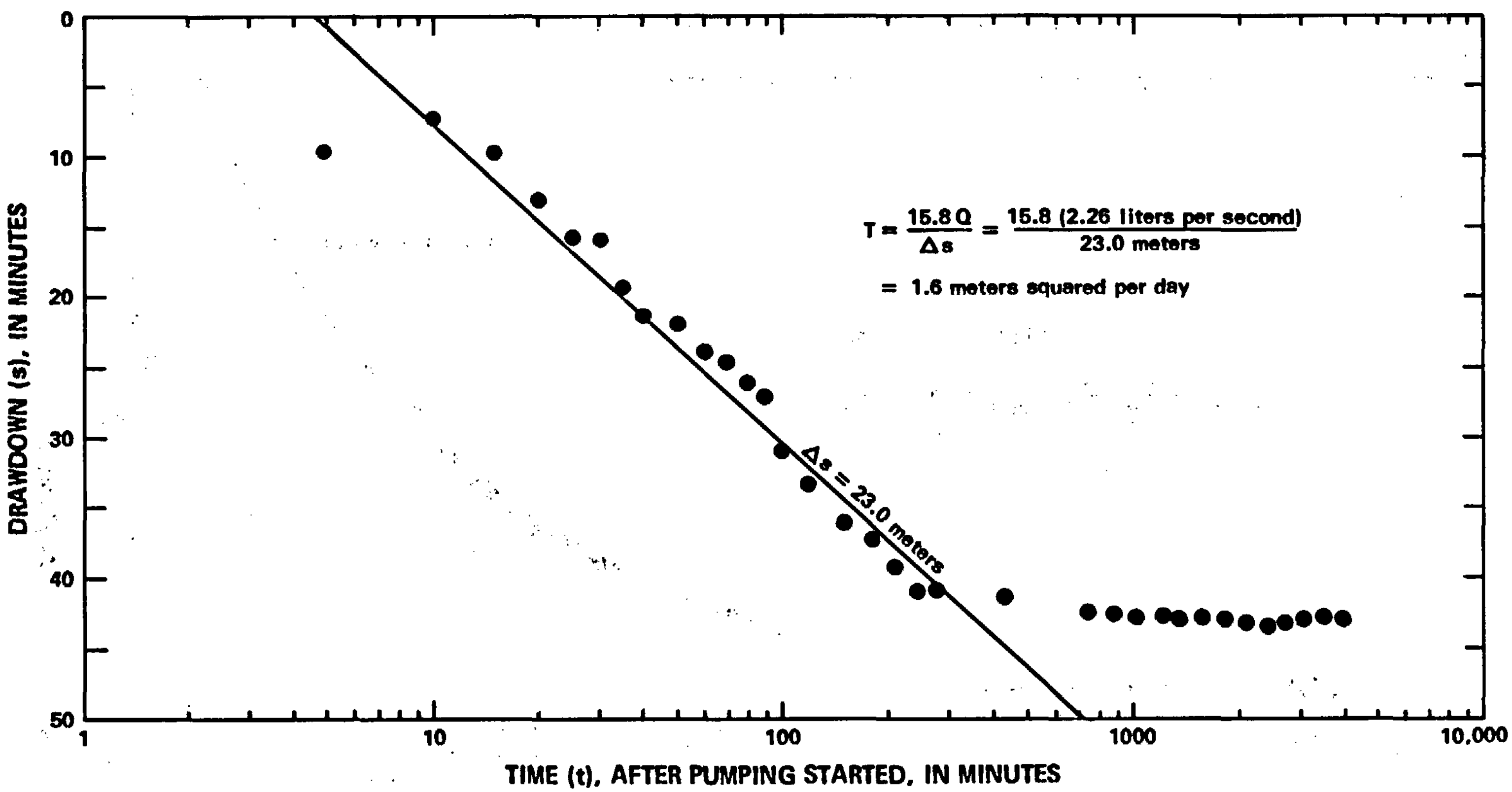

Figure 10.--Analysis of water-level drawdown, pumping test 2, zone from 687 to 1,829 meters in the well, straight-line solution.

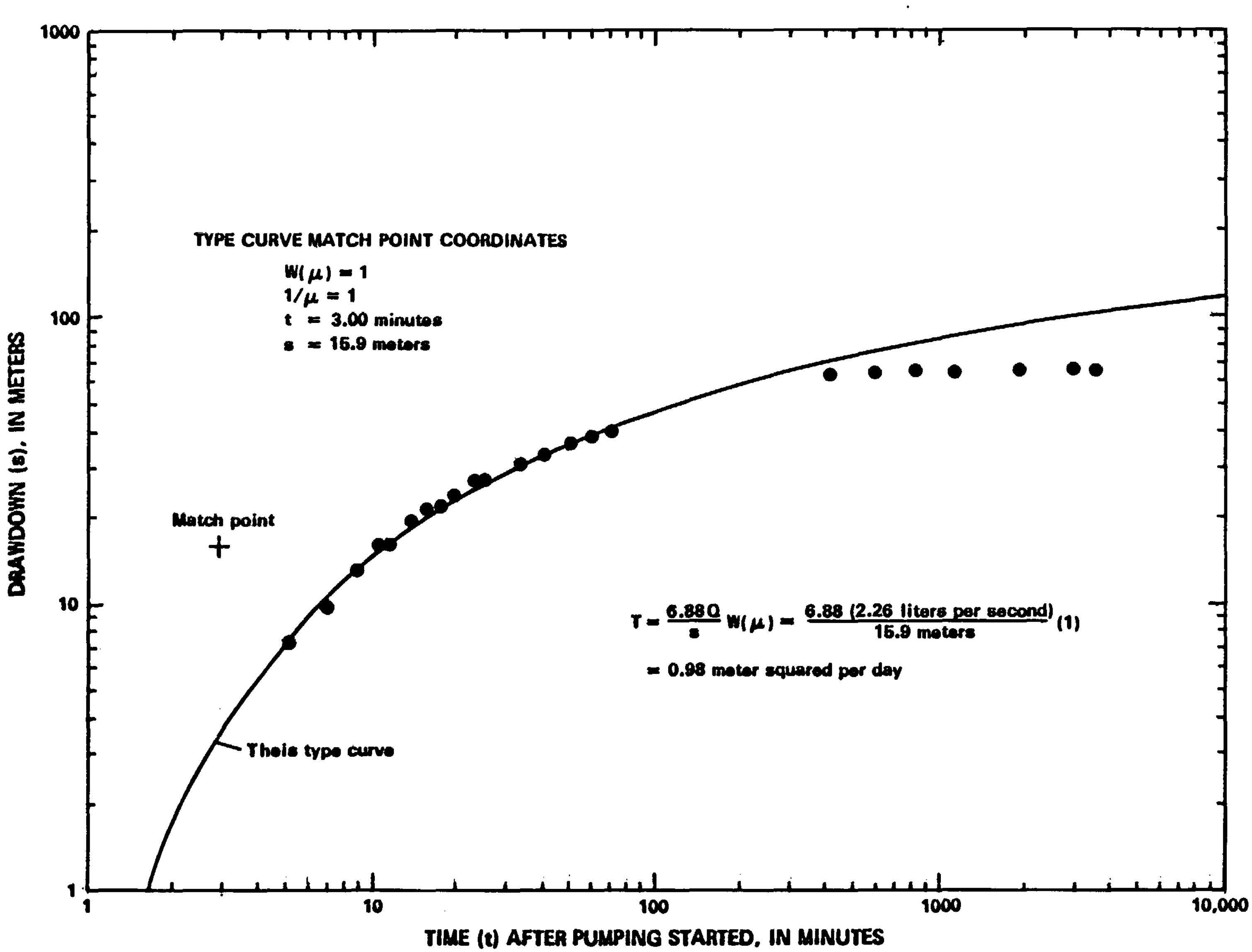

Figure 11.--Analysis of water-level drawdown, pumping test 2, zone from 687 to 1,879 meters in the well, Theis method.

