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Results of Hydraulic Tests in Miocene Tuffaceous Rocks at the C-Hole Complex, 1995 to 1997, Yucca Mountain, Nye County, Nevada

U.S. Geological Survey
Water-Resources Investigations Report 02-4141

Prepared in cooperation with the
U.S. DEPARTMENT OF ENERGY,
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Denver, Colorado
2002

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
cubic meter per day (m^3/d)	35.31	cubic foot per day
centimeter (cm)	0.393	inch
kilometer (km)	0.62139	mile
kilopascal (kPa)	0.14503	pound per square inch
liter (L)	0.26417	gallon
liter per second m (L/s)	15.85	gallon per minute
meter (m)	3.2808	foot
meter per day (m/d)	3.2808	foot per day
meter squared per day (m^2/d)	10.76	foot squared per day
microgram per liter (μg/L)	1	part per billion
milliequivalent per liter (meq/L)	1	equivalent per million
milligram (mg)	2.205×106	pound
milligram per liter (mg/L)	1	part per million
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=1.8 (°C)+32

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

The following abbreviations were used for units in both the metric and inch-pound systems:

ampere: A
hertz: Hz
kilowatt: KW
milliampere: mA
millidarcy: mD
ohm: Ω
volt: V
watt: W

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Abstract

Four hydraulic tests were conducted by the U.S. Geological Survey at the C-hole complex at Yucca Mountain, Nevada, between May 1995 and November 1997. These tests were conducted as part of ongoing investigations to determine the hydrologic and geologic suitability of Yucca Mountain as a potential site for permanent underground storage of high-level nuclear waste.

The C-hole complex consists of three 900-meter-deep boreholes that are 30.4 to 76.6 meters apart. The C-holes are completed in fractured, variably welded tuffaceous rocks of Miocene age. Six hydrogeologic intervals occur within the saturated zone in these boreholes—the Calico Hills, Prow Pass, Upper Bullfrog, Lower Bullfrog, Upper Tram, and Lower Tram intervals. The Lower Bullfrog and Upper Tram intervals contributed about 90 percent of the flow during hydraulic tests.

The four hydraulic tests conducted from 1995 to 1997 lasted 4 to 553 days. Discharge from the pumping well, UE-25 c #3, ranged from 8.49 to 22.5 liters per second in different tests. Two to seven observation wells, 30 to 3,526 meters from the pumping well, were used in different tests. Observation wells included UE-25 c #1, UE-25 c #2, UE-25 ONC-1, USW H-4, UE-25 WT #14, and UE-25 WT #3 in the tuffaceous rocks and UE-25 p #1 in Paleozoic carbonate rocks.

In all hydraulic tests, drawdown in the pumping well was rapid and large (2.9–11 meters). Attributable mostly to frictional head loss and borehole-skin effects, this drawdown could not be used to analyze hydraulic properties. Drawdown and recovery in intervals of UE-25 c #1 and UE-25 c #2 and in other observation wells typically was less than 51 centimeters. These data were analyzed.

Hydrogeologic intervals in the C-holes have layered heterogeneity related to faults and fracture zones. Transmissivity, hydraulic conductivity, and storativity generally increase downhole. Transmissivity ranges from 4 to 1,600 meters squared per day; hydraulic conductivity ranges from 0.1 to 50 meters per day; and storativity ranges from 0.00002 to 0.002.

Transmissivity in the Miocene tuffaceous rocks decreases from 2,600 to 700 meters squared per day northwesterly across the 21-square-kilometer area affected by hydraulic tests at the C-hole complex. The average transmissivity of the tuffaceous rocks in this area, as determined from plots of drawdown in most or all observation wells as functions of time or distance from the pumping well, is 2,100 to 2,600 meters squared per day. Average storativity determined from these plot ranges is 0.0005 to 0.002. Hydraulic conductivity ranges from less than 2 to more than 10 meters per day; it is largest where prominent northerly trending faults are closely spaced or intersected by northwesterly trending faults.

During hydraulic tests, the Miocene tuffaceous rocks functioned as a single aquifer. Drawdown occurred in all monitored intervals of the C-holes and other observation wells, regardless of the hydrogeologic interval being pumped.

This hydraulic connection across geologic and lithostratigraphic contacts is believed to result from interconnected faults, fractures, and intervals with large matrix permeability. Samples of UE-25 c #3 water, analyzed from 1995 to 1997, seem to indicate that changes in the quality of the water pumped from that well are probably due solely to lateral variations in water quality within the tuffaceous rocks.

INTRODUCTION

Information contained in this report is presented as part of ongoing investigations by the U.S. Geological Survey (USGS) regarding the hydrologic and geologic suitability of Yucca Mountain, Nev., as a potential site for permanent underground storage of high-level nuclear waste. This investigation was conducted by the Yucca Mountain Project Branch (YMPB) of the USGS, in cooperation with the U.S. Department of Energy (DOE), under Interagency Agreement DE–AI08–92NV10874.

Purpose and Scope

This report presents information obtained from three cross-hole hydraulic tests conducted together with tracer tests in Miocene tuffaceous rocks at the C-hole complex at Yucca Mountain, Nev. (fig. 1), from June 1995 to November 1997. The report describes the tests that were conducted, discusses changes in water levels and chemistry observed in monitoring wells as a result of pumping, describes analyses performed on the test data, presents values of hydraulic properties determined from test analyses, and evaluates uncertainties associated with the test data, analyses, and quantitative results.

Previous Work

Hydrogeologic intervals discussed in this report were identified by Geldon (1996) on the basis of borehole geophysical logs, borehole flow surveys, cross-hole seismic tomography, and aquifer tests that were done between 1983–84 (when the C-holes were drilled) and 1995. Geophysical logs that have been run in the C-holes include caliper, borehole-deviation, temperature, resistivity, gamma-gamma, acoustic, epithermal neutron, acoustic televiewer, and television logs (Geldon, 1993).

Flow surveys that have been run in the C-holes include tracejector, heat-pulse flowmeter, spinner, and oxygen activation surveys (Geldon, 1993, 1996). Tracejector surveys using radioactive iodide were run in the C-holes during hydraulic tests conducted in 1983 and 1984. Heat-pulse flowmeter surveys were run in the C-holes in 1991 without the boreholes being pumped. Spinner and oxygen-activation surveys were run in borehole UE-25 c #3 during a hydraulic test in June 1995.

In 1993, a seismic tomogram was done between boreholes UE-25 c #2 and UE-25 c #3 by Lawrence Berkeley Laboratory (LBL) for the USGS (Ernie Majer, LBL, written commun., 1993). The tomogram showed many of the hydrogeologic details evident from borehole lithologic and geophysical logs and flow surveys.

The way in which hydrogeologic intervals in the C-holes transmit water and the hydraulic properties of these intervals were determined provisionally by Geldon (1996) from geophysical logs, laboratory analyses, and aquifer tests. A matrix porosity profile for the C-holes was developed by Geldon (1993) from a gamma-gamma log and nine values of core porosity obtained from UE-25 c #1 in 1983. A matrix permeability profile for the C-holes was developed by Geldon (1996) from permeameter tests on 89 core samples obtained from the C-holes and four nearby boreholes between 1980 and 1984. A hydraulic-conductivity profile for the C-holes was developed by Geldon (1996) by analyzing falling-head and pressure-injection tests that were done in UE-25 c #1 in 1983. Transmissivity, hydraulic conductivity, and storativity of discrete intervals within the Calico Hills Formation and Crater Flat Group were determined by Geldon (1996) from analyses of a constant-flux injection test in UE-25 c #2 and three hydraulic tests in UE-25 c #2 and UE-25 c #3 that were done in 1984.

From May 22 to June 12, 1995, immediately prior to the series of hydraulic tests discussed in this report, an open-hole hydraulic test was conducted in borehole UE-25 c #3. Simultaneous monitoring of water-level and atmospheric-pressure fluctuations in 1993 established the barometric efficiency of the C-holes for the 1995 test (Geldon and others, 1997). The open-hole hydraulic test was designed to determine the transmissivity, hydraulic conductivity, and

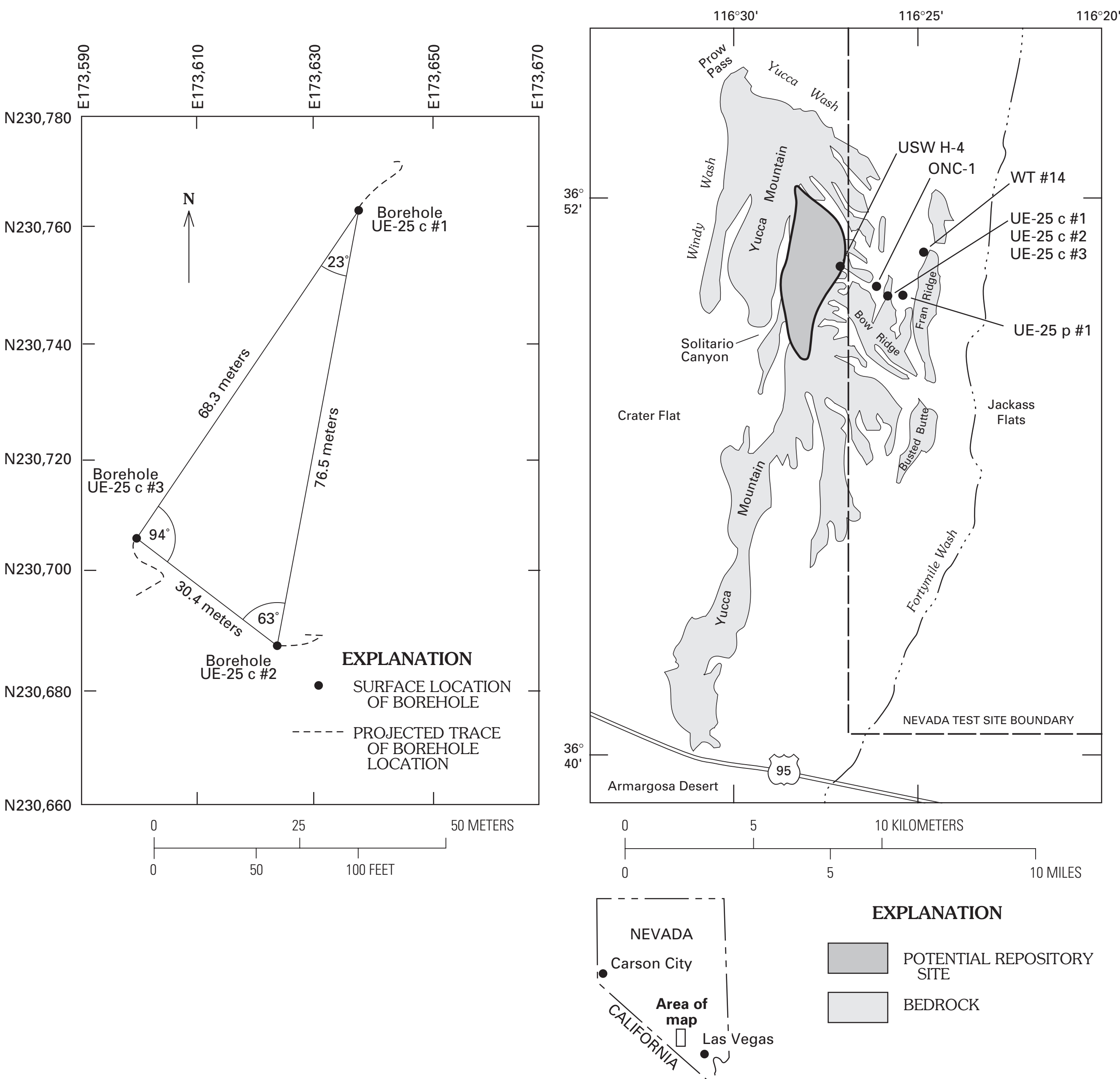


Figure 1. Location of the C-hole complex, boreholes UE-25 c #1, UE-25 c #2, and UE-25 c #3 (C-hole map is referenced to Nevada State, Zone 2, coordinates).

storativity of the composite saturated thickness of Miocene tuffaceous rocks at the C-hole complex, lateral variations in hydraulic properties within a 2-mile radius of the C-hole complex, and possible hydraulic connection between the Miocene tuffaceous rocks and a regional aquifer composed of Paleozoic carbonate rocks. This test is described by Geldon and others (1998) and will be discussed in this report only to support analyses and interpretations presented herein.

Ferrill and others (1999) analyzed the data for the May 1996 to November 1997 hydraulic test at the C-hole complex. They estimated horizontal anisotropy of aquifer transmissivity on the basis of data from four observation wells and determined that the axis of the maximum transmissivity tensor is oriented N30°E (Ferrill and others, 1999, p. 7). The estimated maximum transmissivity in this direction is 5,400 m^2/d, and the estimated minimum transmissivity (oriented perpendicular to the maximum tensor) is

315 m^2/d, although these values are poorly constrained (Ferrill and others, 1999, p. 7).

Acknowledgments

The authors recognize the contributions of several employees and contractors of the USGS who volunteered time and effort beyond the scope of their routine duties to make this study possible. The authors also recognize the contributions of people from the many organizations participating in the Yucca Mountain Project whose cooperation was essential for completion of this study. Russell L. Patterson (U.S. Department of Energy), William B. Distel and Roger Henning (Woodward-Clyde Federal Services), and Andrea Randall and Thomas Pysto (Science Applications International Corporation) coordinated activities among Yucca Mountain Project participants, U.S. Department of Energy, and State of Nevada regulatory agencies to enable the hydraulic tests discussed in this report to proceed. Personnel from Los Alamos National Laboratory, under the direction of Paul Reimus, manned the site from May to November 1996, and shared equipment, data, and ideas.

HYDROGEOLOGIC SETTING

The C-hole complex is located in Nye County, Nev., at the western edge of the Nevada Test Site, about 145 km northwest of Las Vegas (fig. 1). The C-holes are in a channel of an ephemeral stream that cuts through Bow Ridge, a spur of Yucca Mountain (fig. 2). The C-hole complex is a two-tiered drill pad. The lower tier, in which borehole UE-25 c #1 was drilled, is at an altitude of about 1,130.5 m above sea level. The upper tier, in which boreholes UE-25 c #2 and UE-25 c #3 were drilled, is at an altitude of about 1,132.3 m. The C-holes are 30.4–76.5 m apart at the land surface (fig. 1), but interborehole distances vary substantially at depth because of borehole deviation during drilling (table 1 and fig. 1).

The C-holes are completed in Miocene tuffaceous rocks (table 2), that are covered by 0–24 m of Quaternary alluvium. The tuffaceous rocks are estimated to be 1,040–1,590 m thick in the vicinity of the C-holes, where they consist of nonwelded to densely welded ash-flow tuff with intervals of ash-fall tuff and volcaniclastic rocks (Geldon, 1993; Geldon and others, 1998). The tuffaceous rocks are pervaded by tectonic and cooling fractures that strike predominantly north-northeast to north-northwest and dip westward at angles of 50°–87° (Geldon, 1996, p. 4). Paleozoic limestone and dolomite (carbonate rocks) underlie the tuffaceous rocks about 455 m below the bottom of the C-holes (extrapolated from information about borehole UE-25 p #1 by Carr and others, 1986).

In the vicinity of the C-hole complex, northerly and northwesterly trending, high-angle faults, such as the Paintbrush Canyon, Midway Valley, and Bow Ridge Faults, have brecciated, offset, and tilted the Miocene tuffaceous rocks (Day and others, 1998; Dickerson and Drake, 1998). The dip of the tuffaceous rocks increases from 5^{o}–10^{o} eastward at the crest of Yucca Mountain to about 20^{o} eastward at the C-hole complex (Frizzell and Shulters, 1990). At the C-hole complex, the north-striking Midway Valley or Paintbrush Canyon Fault downfaulted Miocene tuffaceous rocks to the west. The Miocene tuffaceous rocks and the Midway Valley or Paintbrush Canyon Fault, later, were recast to the northeast by a northwest-striking fault that cuts through Bow Ridge (fig. 2).

Hydrogeologic data and numerical ground-water-flow modeling indicate that ground water recharged in the Yucca Mountain area discharges mostly to Carson Slough, Ash Meadows, Alkali Flat, the lower Amargosa River valley, and Death Valley (D'Agnese and others, 1997). Locally, ground water flows from mountains to valleys, mainly through Tertiary volcanic and tuffaceous rocks and Quaternary and Tertiary alluvium and lacustrine deposits. Controlled largely by faults and related fractures, ground water flows from basin to basin mainly through Paleozoic carbonate rocks (Faunt, 1997). Geldon and others (1998) concluded that a northwest-trending zone of discontinuous faults between Bow Ridge and Antler Wash also transmits ground water.