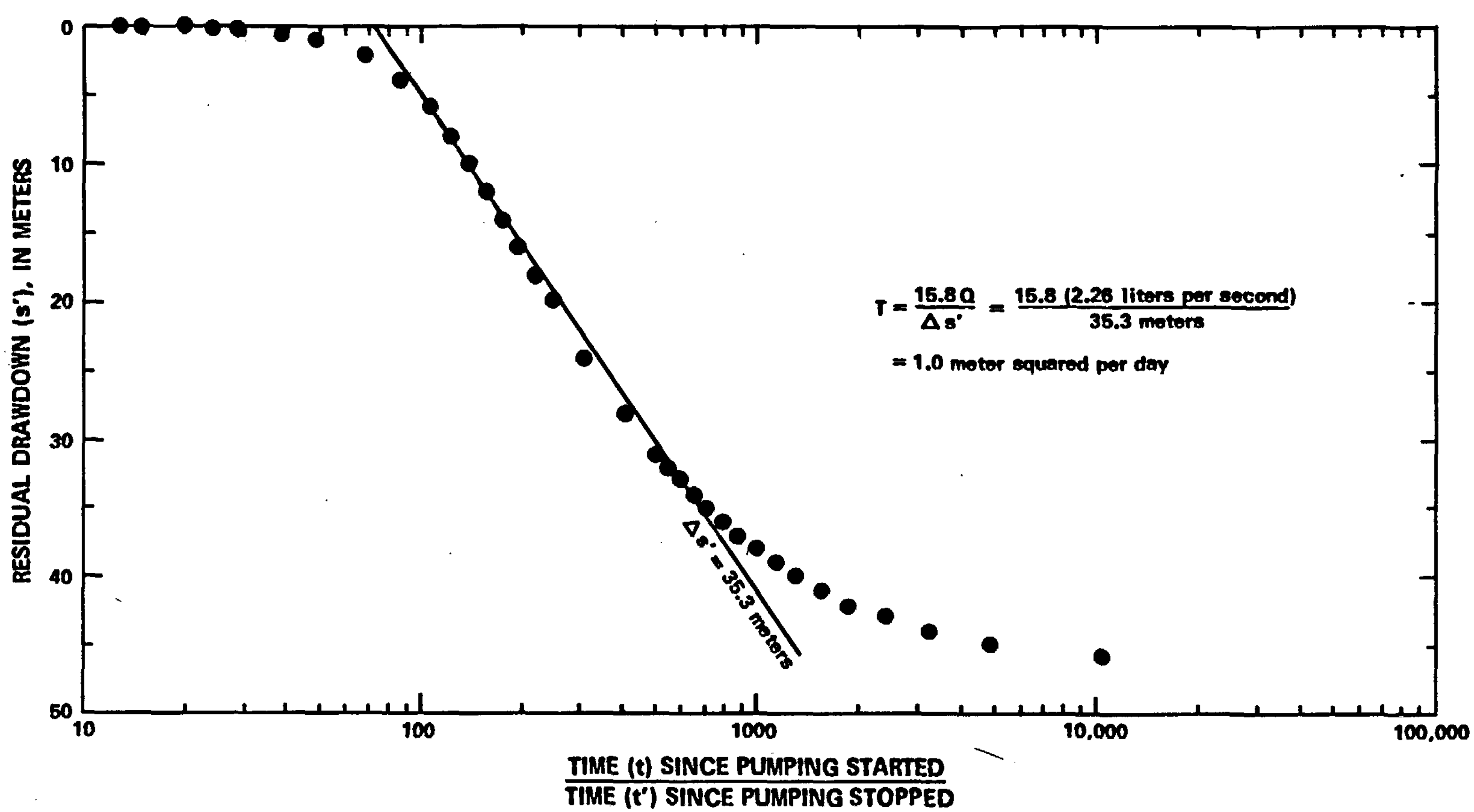

Figure 12.--Analysis of water-level recovery, pumping test 2, zone from 687 to 1,829 meters in the well, straight-line solution.

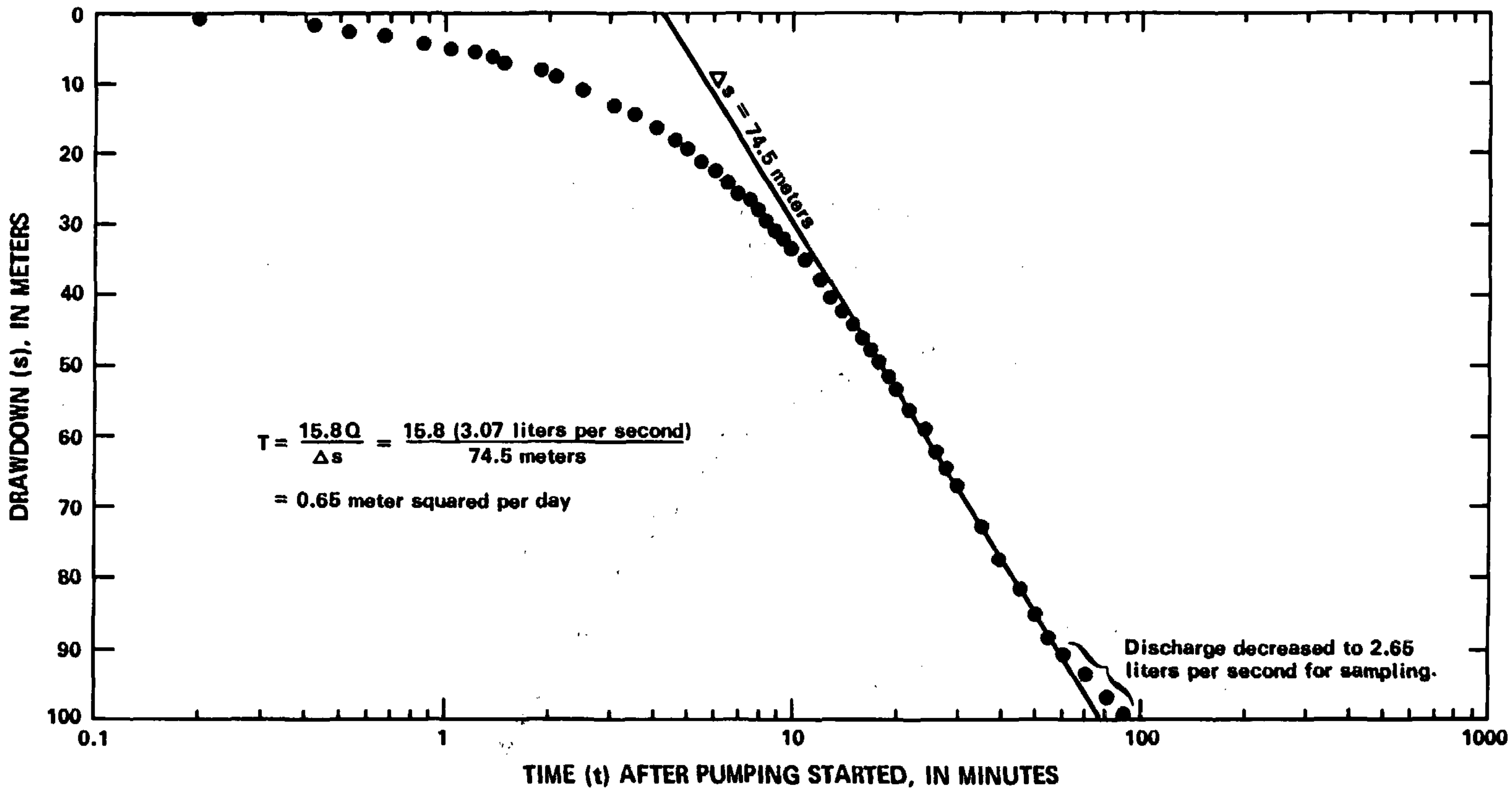

Figure 13.--Analysis of water-level drawdown, pumping test 3, zone from 687 to 1,829 meters in the well, straight-line solution.