The potentiometric surface in the Miocene tuffaceous rocks at Yucca Mountain in the vicinity of the C-holes ranges from about 335 to 520 m below land surface (O'Brien and others, 1995, p. 3). In the C-holes, depths to water range from 400 to 402 m. Water in the tuffaceous rocks generally flows southeasterly (Ervin and others, 1994; Tucci and Burkhardt, 1995), but flow patterns can be disrupted by faults acting as conduits or barriers to flow. Sparse water-level data in the vicinity of the C-holes can be interpreted to show a ground-water divide centered on Bow Ridge and Boundary Ridge that directs flow southward to Dune

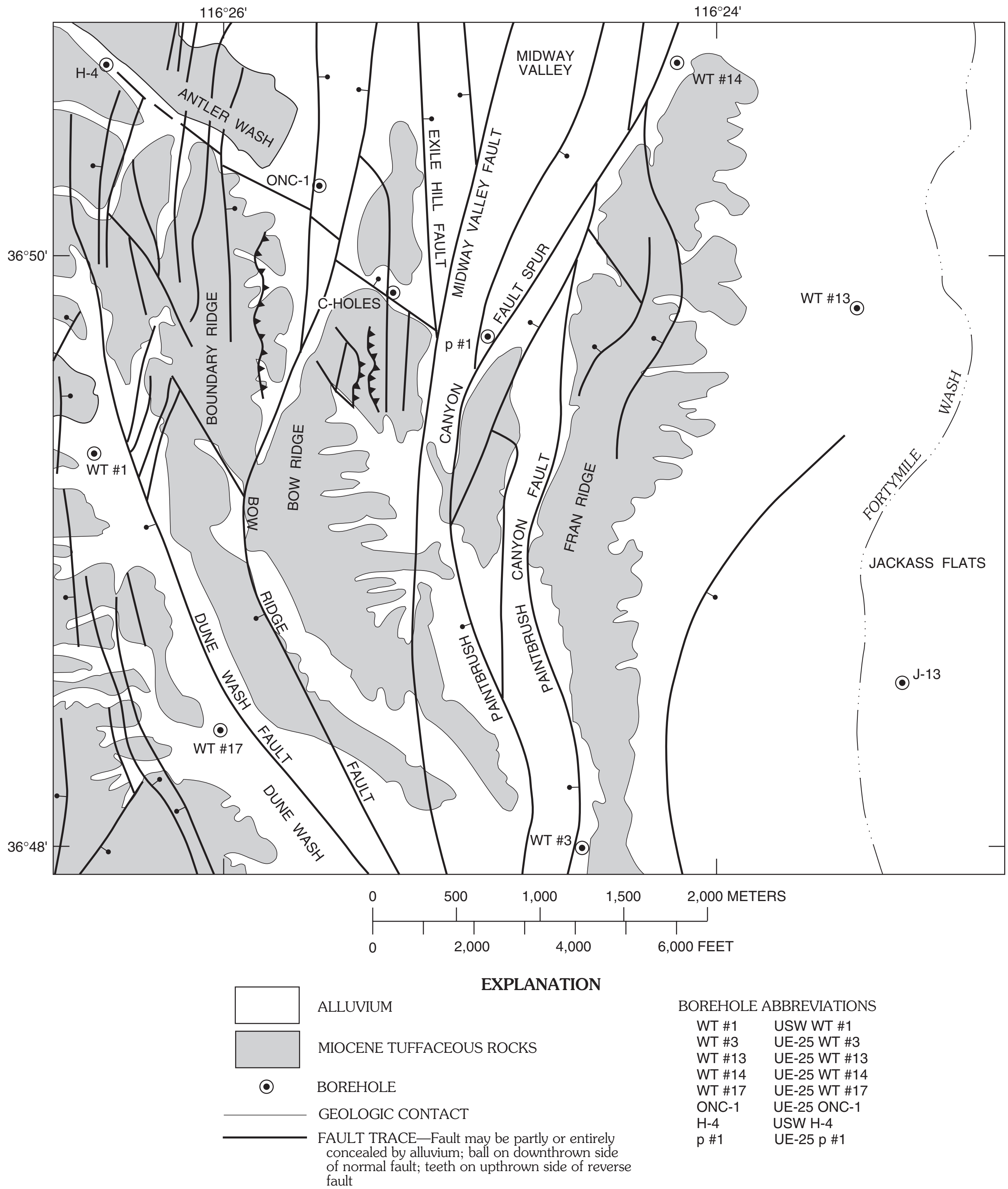


Figure 2. Generalized geologic map showing the location of the C-hole complex and nearby boreholes (Geldon and others, 1998, p. 5).

Table 1. Approximate interborehole distance at the midpoints of hydrogeologic intervals monitored during hydraulic tests at the C-hole complex, August 1995 to April 1996

[All figures in meters; north and south referenced to Nevada State, Zone 2 coordinates; depths in UE-25 c #3 and interborehole distances were changed slightly in April 1996, when instrumentation in UE-25 c #3 was reconfigured; c #1, UE-25 c #1; c #2, UE-25 c #2; c #3, UE-25 c #3; --, not applicable]

Physical Information	UE-25 c #1	UE-25 c #2	UE-25 c #3	c #1-c #3	c #2-c#3
			Calico Hills		
Top depth	418	416	417	78.6	29.0
Bottom depth	547	531	540	--	--
Midpoint depth	483	474	478	--	--
North coordinate	230,771	230,691	230,703	--	--
East coordinate	173,646	173,633	173,607	--	--
Distance north/south from c #3	68.3	12.2	--	--	--
Distance east/west from c #3	39.3	26.2	--	--	--
			Prow Pass		
Top depth	549	533	542	81.1	28.6
Bottom depth	605	606	610	--	--
Midpoint depth	577	569	576	--	--
North coordinate	230,772	230,691	230,702	--	--
East coordinate	173,648	173,634	173,607	--	--
Distance north/south from c #3	70.4	11.0	--	--	--
Distance east/west from c #3	40.2	26.5	--	--	--
			Upper Bullfrog		
Top depth	607	607	612	83.2	28.6
Bottom depth	698	696	695	--	--
Midpoint depth	653	652	653	--	--
North coordinate	230,773	230,691	230,701	--	--
East coordinate	173,648	173,634	173,607	--	--
Distance north/south from c #3	72.2	9.75	--	--	--
Distance east/west from c #3	41.4	26.8	--	--	--
			Lower Bullfrog		
Top depth	700	698	697	85.6	29.3
Bottom depth	797	792	813	--	--
Midpoint depth	749	745	755	--	--
North coordinate	230,774	230,692	230,700	--	--
East coordinate	173,649	173,633	173,606	--	--
Distance north/south from c #3	73.8	8.84	--	--	--
Distance east/west from c #3	43.3	27.7	--	--	--
			Upper Tram		
Top depth	799	794	814	86.9	29.6
Bottom depth	870	870	878	--	--
Midpoint depth	834	832	846	--	--
North coordinate	230,774	230,691	230,700	--	--
East coordinate	173,648	173,632	173,604	--	--
Distance north/south from c #3	74.7	8.53	--	--	--
Distance east/west from c #3	44.2	28.3	--	--	--
			Lower Tram		
Top depth	872	871	879	87.2	29.9
Bottom depth	898	903	900	--	--
Midpoint depth	885	887	890	--	--
North coordinate	230,774	230,691	230,700	--	--
East coordinate	173,648	173,632	173,603	--	--
Distance north/south from c #3	74.7	8.23	--	--	--
Distance east/west from c #3	44.8	28.6	--	--	--

Table 2. Stratigraphy of Miocene tuffaceous rocks in the C-hole area (Geldon and others, 1998, table 1, p. 6)

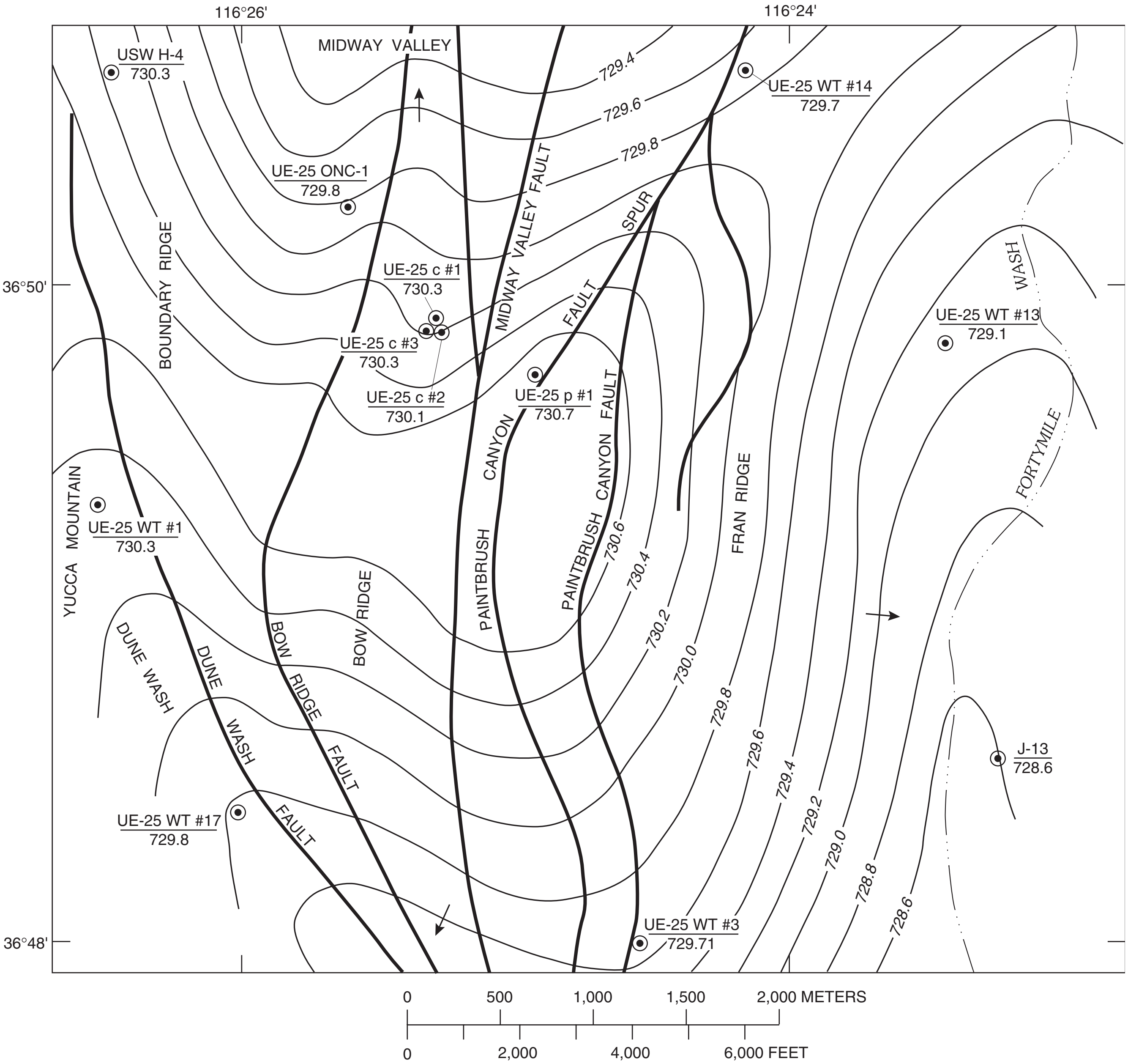
Geologic Unit	Depth, meters below land surface				
	USW H-4	UE-25 c #1	UE-25 c #2	UE-25 c #3	UE-25 p #1
Timber Mountain Group					
Rainier Mesa Tuff	not present	not present	not present	not present	39–55
Paintbrush Group					
Tiva Canyon Tuff	0–65	0–96	21–88	24–88	55–81
Topopah Spring Tuff	65–400	96–406	88–401	88–396	81–381
Calico Hills Formation	400–496	406–516	401–510	396–496	381–436
Crater Flat Group					
Prow Pass Tuff	496–693	516–656	510–652	496–644	436–558
Bullfrog Tuff	693–812	656–828	652–829	644–814	558–691
Tram Tuff	812–1,164	828–914+	829–914+	814–914+	691–873
Lithic Ridge Tuff	1,164–1,219+	not reached	not reached	not reached	873–1,068

Wash, northward to Midway Valley, and eastward to Fortymile Wash (fig. 3). Flow from the west into the area of the C-holes is inhibited by the northerly striking Solitario Canyon Fault (Tucci and Burkhardt, 1995). The Solitario Canyon Fault (fig. 1) is interpreted to be a constant-head boundary, whereas discharge areas north, east, and south of the C-hole complex are interpreted to be head-dependent flux boundaries.

The Miocene tuffaceous rocks in the area of the C-hole complex comprise a single dual-permeability aquifer, in which the volume and direction of ground-water flow are controlled mainly by proximity to faults, fracture zones, and partings (Geldon and others, 1998). Fractures in transmissive intervals have no preferred orientation, and the fracture density appears to be unrelated to the extent of welding and permeability. Matrix permeability of the Calico Hills Formation and Crater Flat Group within 5 km of the C-hole complex can be as much as 20 mD. On the basis of barometric efficiency and specific storage, the average effective porosity of the Calico Hills Formation near the water table in the C-holes was determined by Geldon and others (1997) to be 36 percent. The Crater Flat Group is much less porous than the Calico Hills Formation, and the average porosity of these two geologic units in the C-holes is 21 percent (computed from porosity values reported by Geldon, 1993). Despite the influence of fractures, rock within about 3 km of the C-hole complex consistently responds to hydraulic tests as an equivalent porous medium.

Borehole flow surveys, in combination with geophysical logs and aquifer tests, show that flow within the Miocene tuffaceous rocks at the C-hole complex occurs within discrete intervals (fig. 4). The total thickness of transmissive intervals identified in individual boreholes ranges from 165 to 274 m (Geldon, 1996). Hydraulic tests conducted in 1984 indicated that these intervals have layered heterogeneity (Geldon, 1996, p. 69). A hydraulic test conducted at the C-hole complex from May 22 to June 12, 1995, indicated that the composite section of Miocene tuffaceous rocks in the vicinity of the C-holes has a transmissivity of 2,300 m^2/d and a storativity of 0.003 (Geldon and others, 1998, p. 25). This same test indicated transmissivity values of 1,600 to 3,200 m^2/d and storativity values of 0.001 to 0.003 for the rocks in individual boreholes (UE-25 c #1, UE-25 c #2, UE-25 ONC-1, and USW H-4).

Because only one borehole (UE-25 p #1) penetrates the Paleozoic carbonate rocks in the vicinity of the C-holes, little is known about hydrologic properties of these rocks in this area. An estimated transmissivity of 111 m^2/d is reported for the Paleozoic carbonate rocks penetrated by borehole UE-25 p #1 (Craig and Robison, 1984, p. 22–28). The closest cross-hole hydraulic tests, which were conducted in the Amargosa Desert about 38 km southeast of the C-hole complex, indicated transmissivity values



EXPLANATION

USW H-4 / 730.3 — BOREHOLE WITH BOREHOLE NUMBER ABOVE LINE AND WATER-LEVEL ALTITUDE, IN METERS ABOVE NGVD OF 1929 BELOW LINE

730.0 — POTENTIOMETRIC-SURFACE CONTOUR—Shows altitude above NGVD of 1929 at which water would have stood in tightly cased wells completed in the Miocene tuffaceous rocks in May 1995. Water-level altitude in UE-25 p #1 estimated from the measured hydraulic head of Paleozoic carbonate rocks and the vertical head gradient between the Paleozoic carbonate rocks and Miocene tuffaceous rocks in the borehole. Arrow indicates approximate direction of ground-water flow. Contour interval is 0.2 meter

TRACE OF MAJOR FAULT

Figure 3. Potentiometric surface of the Miocene tuffaceous rocks in the vicinity of the C-hole complex, May 1995 (water-level altitudes from Graves and others, 1997; Nye County Nuclear Waste Repository Project Office, written commun., 1995).

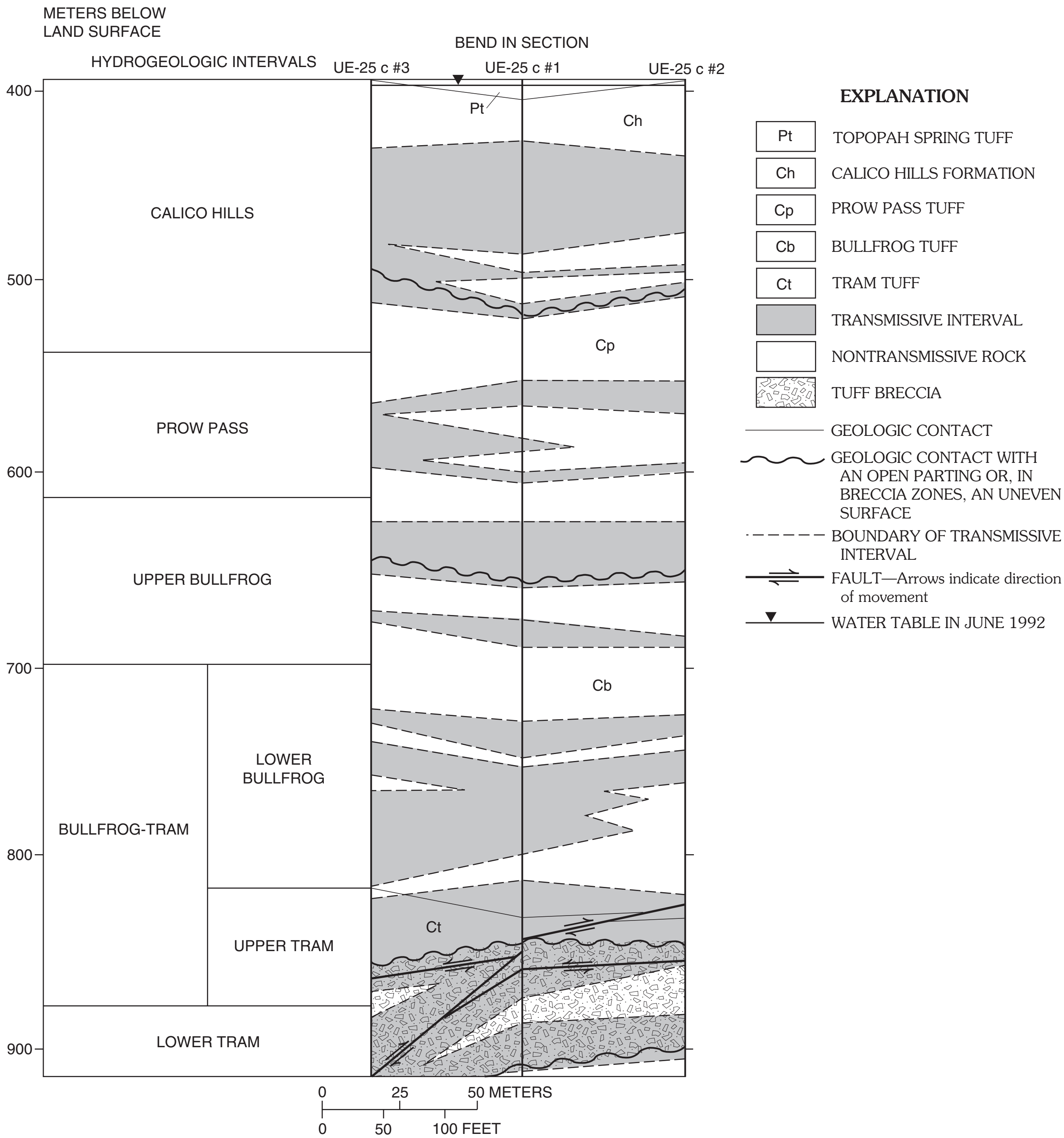


Figure 4. Hydrogeologic intervals in the C-holes, May 1995 to December 1997 (modified from Geldon, 1996, fig. 7A, p. 18).