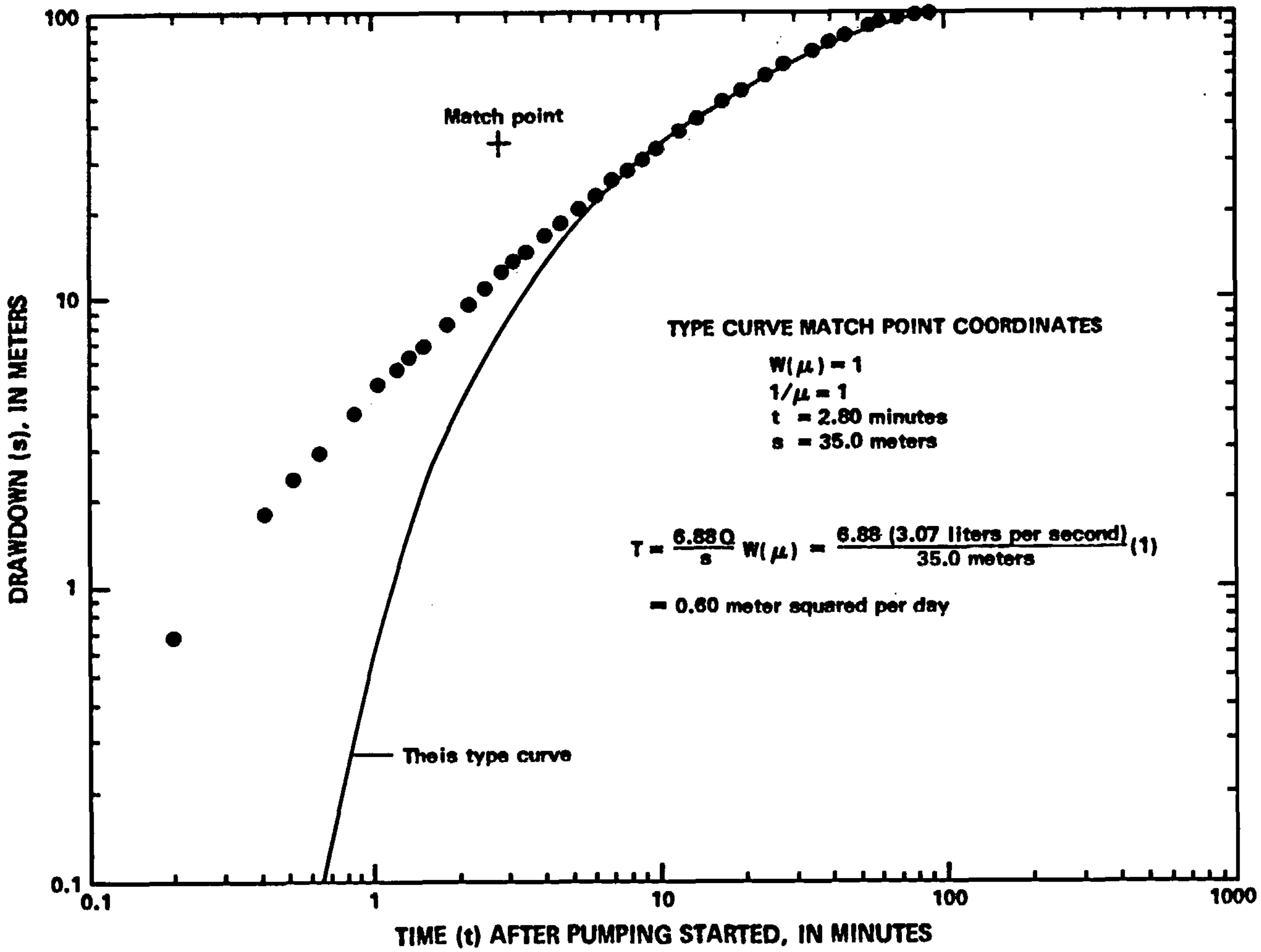

Figure 14.--Analysis of water-level drawdown, pumping test 3, zone from 687 to 1,829 meters in the well, Theis method.

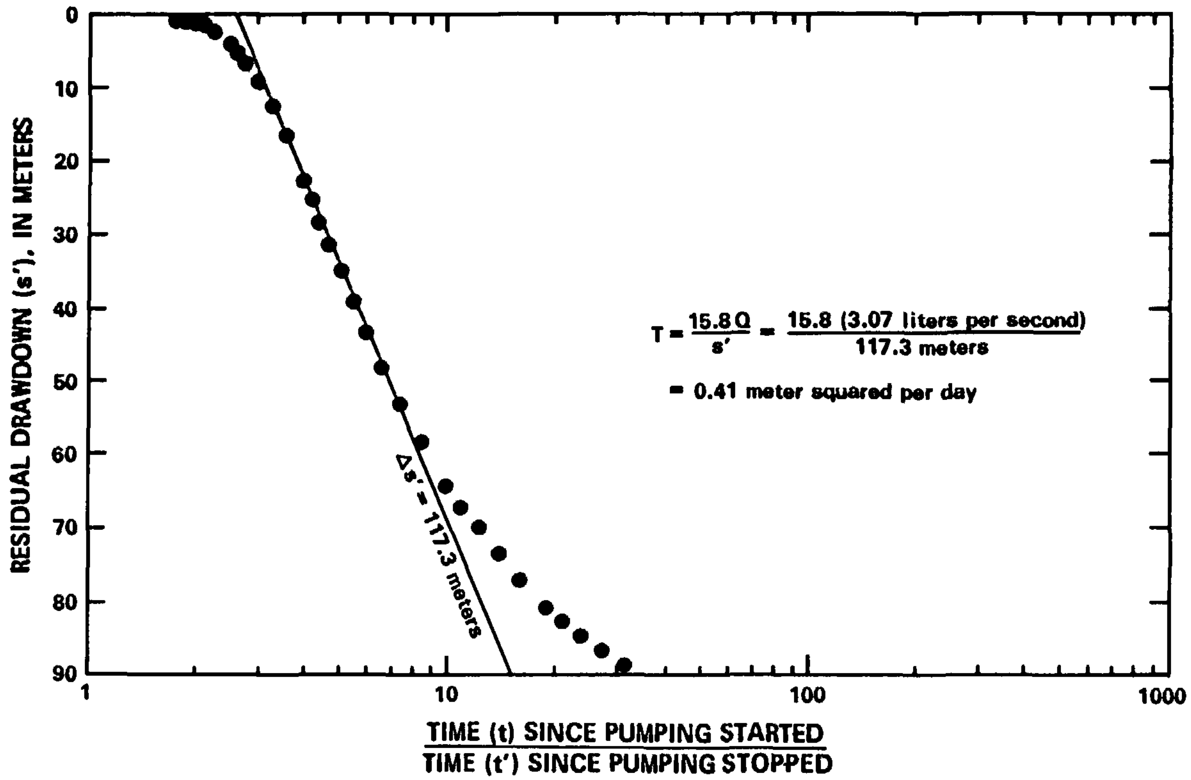

Figure 15.--Analysis of water-level recovery, pumping test 3, zone from 687 to 1,829 meters in the well, straight-line method.

For recovery after pumping of the well, time after pumping started divided by time after pumping stopped (t/t'), was plotted on the logarithmic scale, the equation becoming

$$T = \frac{15.8Q}{\Delta s'} \qquad (2)$$

where $\Delta s'$ is residual drawdown for one log cycle in meters.

For the Theis method, drawdown, s, was plotted against time after pumping started, t, on logarithmic coordinate paper. The data curve was then superimposed on a type curve to obtain the best fit of the data to the type curve. An arbitrary match-point was selected anywhere on the overlapping part of the sheets, and the four coordinates of common point on the two sheets were determined. The following equation was then used:

$$T = \frac{6.88Q}{s}W(\mu) \qquad (3)$$

where T is transmissivity, in meters squared per day;
Q is constant rate of discharge, in liters per second;
$W(\mu)$ is well function, a match-point coordinate; and
s is drawdown in meters, another match-point coordinate.

For the test zone 572 to 688 m in the Prow Pass Member, two analyses of the water-level drawdown (figs. 7 and 8) yielded similar values (157 and 151 m^2/d) for apparent horizontal transmissivity, and one analysis of water-level recovery (fig. 9) yielded a larger value (183 m^2/d). The authors consider data for the late times more representative of the aquifer during recovery. The earlier, steeper-sloping data segment may be affected by well-bore storage and skin effects. If, however, the early data are used to determine transmissivity, the resulting value would be about 140 m^2/d rather than 183 m^2/d. Because the two drawdown-data analyses of figures 7 and 8 were more precise, the data showing only smaller departures from the ideal, the average value resulting from the two drawdown tests,154 m^2/d, or rounded, about 150 m^2/d, probably is a representative value for this zone. The drawdown data (figs. 7 and 8) for the test interval 572 to 688 m showed some fluctuation after about 200 minutes into the test. The variation in data probably is the result of about a 5-percent variation in pumping rate, and also possibly the result of barometric fluctuations.

The drawdown data for test 2 interval 687 to 1,829 m, prior to 230 minutes into the pumping period (figs. 10 and 11) have fluctuations of unknown cause; the abrupt change in slope of the data plots at 230 minutes indicates either leaky-aquifer conditions, a recharging boundary had been reached by the cone of depression caused by pumping, or the transition from early time to late time was reached. The decrease in pumping rate identified in figure 13 for the drawdown in pumping test 3 also applies to the upper part of the data plot in figure 15, where the data departs from a straight line. Other erratic data fluctuations for hydraulic tests seem of minor consequence and are not commented on.

During drawdown and recovery tests described above, a drawdown in well USW G-1 resulted from pumping of well USW H-1, indicating hydraulic connection between these wells. Well USW G-1 is 430 m northwest of well USW H-1 and was drilled as an exploratory core hole to the same depth as USW H-1. The decline of water level in the well during the testing periods was about 1 m, only part of which is believed to be drawdown from pumping of the nearby well and therefore not representative of aquifer conditions (Earlougher, 1977, p. 10-13). Therefore, no attempt was made to determine aquifer properties from well USW G-1 data.

For the depth interval 687 to 1,829 m, which includes the lower 20 m of Prow Pass Member and all underlying penetrated stratigraphic units, two pumping periods with different pumping rates were used to evaluate transmissivity (table 10). Both drawdown and recovery tests were made in conjunction with each pumping period. Computed values of apparent transmissivity ranged from 0.41 to 1.6 m^2/d. The 6 values within this range are much smaller than values obtained for the upper test zone, despite the fact that this zone is nearly 10 times as thick. The analyses of drawdown data in figures 10, 13, and 14 seem to have the least departure from the ideal. As a result the best value of apparent transmissivity is the average of the three or 0.95 m^2/d, or rounded, about 1 m^2/d.

In summary, nearly all the permeable rock penetrated by this well is in the Prow Pass Member above a depth of 688 m. Based on these pumping tests and a technique by Theis (1963) for the computation of the relation between well-pumping rate, drawdown, and length of pumping time if the two zones were pumped at a constant rate and a drawdown in water level of 100 m occurred at the end of 24 hours, the yield would be about 130 L/s for the upper zone and 1 L/s for the lower zone.

Values of apparent transmissivity and apparent average hydraulic conductivity can be assigned to 11 zones (table 11) based on pumping tests and the associated radioactive-tracer surveys. The assigned values are computed by proportioning the transmissivity values obtained from pumping tests to the zones equal to their relative ability to produce water during pumping, assuming no significant hydraulic-head loss in the well bore during the pumping period. The 1-m-thick zone, 652 to 653 m in the Prow Pass Member, has relatively significant permeability. Most of the remaining permeable rocks occurs above this zone; all the rocks below this zone have small average values of apparent hydraulic conductivity.