between 4,800 and 10,900 m^2/d and a storativity of 0.0005 (Leap and Belmonte, 1992, p. 89).

INSTRUMENTATION

Principal components of the equipment installed at the C-hole complex to conduct hydraulic tests from 1995 to 1997 are described briefly in this report. Although available commercially, much of this hardware and software has not been used extensively because of its relatively recent development. Consequently, all of the equipment received extensive performance evaluation during prototype hydraulic tests conducted jointly with Lawrence Berkeley Laboratory (LBL) from 1992 to 1994 at a research site near Raymond, Calif. Modifications to system components and their assembly were made to address problems encountered during prototype testing and after the equipment was installed and used initially at the C-hole complex. With few exceptions (discussed below), most system components performed remarkably well, despite being operated almost continuously for more than 2 years.

Packers

Dual-mandrel packers manufactured by TAM International, Inc., were installed in UE-25 c #1 and UE-25 c #2 throughout the tests and in UE-25 c #3 after August 1995. The packers are about 1.83 m long (fig. 5) and have a diameter of about 21.6 cm when deflated. Suspended on 7.30-cm-diameter tubing, each packer contains 12 pass-through tubes to allow packer-inflation lines and electrical cable to be installed in the borehole. The packers are inflated individually by the injection of argon gas through 0.64-cm, stainless steel tubing. Inflation pressures, which are about 1,034 kPa above hydrostatic pressure, range from about 2,758 to 5,861 kPa at the depths at which packers were set in the C-holes from 1995 to 1997. Packer depths from 1995 to 1997, as measured from the land surface, are listed in table 3.

Transducers

Continuous records of pressure and temperature in packed-off intervals during hydraulic tests were obtained using absolute pressure transducers manufactured by Paroscientific, Inc. (Absolute pressure transducers record water pressure plus atmospheric pressure, whereas differential pressure transducers record only the water pressure.) The transducers used in the C-holes were strapped into brackets welded onto the 7.30-cm-diameter tubing, on which the packers were suspended (fig. 5).

Paroscientific transducers measure the oscillating frequency of a quartz crystal as it changes in response to changes in pressure. An internal sensor simultaneously records the temperature of the water in which the transducer is immersed. A digital serial interface board passes the pressure and temperature signals through a microprocessor-controlled operating program stored in permanent memory that calculates temperature-compensated pressures at user-specified intervals. The user communicates with the transducer through an RS-232 interface. Factory calibrations indicate that the transducers have an accuracy of ±7.04 cm of hydraulic head. Field determinations indicated a precision of 0.30 cm under pumping conditions and 0.061 cm under nonpumping conditions.

Although transducers were installed in all hydrogeologic intervals, several of the transducers failed after installation. Transducers that were operative during some or all of the hydraulic tests conducted from 1995 to 1997 and the locations of these transducers, as determined by subtracting recorded pressure heads from static water-level altitudes, are listed in table 4. Listed transducer altitudes have an accuracy of ± 0.3 m.

Barometers

A nonsubmersible, temperature-compensated pressure transducer manufactured by Paroscientific, Inc., was used as a barometer during the hydraulic tests discussed in this report. The barometer, which was emplaced in a temperature-controlled office trailer at the C-hole complex, operates in the same way as the transducers installed in the C-holes to record water pressure. The factory-calibrated accuracy of this barometer is ± 0.005 percent of its full operating range (103 kPa). The barometer was checked periodically against another barometer of the same type, which was located at the site.

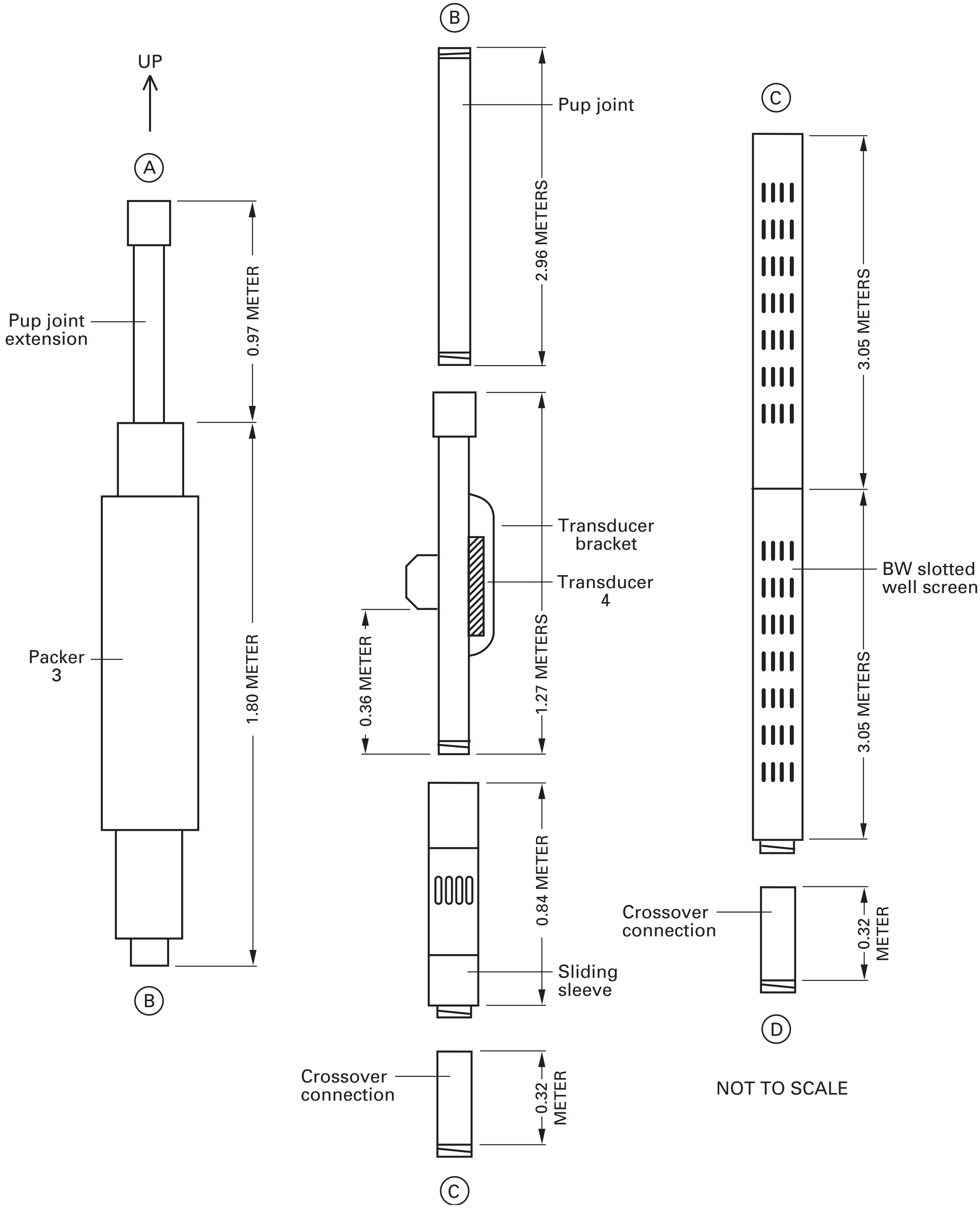


Figure 5. Instrument-string assembly in UE-25 c #3, Lower Bullfrog interval, April 1996 to December 1997.

Table 3. Location of packers emplaced in the C-holes for hydraulic tests, 1995 to 1997

[No packers in UE-25 c #3 before August 1995]

Packer number	Packer depth (meters below land surface)			
	UE-25 c #1	UE-25 c #2	UE-25 c #3	
			8/95–4/96	4/96–Present
1	547.4–549.3	531.3–533.1	540.4–542.2	None
2	605.3–607.2	605.6–607.5	609.9–611.7	None
3	698.3–700.1	696.5–698.3	695.0–696.8	694.6–696.5
4	797.1–798.9	791.9–793.7	812.6–814.4	812.9–814.7
5	869.9–871.7	869.6–871.4	877.5–879.4	878.1–880.0

Table 4. Operative transducers in the C-holes, 1995 to 1997

Borehole	Interval	Transducer		
		Number	Depth (meters)	Altitude (meters)
UE-25 c #1	Prow Pass	2	552.09	578.51
	Upper Bullfrog	3	610.03	520.57
	Lower Bullfrog [1]	4	703.04	427.56
UE-25 c #2	Calico Hills	1	519.83	612.36
	Prow Pass	2	536.28	595.91
	Upper Bullfrog	3	610.70	521.49
	Lower Bullfrog [1]	4	701.58	430.61
UE-25 c #3	Calico Hills [2]	1	533.81	598.62
	Upper Bullfrog	3	614.49	517.93
	Lower Bullfrog [3]	4	708.93	423.49
	Upper Tram [4]	5	817.68	314.75

[1]Monitored Lower Bullfrog and Upper Tram, combined, February to March 1996.

[2]Listed transducer locations are for August 1995 to March 1996. Prior to August 1995, a single transducer was installed in the Calico Hills interval at a depth of 441.12 meters (altitude=691.30 meters) to monitor the composite geologic section in UE-25 c #3. After April 1996, a new transducer was installed at a depth of 691.31 meters (altitude=441.11 meters) to monitor the Calico Hills, Prow Pass, and Upper Bullfrog intervals combined.

[3]Operative after April 1996.

[4]Monitored Lower Bullfrog and Upper Tram, combined, in February and March 1996; replaced in April 1996 by a transducer at a depth of 819.32 meters (altitude = 313.11 meters).

Pumps

A 37-stage, 25.2-L/s capacity, Centrilift submersible pump was used during a hydraulic test in June 1995. The pump, enclosed in a protective shroud, was suspended in borehole UE-25 c #3 on 13.9-cm-diameter tubing. The pump intake depth was 450.1 m (48.0 m below the water-level altitude prior to pumping). The pump was powered by a 250-KW generator, and its frequency was regulated by a variable-speed controller. Water discharged by the pump was transported by a 15-cm-diameter pipeline to a leachfield in Fortymile Wash, about 8 km from the C-hole complex.

The original pump was replaced in August 1995 by a 43-stage, 12.6 L/s-capacity, Centrilift submersible pump. The pump, enclosed in a protective shroud, was offset from the main part of the 7.30-cm-diameter tubing on which the packers were suspended by a 22.9-m-long "Y-block" assembly (fig. 6). The Y-block

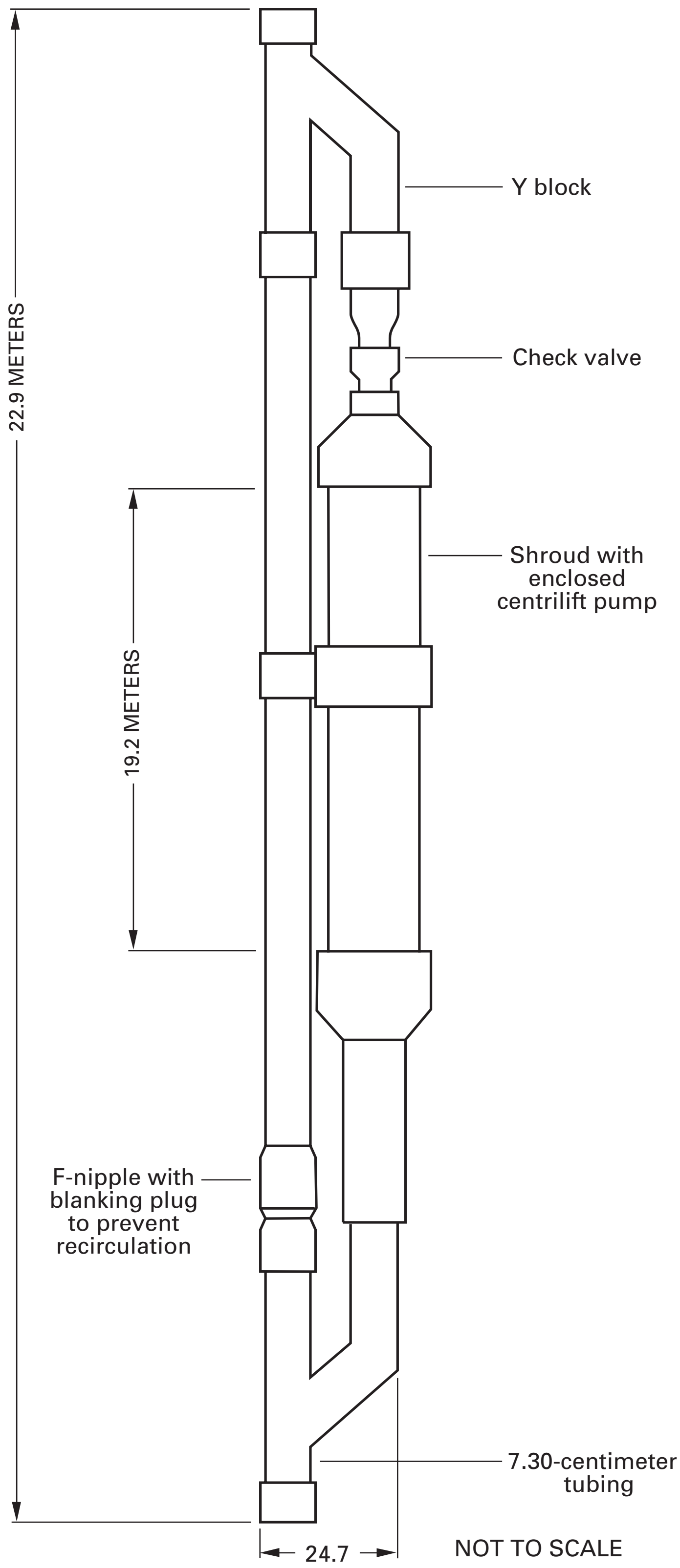


Figure 6. Pump assembly in borehole UE-25 c #3, May 1995 to April 1996.

assembly was designed to allow wireline-tool access past the pump for opening and closing sliding sleeves (screens installed to allow water movement to or from test intervals) and for landing a plug in the tubing to prevent recirculation of water through the pump shroud.

Although the Y-block assembly facilitated operations, its placement in the instrument string created problems that eventually caused pump performance to degrade beyond an acceptable level during hydraulic and tracer tests conducted in February and March 1996. Because the combined diameter of the Y-block assembly and main section of the instrument tubing (24.7 cm) was about the same as the borehole diameter below a depth of 463.4 m, the pump intake had to be set about 247 m above the top of the well screen open in the test interval. Frictional head losses produced by water flowing through small openings in the well screen and through the tubing from the test interval to the pump intake caused the pump to operate at the outer limit of its designed performance range. Consequently, discharge decreased from 8.77 L/s when pumping started on February 8, 1996, to 6.18 L/s when pumping terminated on March 29, 1996.

In April 1996, the pump performance problem was addressed by (1) discarding the Y-block; (2) suspending a 72-stage, 12.6-L/s-capacity Centrilift pump enclosed within a narrower shroud directly on the 7.30-cm-diameter tubing; (3) lowering the pump to within about 47 m of the next interval to be tested, the Lower Bullfrog; and (4) adding 6.1 m of slotted well screen in the test interval. From May 1996 to March 1997, the reconfigured pump assembly performed without major problems and sustained a relatively constant discharge of 9.34–9.84 L/s. Problems with one of the generators providing power to the pump caused the pump to operate erratically between March 26 and May 8, 1997, but the pump performed adequately again after the generator problem was resolved.

Flowmeters

A McCrometer turbine-type flowmeter was used during the hydraulic test in June 1995. Subsequently, the primary device used for monitoring discharge was a differential switched capacitor, vortex flowmeter manufactured by Endress and Hauser.

A vortex flowmeter measures the frequency of vortices produced as fluid flows past a bluff body. The frequency of vortex production is directly proportional to the flow rate and independent of fluid density. Signal output from the flowmeter was converted from milliamperes to volts by wiring the flowmeter circuit to a temperature-compensated, 100-ohm resistor and using a multimeter to measure the voltage drop across the resistor.

The flowmeter signal was recorded at user-specified intervals by monitoring software installed on a personal computer (PC) in the office trailer at the C-hole complex. A regression equation developed on the basis of the flowmeter calibration was used by the software program to convert the voltage signal from the flowmeter to a discharge rate. Periodically, discharge recorded by the PC was checked against total volume pumped (recorded at the wellhead) divided by the length of time of pumping. Generally good agreement was maintained between recorded and computed discharge rates.