Table 10.--*Summary of pumping-test results for the well*

[As a homogeneous equivalent model]

Test interval (meters)	Stratigraphic unit(s) tested (see table 1 for rank and affiliated rock unit)	Type of test	Pumping rate, Q (liters per second)	Pumping period, t (minutes)	Computed trans-missiv-ity, T (meters squared per day)	Method of analysis and data-plot figure; departure of data from ideal
572-688	Prow Pass Member.	Drawdown	3.5	2,880	154	Straight-line solution and Theis method in figures 8 and 9, respectively; very small departures.
572-688	Prow Pass Member.	Recovery	[1]3.5	[1]2,880	183	Straight-line solution in figure 10; moderate departure.
687-1,829	Prow Pass Member and underlying penetrated units.	Drawdown	2.3	3,383	1.6	Straight-line solution in figure 11; very small departure.
					.98	Theis method in figure 12; moderate departure.
687-1,829	do.	Recovery	[1]2.3	[1]3,383	1.0	Straight-line solution in figure 13; moderate departure.
687-1,829	do.	Drawdown	3.1	90	.65	Straight-line solution in figure 14; small departure.
					.60	Theis method in figure 15; very small departure.
687-1,829	do.	Recovery	[1]3.1	[1]90	.41	Straight-line solution in figure 16; moderate departure.

[1]For pumping prior to recovery test.

Table 11.--*Distribution of transmissivity and hydraulic conductivity based on pumping tests and radioactive-tracer surveys in the well*

[As a homogeneous equivalent model]

Stratigraphic unit (see table 1 for rank and affiliated rock unit)	Depth interval (meters)	Apparent horizontal transmissivity, *T* (meters squared per day)	Apparent average hydraulic conductivity, *K* (meters per day)
Prow Pass Member--------------------	572-597	74	3
	597-616	18	1
	616-652	40	1
	652-653	18	18
	653-688	≤ 1	4×10^{-2}
	687-694	1×10^{-1}	2×10^{-2}
Prow Pass and Bullfrog Members-------	694-736	$\leq 1\times10^{-2}$	$\leq 2\times10^{-4}$
Bullfrog Member---------------------	736-741	6×10^{-1}	1×10^{-1}
	741-758	2×10^{-1}	1×10^{-2}
	758-792	1×10^{-2}	3×10^{-4}
Bullfrog Member and underlying penetrated units----------------------	792-1,829	$\leq 1\times10^{-2}$	$\leq 1\times10^{-5}$

Injection Tests

Injection tests were made by using inflatable packers in the well to isolate the test zones. Injection-test data were analyzed by a method described by Cooper and others (1967) and Papadopulos and others (1973). The method assumptions are discussed in the cited references. Six tests were successful, but other attempts failed, mostly because borehole conditions prevented adequate seating of packer elements. Some of these adverse conditions were described in preceding sections of this report.

The ratio of hydraulic head (H) at a given time to hydraulic head (H_o) at time 0, H/H_o, was plotted against time after injection started, t, on semilogarithmic coördinate paper. H/H_o was plotted on the arithmetic scale, and time on the logarithmic scale. A family of type curves was used to determine transmissivity and storage coefficient. A match point was selected on the logarithmic scale of the type-curve graph, with a value of 1.0. The corresponding time, t, match point on the logarithmic scale of the data graph was determined. The following equation was then used to determine transmissivity:

$$T = \frac{8.64 r_c^2}{t} \qquad (4)$$

where T is transmissivity, in meters squared per day;
r_c is radius of the tubing used in the packer string, in centimeters; and
t is the match-point time, in seconds.

To estimate the coefficient of storage, S, the following equation was used:

$$S=\alpha\frac{r_c^2}{r_s^2} \qquad (5)$$

where α is the recorded matching curves value; and
r_s is the radius of the open hole, in centimeters.

Based on the results of the injection tests, a fracture model probably is the predominant flow system during these short tests. Data analyses for the successful tests are presented in figures 16 through 21; a summary of the results is given in table 12. All data had only small departures from ideal. The 10-m zone from 687 to 697 m in the Prow Pass Member has much greater apparent transmissivity and average horizontal hydraulic conductivity than the other, deeper zones tested (table 12); for example, using a technique (Theis, 1963) described in the pumping-test section of this report, if the zone from 811 to 1,829 m were pumped at a constant rate and a drawdown in water level of 100 m occurred at the end of 24 hours, yield would be only 0.01 L/s; for the zone 688 to 697 m, comparable yield would be about 0.1 L/s.

The storage-coefficient values listed in table 12 indicate that the tested zones are under artesian conditions. Based on estimates for storage coefficients by Lohman (1979, p. 8), the values listed in the table appear to be of reasonable magnitude.

The computed values of average horizontal hydraulic conductivity given in table 12 for injection tests are quite similar to those values computed from pumping tests and radioactive-tracer surveys in table 11, where comparisons can be made for similar-depth zones.

GROUND-WATER CHEMISTRY

Water samples were collected for chemical analyses near the end of pumping tests of zones from 572 to 688 m and from 687 to 1,829 m. Because of the distribution of transmissivity, the samples mostly represent the zones from 572 to 653 m (upper part of the Prow Pass Member, table 10) and from 687 to 694 m and 736 to 758 m (mostly the upper part of the Bullfrog Member, table 11). The samples (table 13) are typical of water that is in tuffaceous rocks of southern Nevada, in that they are predominantly a sodium bicarbonate type containing small quantities of calcium, magnesium, and sulfate (Winograd and Thordarson, 1975, p. C97). Isotope-ratio determination for oxygen-18 and oxygen-16, deuterium-hydrogen, and carbon-14 determination indicate that the ground water was derived from precipitation apparently about 12,000 to 13,000 years before present and has been in transit in the ground-water system since. The apparent age is based on a carbon-14 half-life of either 5,568 or 5,730 years.

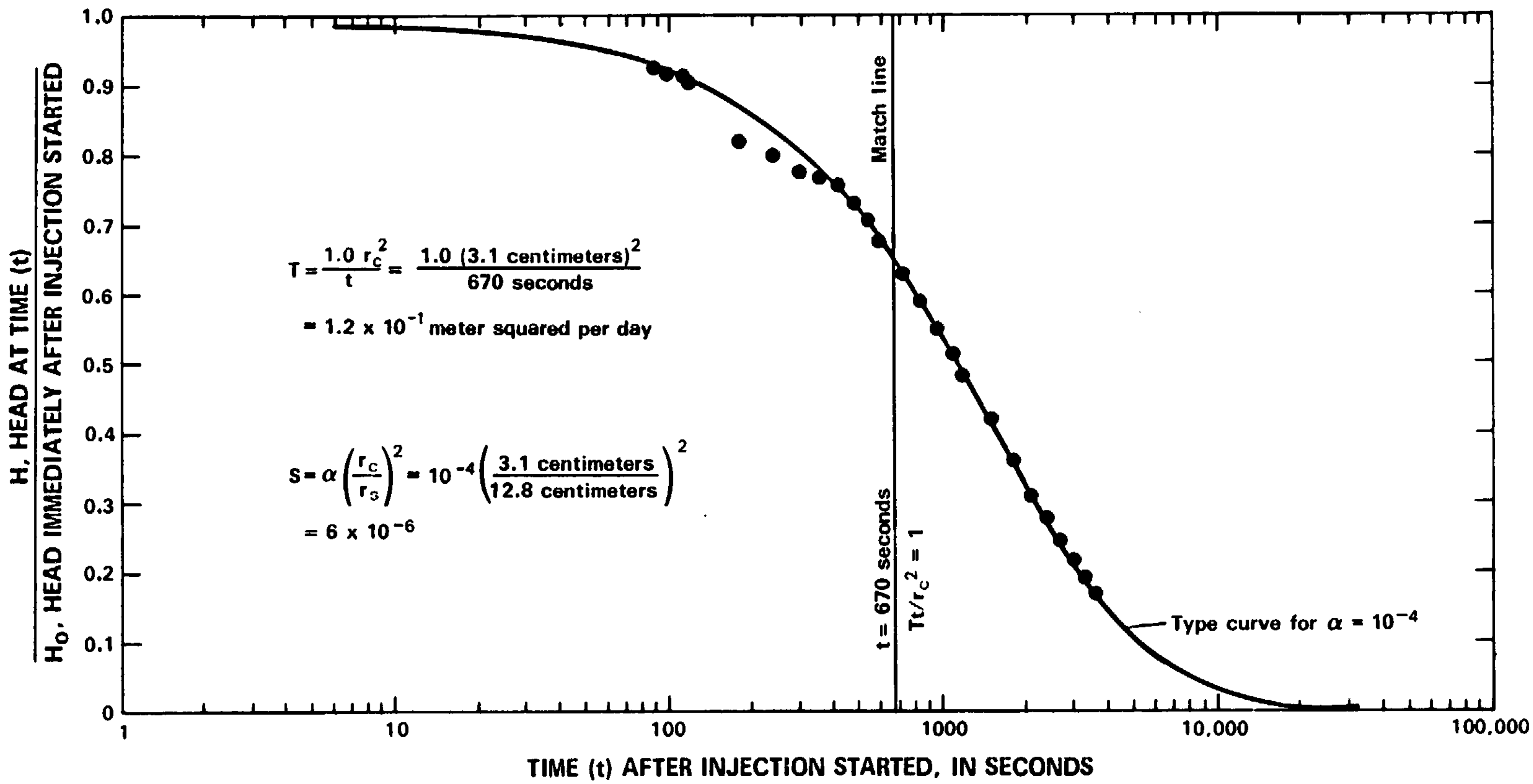

Figure 16.--Analysis of injection test for zone from 687 to 697 meters.

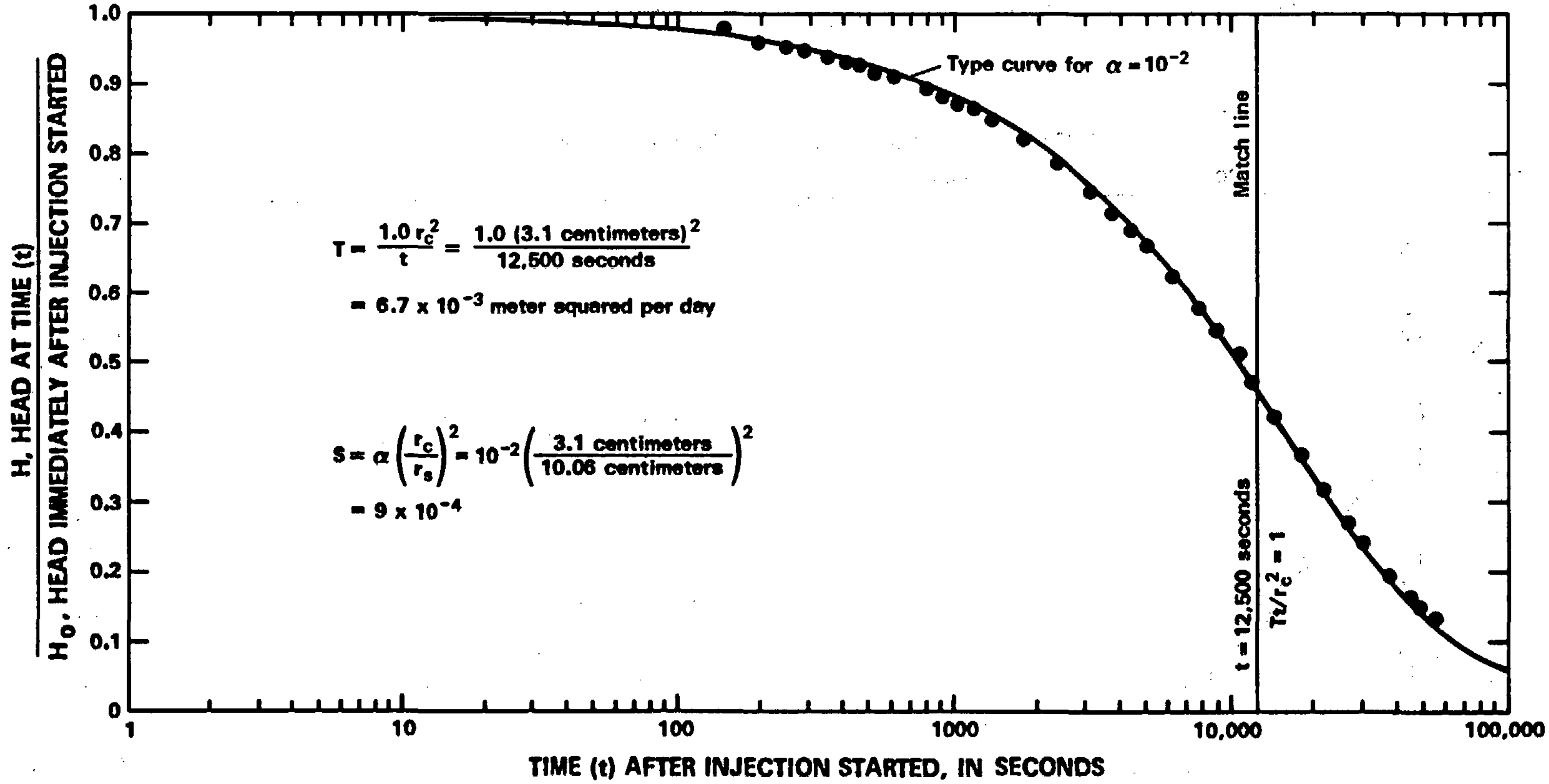

Figure 17.--Analysis of injection test for zone from 811 to 1,829 meters.

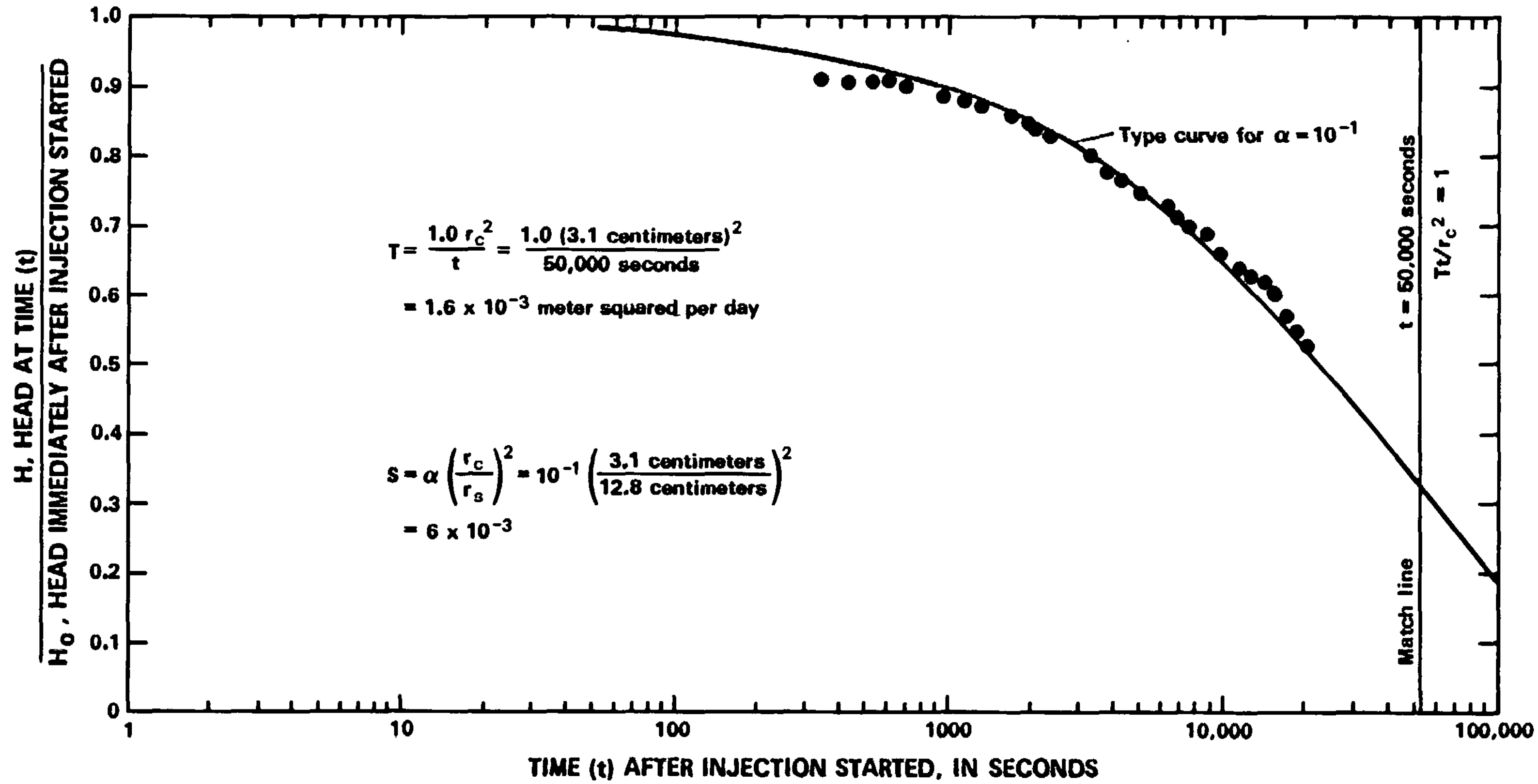

Figure 18.--Analysis of injection test for zone from 926 to 1,829 meters.