Data Acquisition and Instrument Control

Data acquisition from, and control of, the transducers, barometer, flowmeter, and an automated water sampler used for tracer tests at the C-hole complex were accomplished with commercially available, graphic-language software called Labview (Johnson, 1995), which was installed on the PC in the office trailer. Labview is a Windows-based application that makes the PC monitor screen look and act like an instrument panel.

In addition to the simulated instrument panel, Labview displays a schematic command-structure diagram, which is analogous to a wiring scheme. Instructions are passed by the user to the command-structure diagram and on to the instrumentation, using buttons and text/numerical input windows on the simulated instrument panel. Data are passed from the instrumentation back to the command-structure diagram and displayed numerically and graphically within output windows on the simulated instrument panel.

Two separate programs were written for data acquisition and instrument control. One program communicated with the transducers, barometer, and flowmeter; the other program communicated with the automated water sampler during tracer tests. The two programs ran simultaneously. Small utility programs (called “transfer programs”) were written to transfer information back and forth between the two main programs in order to facilitate synchronization of the automated sampler operation with data acquisition from the transducers, barometer, and flowmeter.

The program communicating with the transducers, barometer, and flowmeter processes digital signals from these instruments through the serial-communications port of the PC, and a digital multimeter. Signals are received through the serial-communications port of the PC as alphanumeric characters representing either serial numbers of the instruments, or pressures and temperatures sensed by the transducers and barometer. The flowmeter signal is processed through a Keithley multimeter and adaptor board before reaching the PC. Equations written into the schematic diagram part of the program convert signal output into standard engineering units. This information is displayed on the PC monitor screen, written to a text file on the PC's hard drive, and backed up to a disk drive at user-specified intervals.

HYDRAULIC TESTS

Hydraulic tests were conducted at the C-hole complex June 12–22, 1995, February 8–13, 1996, and May 8, 1996, to November 12, 1997. The hydraulic test in June 1995 involved pumping UE-25 c #3, without packers installed and observing drawdown and recovery in six hydrogeologic intervals in UE-25 c #1 and UE-25 c #2 (shown in fig. 4) that were separated by packers.

From February 8 to 13, 1996, UE-25 c #3, with packers installed and inflated to isolate the Bullfrog-Tram interval, was pumped to establish a steady-state hydraulic gradient for a tracer test in the Bullfrog-Tram interval that continued until March 29, 1996. Drawdown in the Bullfrog-Tram interval and in all other packed-off intervals of UE-25 c #1 and UE-25 c #2 that responded to pumping prior to the tracer test was analyzed.

In the third hydraulic test, UE-25 c #3, with packers inflated to isolate the Lower Bullfrog interval, was pumped for 553 days before and during a series of tracer tests in the Lower Bullfrog interval. Drawdown in the Lower Bullfrog interval and in all other intervals of UE-25 c #1 and UE-25 c #2 that responded to this pumping before mechanical problems developed on

March 26, 1997, was analyzed. Drawdown in UE-25 ONC-1, USW H-4, UE-25 WT #14, and UE-25 WT #3 during periods ranging from 7 to 18 months was analyzed to evaluate heterogeneity and scale effects in the Miocene tuffaceous rocks. Water levels in UE-25 p #1 were observed to detect a potential pumping response indicative of hydraulic connection between the Miocene tuffaceous rocks and Paleozoic carbonate rocks in the area of the C-holes.

Analytical Methods

Although rock at the C-hole complex is fractured pervasively, hydrogeologic intervals respond to pumping as an equivalent porous medium (Geldon, 1996; Geldon and others, 1998). Because the water table occurs at or near the top of the Calico Hills interval in the vicinity of the C-hole complex, this interval typically responds to pumping as an anisotropic, unconfined aquifer. Pervaded by fractures that extend to the water table, the Prow Pass and Upper Bullfrog intervals can respond to pumping as either an unconfined, fissure-block, or confined aquifer. Isolated by intervals of nonfractured rock, the Lower Bullfrog interval typically responds to pumping as a confined aquifer. Recharged by flow from fractures related to faults (Geldon, 1993), the Upper Tram interval typically responds to pumping as a leaky, confined aquifer without confining-bed storage.

Analytical methods used for hydraulic tests discussed in this report are those of Theis (1935) and Cooper and Jacob (1946) for an infinite, homogeneous, isotropic, confined aquifer; Neuman (1975) for an infinite, homogeneous, anisotropic, unconfined aquifer; and Streltsova-Adams (1978) for a fissure-block aquifer. Assumptions, equations, and application of these analytical methods in hydraulic tests at the C-hole complex are discussed by Geldon (1996). Analysis of drawdown in this study was restricted to observation wells because drawdown in pumping wells at the C-hole complex typically is too large and rapid to be explained solely by hydraulic properties of the pumped interval (Geldon, 1996). This observation can be illustrated by looking at the drawdown in UE-25 c #3 464,000 minutes (about 323 days) after pumping began on May 8, 1996. This drawdown was 599 cm. With hydraulic properties computed for the Lower Bullfrog interval in UE-25 c #1 and UE-25 c #2 inserted into an approximation of the Theis (1935) equation given by (Lohman, 1972), the drawdown in UE-25 c #3 attributable to aquifer characteristics should have been no more than 69–72 cm after about 323 days of pumping, or 12 percent of the recorded drawdown. Most of the drawdown in UE-25 c #3 probably can be attributed to frictional head loss or borehole-skin effects. Therefore, calculation of hydraulic properties from this drawdown is not reliable.

All of the methods used for analyzing hydraulic tests in this study assume that flow from observation wells to the pumping well is radial. However, in hydraulic tests of the Bullfrog-Tram interval (February 1996) and the Lower Bullfrog interval (May 1996 to March 1997), drawdown was observed in the Calico Hills, Prow Pass, and Upper Bullfrog intervals, even though these intervals did not contain open screens. For water to reach the pumping well from the nonscreened intervals, a downward component of flow must be recognized. This downward flow was assumed to be much less than radial flow to the pumping well, in order to analyze the drawdown from the nonscreened intervals by the methods indicated in this section. Hydraulic properties calculated under this assumption have a high level of confidence because they generally are consistent with quantitative results of the hydraulic test in June 1995 in which flow from hydrogeologic intervals in UE-25 c #1 and UE-25 c #2 to UE-25 c #3 was designed to be radial.

Earth Tides and Barometric Effects

Previous monitoring of water levels in observation wells before, during, and after hydraulic tests conducted in the C-holes indicated that all boreholes respond to Earth tides and atmospheric pressure changes. With frequencies of 0.9 to 2.0 cycles per day (Galloway and Rojstaczer, 1988), Earth tides caused water-level altitudes in the C-holes to fluctuate as much as 12 cm during a 10-day hydraulic test conducted at the C-hole complex from May to June 1995 (Geldon and others, 1998). Consequently, in this study, Earth-tide effects were removed from simultaneously recorded water levels and atmospheric pressures before computing the barometric efficiency of most borehole intervals. Earth-tide effects also were removed from the records of observation wells in which drawdown caused by pumping was expected to be obscured by Earth tides (boreholes USW H-4, UE-25 WT #14, UE-25 WT #3, and UE-25 p #1). The boreholes requiring an Earth-tide correction to water-level records either are completed in the Miocene tuffaceous rocks more than 1,500 m from UE-25 c #3 or are completed in a different aquifer than the C-holes (the Paleozoic carbonate rocks). Earth-tide effects were removed from records of water levels and atmospheric pressure by applying a low-pass filter with a cutoff frequency of 0.8 cycle/day to these records. As shown in figure 7, this filtering removes semidiurnal changes in water levels while preserving longer term trends.

As shown in figure 8, changes in atmospheric pressure in the vicinity of the C-holes typically produce synchronous (but opposite) changes in the water level in boreholes. The slope of a line fit to a plot of water-level change as a function of atmospheric-pressure change is called the barometric efficiency. Determination of the barometric efficiency of the Lower Bullfrog interval in UE-25 c #2 is shown in figure 9. Barometric efficiency values of borehole intervals for which drawdown was computed during this study ranged from 0.75 to 0.99 (table 5). Barometric effects were removed from borehole records by subtracting atmospheric-pressure change, multiplied by barometric efficiency, from the change in water level to compute drawdown.

Flow Distribution in the C-holes

During hydraulic tests conducted in the C-holes in February 1996 and from May 1996 to November 1997, all hydrogeologic intervals in the C-holes that were being monitored responded to pumping, regardless of the interval being pumped. Leakage around packers could have occurred, although the packers were seated in nonrugose, sparsely fractured zones, but it is extremely unlikely that all packers failed to seal properly. A more reasonable interpretation is that fractures beyond borehole walls are so interconnected that packers emplaced in the C-holes do not isolate the interval being pumped from other transmissive intervals within the volume of aquifer stressed by the pumping.