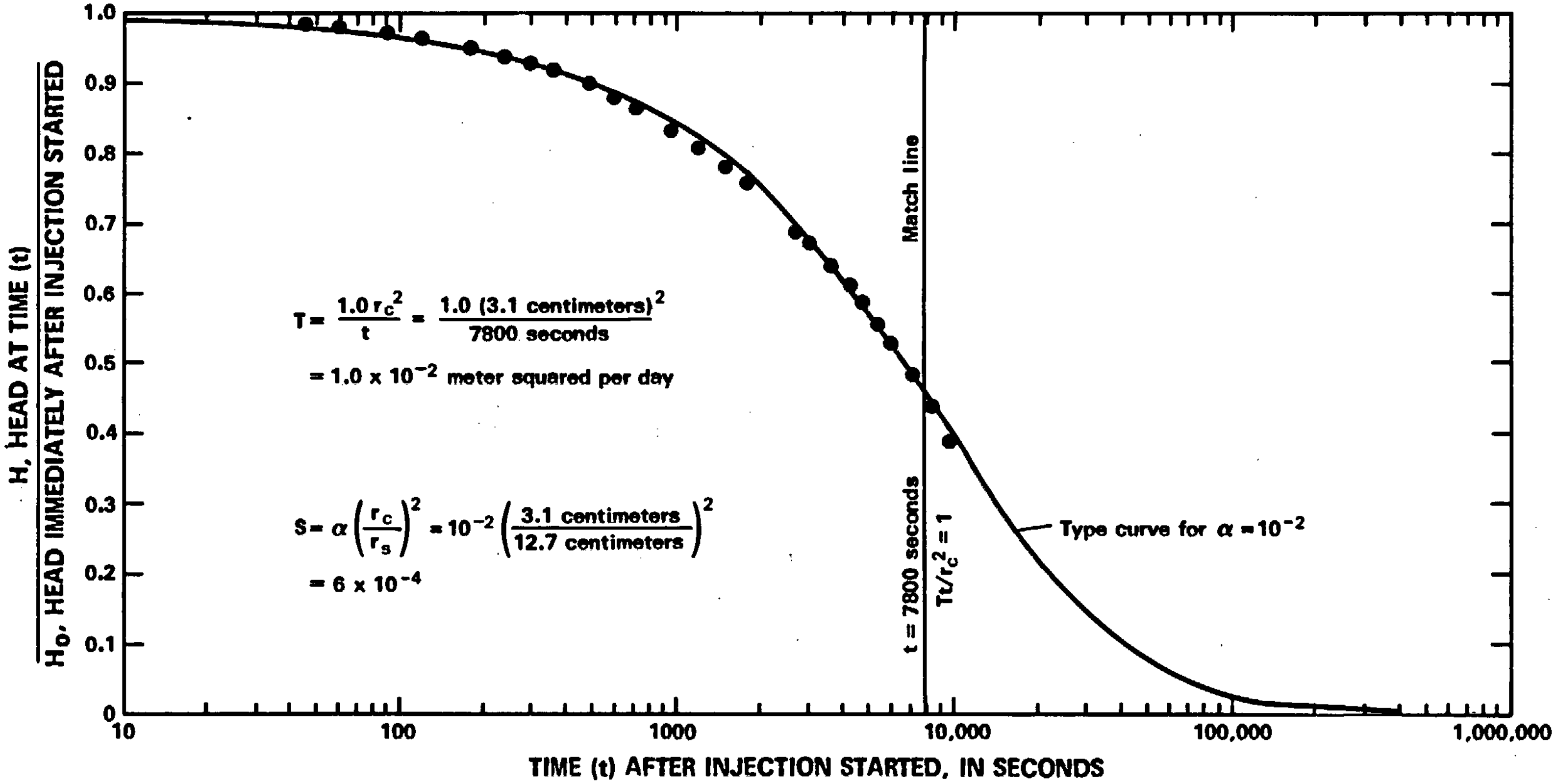

Figure 19.--Analysis of injection test for zone from 1,200 to 1,829 meters.

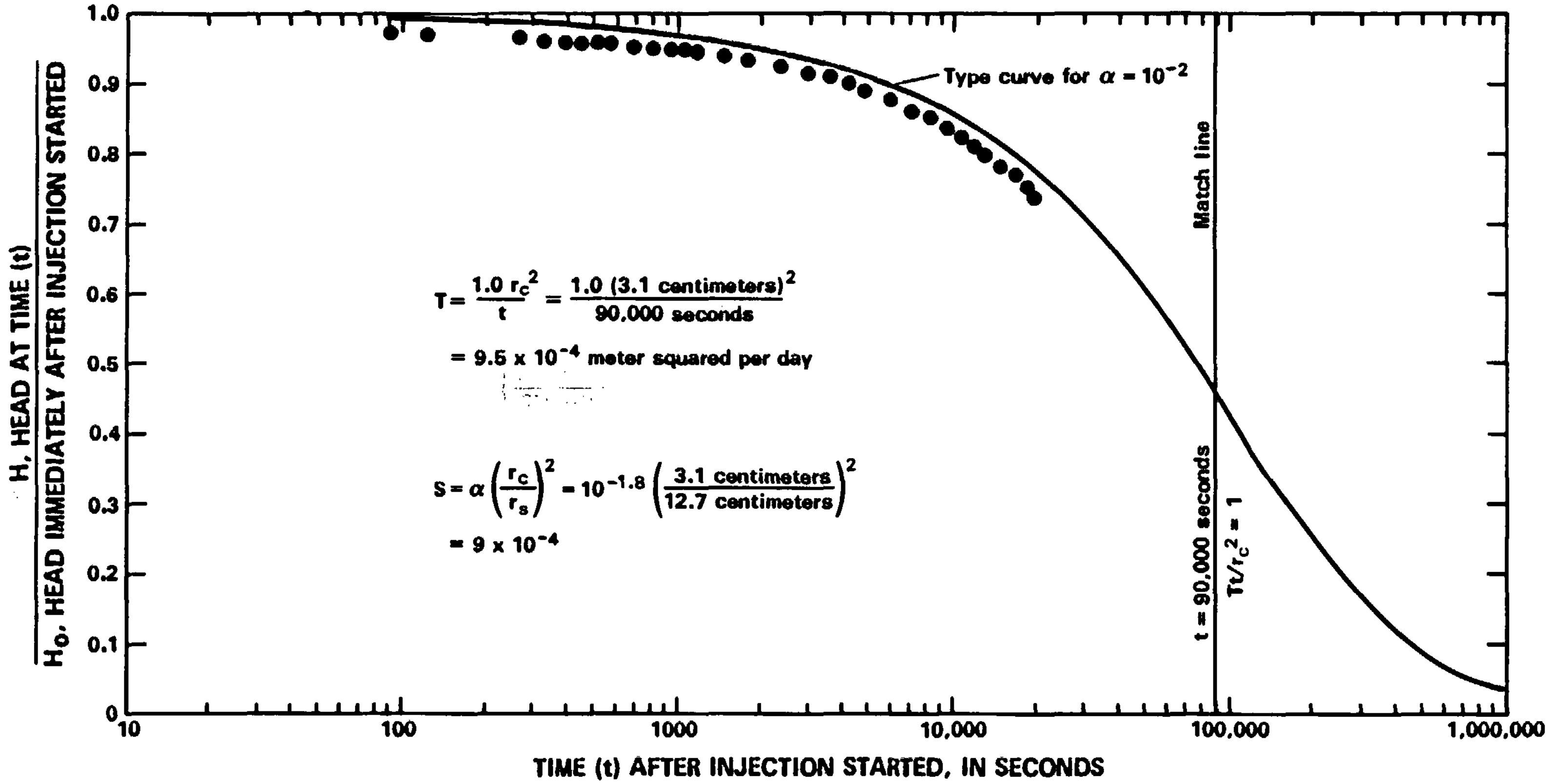

Figure 20.--Analysis of injection test for zone from 1,407 to 1,829 meters.

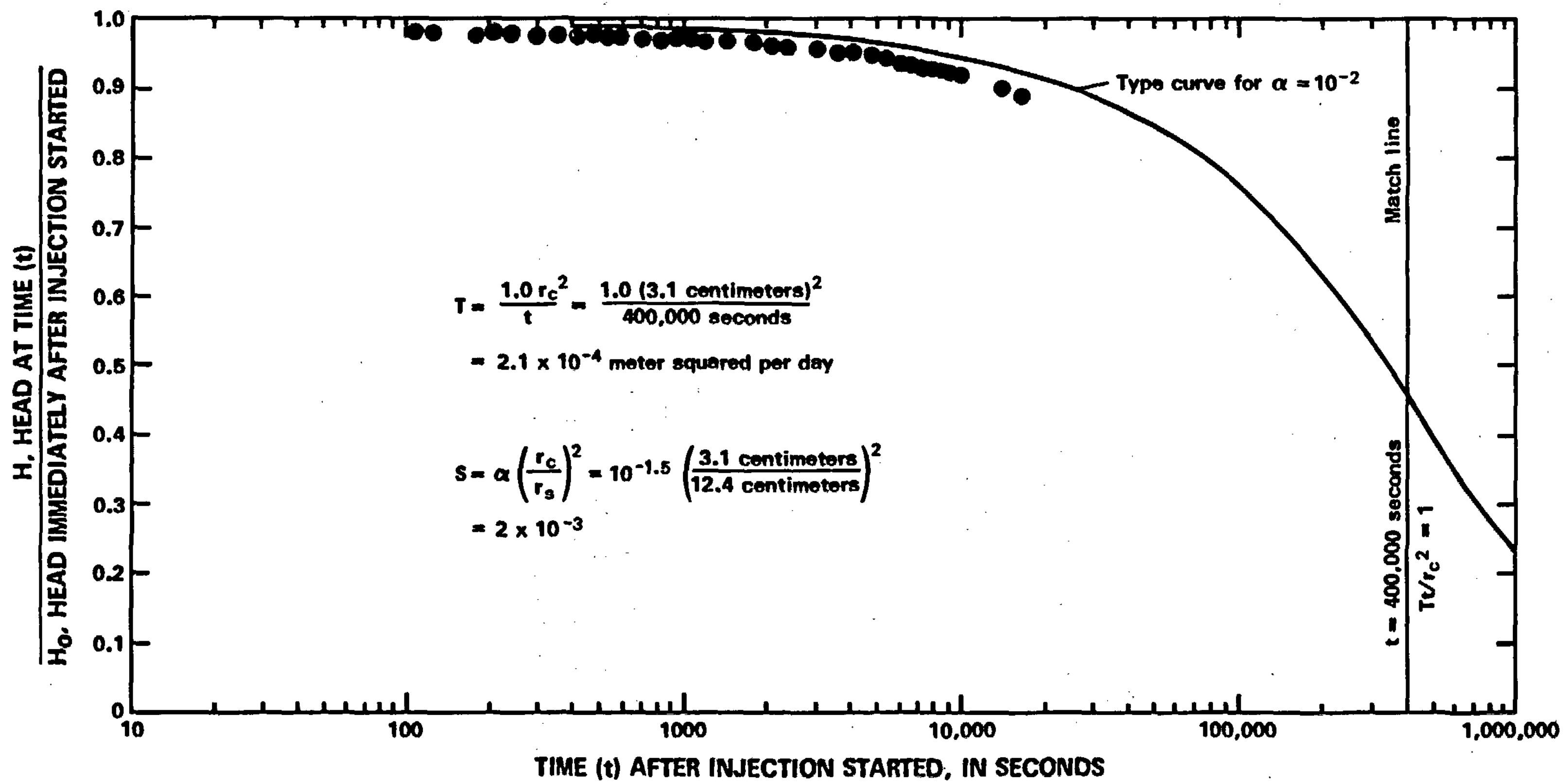

Figure 21.--Analysis of injection test for zone from 1,621 to 1,829 meters.

Table 12.--*Summary of injection-test results*

[As a homogeneous equivalent model]

Test interval (meters)	Stratigraphic unit(s) tested (See table 1 for rank and affiliated rock unit)	Apparent transmissivity, *T* (meter squared per day)	Estimated storage coefficient	Computed average horizontal hydraulic conductivity, *T* (meters per day)
687-697	Prow Pass Member----------------	1×10^{-1}	6×10^{-6}	1×10^{-2}
811-1,829	Bullfrog Member and underlying penetrated units.	7×10^{-3}	9×10^{-4}	7×10^{-6}
926-1,829	Tram Member and underlying penetrated units.	2×10^{-3}	6×10^{-3}	2×10^{-6}
[1]1,200-1,829	Flow breccia and underlying penetrated units.	[1]1×10^{-2}	6×10^{-4}	[2]3×10^{-6}
1,407-1,829	Lithic Ridge Tuff and older tuffs.	1×10^{-3}	9×10^{-4}	2×10^{-6}
1,621-1,829	Older tuffs--------------------	2×10^{-4}	2×10^{-3}	1×10^{-6}

[1]Results of this test are of questionable accuracy for unknown reasons. The transmissivity should be smaller than or equal to the value for the thicker zone that includes this zone, or $\leq 2\times10^{-3}$ meter squared per day.

[2]Computed from above footnote values of transmissivity.

Table 13.--*Results of chemical analyses of water samples*

[All units are milligrams per liter unless otherwise indicated]

Constituents	Sampled during pumping of interval 572 to 688 meters	Sampled during pumping of interval 687 to 1,829 meters
Data collected	10/20/80	12/08/80
Quantity of water pumped from zone prior to sampling (liters)	580,000	420,000
Bicarbonate (HCO^3)	115	122
Calcium (Ca)	4.5	6.2
Carbon-13/carbon-12 ratio	---------	-11.4
Carbon-14 (percent of modern standard)	19.8±4	22.4±1.5
Chloride (Cl)	5.7	5.8
Deuterium-hydrogen ratio	-103	-101
Fluoride (F)	1.2	1.0
Lithium (Li, micrograms per liter)	40	40
Magnesium (Mg)	0.0	0.0
Oxygen-18/oxygen-16	-13.4	-13.5
pH, laboratory	7.8	8.0
pH, onsite	7.7	7.5
Potassium-40 (picocuries per liter)	1.8	1.2
Potassium (K)	2.4	1.6
Residue on evaporation	176	188
Silica (SiO_2)	47	40
Sodium (Na)	51	51
Specific conductance, onsite (microsiemens[1])	255	247
Specific conductance, laboratory (microsiemens)	258	266
Strontium (Sr, micrograms per liter)	5	20
Sulfate (SO_4)	18	19
Temperature (degrees Celsius)	33	34.7
Tritium (picocuries per liter)	<20	<20
Cations (milliequivalents per liter)	2.50	2.57
Anions (milliequivalents per liter)	2.48	2.61
Difference (percent)	0.55	0.79

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

WELL-SITE GEOHYDROLOGY

In the previous sections of this report, results of the analyses of various sets of data have been presented. In this section, all results are considered, and data conflicts resolved, to develop a composited geohydrologic interpretation of each stratigraphic unit in the saturated-zone conceptual model and the units in the overlying unsaturated zone.

The Tiva Canyon Member crops out at the well site and has a thickness of 29 m (table 1). It is a partially welded to nonwelded ash-flow tuff with a thin-bedded tuff at the base. The unit probably is intensely fractured (table 7), especially the lower part, fractures extending from a depth of 12 m to its base, and into the underlying Yucca Mountain Member to a depth of 34 m. The unit is able to absorb percolating water from infiltration of the infrequent runoff in Drill Hole Wash (p. 5), along which the well was drilled. Runoff is from infrequent, localized, but commonly intense thundershowers during the spring and summer and occasionally is from rapid snowmelt. The small quantity of water that is not returned to the atmosphere by evapotranspiration before it reaches a depth of about 15 m will continue percolating toward the regional water table through this unit and several underlying units.

Underlying the Tiva Canyon Member is the 29-m-thick Yucca Mountain Member, a partially welded to nonwelded ash-flow tuff with about 9 m of bedded tuff at its base (table 1). Matrix porosity is about 40 to 45 percent (table 2), and pore saturation is about 50 percent. Like the overlying unit, the Yucca Mountain Member probably has abundant fractured rock (table 7). As indicated previously, a zone at the top of the unit from 29 to 34 m is especially fractured. A similar fracture zone is present at the base of the unit and extends into the underlying unit, from 44 to 74 m.

The Pah Canyon Member is present from a depth of 58 to 85 m and is a nonwelded ash-flow tuff (table 1). This unit is unusual in that it has no basal, bedded, or air-fall tuff. Core analysis of one sample indicates a porosity of 48 percent and a pore saturation of 34 percent (table 2). Like the two overlying stratigraphic units, this unit has an abundance of relatively porous rock (fig. 3 and p. 13) and is commonly fractured (table 7). A fracture zone extends into the unit from the overlying unit. In addition, an intensely fractured zone extends from 78 m to the lower contact at 85 m, and to 91 m in the underlying unit.

The Topopah Spring Member differs from the three overlying stratigraphic units because: (1) The unit is mostly a densely welded tuff (table 1) and is therefore brittle and intensely fractured (p. 8 and table 7) in several thick zones because of mechanical (geological) stress; (2) matrix porosity is much less (table 2), also related to the dense welding, ranging from about 20 percent near its upper contact to about 10 percent near its lower contact; and (3) pore saturation is greater (table 2), in the range of 50 to 80 percent.

Similarities among the overlying units are: (1) Fractures generally are abundant and able to transmit downward percolation of water; and (2) a basal bedded tuff (table 1), nearly 5 m thick, is present. This basal bed probably is perching downward-percolating water above it in the overlying 6 m (depth 448 to 454 m) of moderately to densely welded ash-flow tuff (p. 24). In addition, small water seeps issuing from moderately to densely welded tuff were observed at a depth of about 358 m (table 8).

The tuffaceous beds of Calico Hills are a 107-m thick unit of nonwelded ash-flow tuff and a basal bedded tuff (table 1). The two core samples of the ash-flow tuff had matrix porosities of about 40 percent, and pore saturations of 96 percent (table 2). The matrix porosity is similar to the stratigraphic units above the Topopah Spring Member, but the samples had much greater pore saturation. Small seeps of water were observed throughout the unit (table 8), especially at depths of 472 to 495 m and 526 to 533 m. Both zones are above the basal ash-flow tuff.

The Prow Pass Member contains the water table at a depth below land surface of 572 m (p. 24), 6 m below the top of the unit. The unit is 141 m of partially welded ash-flow tuff and a basal bedded tuff (table 1). Similar to the overlying unit, relatively porous rock is abundant at the contacts (fig. 3) but much less abundant toward the center of the interval. However, core analyses of these closely spaced samples from near the middle of the member had porosities of about 30 percent (table 3). Six fracture zones in the member were identified from the acoustic-televiewer log (table 5), two of which probably are open fractures at depths of 580 and 608 m (p. 15), near the top of the unit. Above the water table, at a depth of 570 m, relatively large water seeps were observed (table 8).

Vertical distribution of apparent transmissivity and apparent average hydraulic conductivity in eight saturated zones in the Prow Pass Member are summarized in table 14. The most permeable zone, 652 to 653 m, has an apparent average hydraulic conductivity of 18 m/d. Overlying zones in the interval 572 to 652 m have apparent hydraulic conductivities about one order of magnitude less; whereas, underlying zones in the interval 653 to 697 m generally are about three orders of magnitude less.

Comparisons of results between hydraulic conductivity values from in-situ tests of both fractures and matrix and core-sample analyses of matrix are given in table 15. For the Prow Pass Member, two zones are compared. The more permeable zone, depth 616 to 652 m, has mostly fracture permeability; whereas the lower zone, 697 to 736 m and the listed deeper zones, have only minor fracture permeability.

The Bullfrog Member is 125 m thick (table 1), at a depth of 707 to 832 m. It is an ash-flow tuff; the upper one-half is nonwelded and the lower one-half is partially to moderately welded. Near the contacts, a large percentage of the rock is relatively porous (table 4) and the interval from 707 to 762 m has a possible abundance of fractures (table 7), only that part of the interval below 736 had significant water production during pumping tests (fig. 5).

Table 14.--*Summary of transmissivity and average hydraulic conductivity for saturated zones, based on results of pumping and injection tests and radioactive-tracer surveys*

Depth interval (meters)	Apparent horizontal transmissivity, *T* (meters squared per day)	Apparent horizontal average hydraulic conductivity, *K* (meters per day)
	PROW PASS MEMBER	
572-597	74	3
597-616	18	1
616-652	40	1
652-653	18	18
653-688	<1	$\le 3\text{x}10^{-2}$
687-694	$1\text{x}10^{-1}$	$1\text{x}10^{-2}$
687-697	$1\text{x}10^{-1}$	$1\text{x}10^{-2}$
	PROW PASS AND BULLFROG MEMBERS	
694-736	$\le 1\text{x}10^{-2}$	$\le 2\text{x}10^{-4}$
	BULLFROG MEMBER	
736-741	$6\text{x}10^{-1}$	$1\text{x}10^{-1}$
741-758	$2\text{x}10^{-1}$	$1\text{x}10^{-2}$
758-792	$1\text{x}10^{-2}$	$3\text{x}10^{-4}$
792-811	$\le 3\text{x}10^{-3}$	$\le 2\text{x}10^{-4}$
	BULLFROG MEMBER AND TRAM MEMBER	
[1]811-926	$5\text{x}10^{-3}$	$4\text{x}10^{-5}$
	TRAM MEMBER AND FLOW BRECCIA	
[1]926-1,200	$\le 2\text{x}10^{-3}$	$\le 7\text{x}10^{-6}$
	FLOW BRECCIA AND LITHIC RIDGE TUFF	
[1]1,200-1,407	$\le 2\text{x}10^{-3}$	$\le 1\text{x}10^{-5}$
	LITHIC RIDGE TUFF AND OLDER TUFFS	
[1]1,407-1,621	$8\text{x}10^{-4}$	$4\text{x}10^{-6}$
	OLDER TUFFS	
[1]1,621-1,829	$2\text{x}10^{-4}$	$1\text{x}10^{-6}$

[1]Values for interval computed by difference from overlapping injection-test intervals.

Table 15.--*Comparison of hydraulic-conductivity values from in-situ tests and core-sample analyses*

[Only depth intervals listed that had three or more core samples. Fractures considered to be minor based on difference between total and matrix values for depth interval]

Stratigraphic unit (see table 1 for rank and affiliated rock unit)	Selected depth interval from table 14 (meters)	Apparent horizontal average hydraulic conductivity (meters per day)		
		Total, from in-situ tests (table 14)	Matrix, from core analyses (table 3)	Fractures (computed and rounded)
Prow Pass Member---------	616-652	1	[1]$8x10^{-5}$	1
Prow Pass and Bullfrog Members----------------	694-736	$\leq 2x10^{-4}$	[2]$3x10^{-4}$	minor.
Bullfrog Member----------	758-792	$3x10^{-4}$	[3]$4x10^{-4}$	Do.
Bullfrog and Tram Members	811-926	$4x10^{-5}$	[2]$4x10^{-5}$	Do.
Tram Member and flow breccia----------------	926-1,200	$\leq 7x10^{-6}$	[4]$2x10^{-4}$	-----

[1]Average for three core-sample analyses.
[2]Average for four core-sample analyses.
[3]Average for five core-sample analyses.
[4]Average for six core-sample analyses.

The stratigraphic unit is divided into six intervals for the purpose of defining distribution of horizontal transmissivity and hydraulic conductivity (table 14). All these intervals have minimal horizontal transmissivity and hydraulic conductivity except the interval from 736 to 741 m. This zone has an apparent horizontal average hydraulic conductivity of $1x10^{-1}$ m/d, an order of magnitude or more larger than the other zones (table 14). Based on data from tables 14 and 15, no fractures may be transmitting water in the approximate depth interval of 790-1,829 m.

The Tram Member is mostly a 284-m-thick, nonwelded to partially welded, ash-flow tuff, except for a very thin bedded tuff interval (about 1-m thick) near the top of the unit and a 12-m-thick bedded tuff at the base of the unit. Like the three overlying stratigraphic units, it has an abundance of porous rocks at its contacts. No fracture zones were identified at this site; only matrix porosity is present.

The Tram Member and small thicknesses of overlying and underlying stratigraphic units are divided into two zones at a depth of 926 m, for the purpose of evaluating hydraulic properties. The two zones have very similar values of transmissivity, about 10^{-3} m^2/d or less, and hydraulic conductivity, about 10^{-5} m/d. These are very small values, indicating relatively impermeable rock with few, if any open fractures.

Flow breccia, 119-m thick, underlies the Tram Member and contains an 8-m-thick tuff at its base (table 1). This unit is lithologically distinctive from the general stratigraphic sequence of ash-flow tuffs penetrated by the well. The unit is relatively porous (fig. 3) and probably contains minor fractures near the top, but they may not transmit water (p. 18). The unit has little apparent horizontal average hydraulic conductivity, about 10^{-5} m/d (table 14).

The Lithic Ridge Tuff is a thick (274 m) unit of partially welded ash-flow tuff with an 9-m-thick bedded or reworked tuff at the base (table 1). As in most of the penetrated stratigraphic units, there are relatively porous rocks at its contacts (fig. 4); otherwise, the unit has very little porous rock. No fractures were identified in the unit (table 7). Apparent horizontal average hydraulic conductivity of the unit is very small, about 10^{-5} to 10^{-6} m/d (table 14).

The lowest stratigraphic unit penetrated by the well, the older tuffs, extends from a depth of 1,509 m to a depth greater than the well (table 1). Three hundred and twenty meters of partially to moderately welded ash-flow tuff interbedded with bedded tuff were penetrated. An abundance of relatively porous rock is present at the upper contact for the unit (fig. 3), as well as within the penetrated part of the unit. Probably all the porosity is in the matrix. Five zones were identified from geophysical logs that are either fractured rock or bedded tuff (table 7). If these zones are fractured rock, the fractures are functionally closed because the apparent average horizontal hydraulic conductivity is about 10^{-6} m/d (table 14).

Data departure from ideal was small for pumping and injection tests that formed the principal basis for defining horizontal transmissivity.

CONCLUSIONS

Results of hydraulic tests, hydrologic monitoring, and geophysical log interpretations indicate:

1. The Topopah Spring Member and overlying Tiva Canyon, Yucca Mountain, and Pah Canyon Members generally are intensively fractured, relatively porous, and unsaturated. They also are permeable to downward percolating water recharging the ground-water system from precipitation and runoff. However, the quantity of recharge from precipitation and runoff is small because of the water-availability limits imposed by the desert climate.

2. The water table is at a depth of 572 m in the upper part of the Prow Pass Member. In the interval from 448 to 572 m, the rock is nearly saturated, with probably a perched saturated zone in the interval from 448 to 458 m.

3. Within the main saturated zone, moderately permeable rock is in the interval from 572 to 653 m in the Prow Pass Member. All underlying strata to the total depth of the well have minimal permeability, except for the interval from 736 to 741 m in the upper part of the Bullfrog Member, which is intermediate in permeability.

4. The most permeable part of the saturated zone, the interval from 572 to 688 m, has an apparent horizontal transmissivity of about 150 m^2/d. Below a depth of 688 m, the apparent horizontal transmissivity is about 1 m^2/d.

5. Hydraulic heads in the Tram Member and older ash-flow and bedded tuff are higher than in the overlying Prow Pass and Bullfrog Members, indicating an upward component of ground-water flow at the well. However, because of the minimal permeability of the rocks below the Bullfrog Member, the rate of upward flow is very small.

6. No fractures may be transmitting water in the depth interval 790-1,829 m. Any flow in this depth zone apparently is through rock matrix.

7. Water chemistry is typical for tuffaceous rocks of southern Nevada. The water has an apparent age of 12,000 to 13,000 years.

8. The conceptual model presented in this report probably is a good representation of the actual fracture-flow system near the well.

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