Spinner and oxygen-activation flow surveys (fig. 10) were run in UE-25 c #3 during the hydraulic test in June 1995 to determine the flow distribution in the C-holes under pumping conditions. However, these flow surveys failed to detect flow from the Prow Pass interval that was indicated by heat-pulse flowmeter surveys conducted without pumping in the C-holes in 1991 (Geldon, 1996). Results of the 1991 and 1995 flow surveys were combined algebraically to estimate a flow distribution during the hydraulic test in June 1995 (table 6). This flow distribution was adjusted for

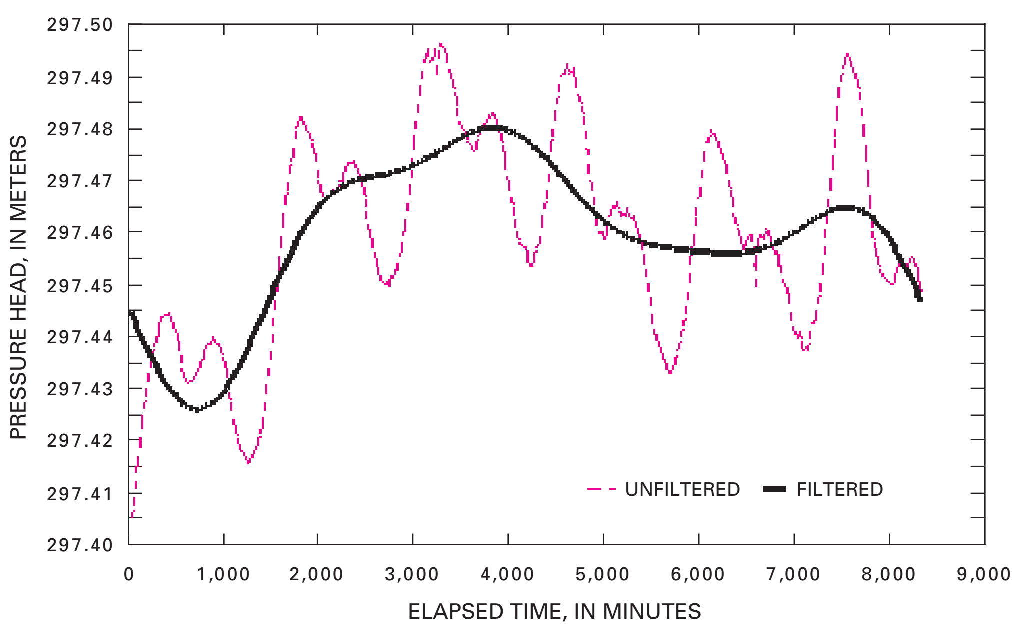


Figure 7. Result of filtering out Earth tides on UE-25 c #2 Lower Bullfrog interval pressure heads, June 23–29, 1995.

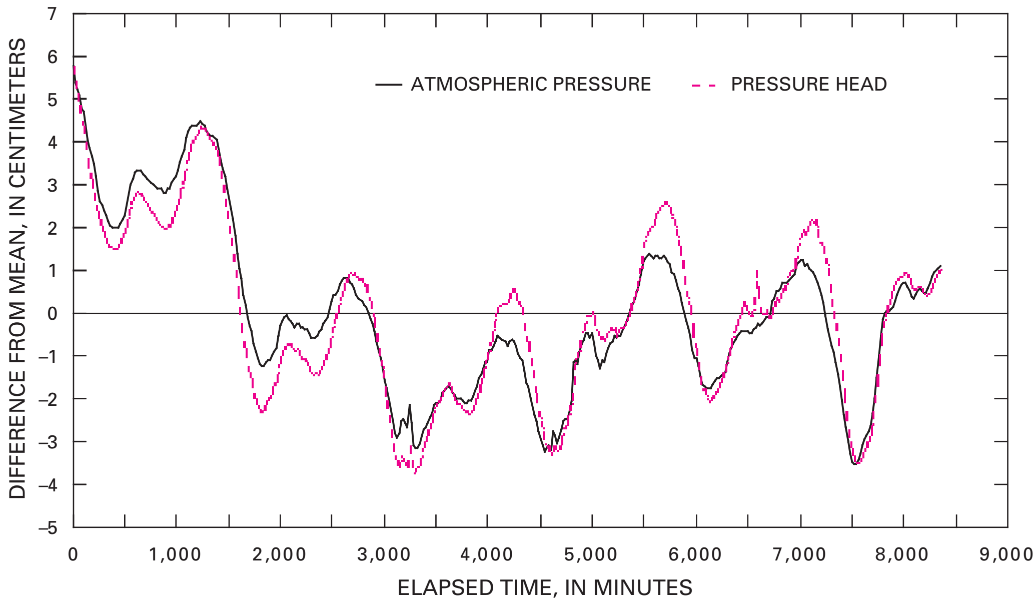


Figure 8. Difference from mean pressure head in UE-25 c #2 Lower Bullfrog interval and atmospheric pressure at the C-hole complex, June 23–29, 1995.

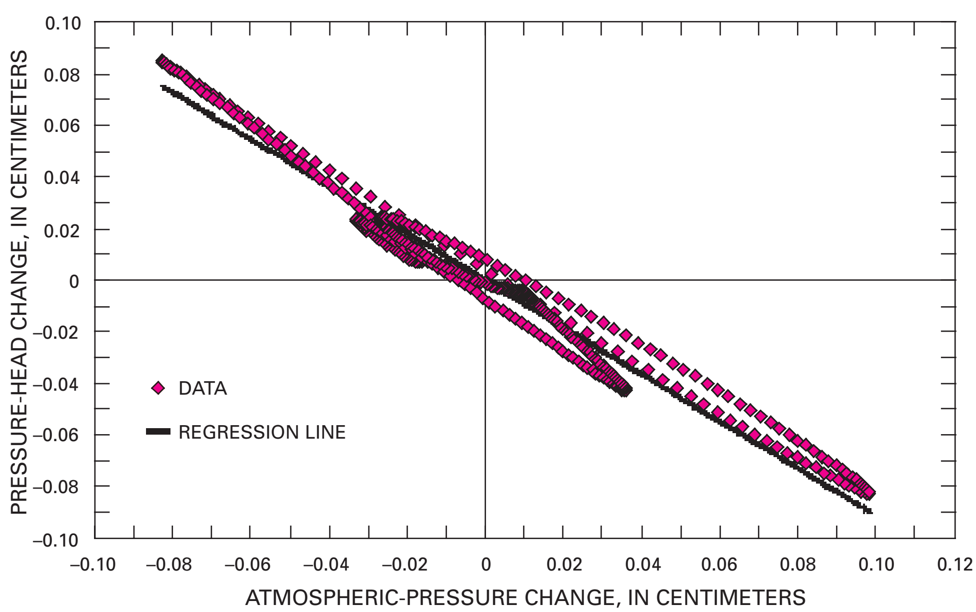


Figure 9. Filtered pressure-head change in UE-25 c #2 Lower Bullfrog interval as a function of filtered atmospheric-pressure change at the C-hole complex, June 23–29, 1995.

Table 5. Barometric efficiency values determined for borehole intervals monitored at the C-hole complex, May 1996 to December 1997

Borehole	Interval	Barometer location	Period of record	Barometric efficiency	Regression coefficient
UE-25 c #1	Prow Pass	C-holes	June 23–29, 1995	0.96	0.98
	Upper Bullfrog	C-holes	June 24–29, 1995	.99	.97
	Lower Bullfrog [1]	C-holes	June 23–29, 1995	.97	.98
UE-25 c #2	Calico Hills	C-holes	June 23–29, 1995	.93	.94
	Prow Pass	C-holes	June 23–29, 1995	.93	.97
	Upper Bullfrog	C-holes	June 23–29, 1995	.93	.97
	Lower Bullfrog[1]	C-holes	June 23–29, 1995	.91	.96
UE-25 c #3	Calico Hills [2]	C-holes	February 7–8, 1996	.83	.89
	Lower Bullfrog	C-holes	May 9–13, 1996	.87	.92
	Bullfrog-Tram	C-holes	Not applicable	.94 [3]	Not applicable
UE-25 ONC-1	Prow Pass	ONC-1	July 1–September 13, 1995	.99	.90
USW H-4	Prow Pass to Lithic Ridge	ONC-1	June 8–12, 1995	.91	.87
UE-25 WT #14	Calico Hills	C-holes	June 4–12, 1995	.89	.94
UE-25 WT #3	Lower Bullfrog	C-holes	June 4–12, 1995	.91	.82
UE-25 p #1	Paleozoic carbonates	C-holes	January 1–June 20, 1986	.75	Not applicable

[1]Barometric efficiency of Lower Bullfrog also used for Bullfrog-Tram in hydraulic test February 8–13, 1996.
[2]Barometric efficiency of Calico Hills also used for Calico Hills-Upper Bullfrog in hydraulic test February 8–13, 1996.
[3]Barometric efficiency estimated from values for Bullfrog-Tram in UE-25 c #1 and UE-25 c #2.

the hydraulic tests conducted in February 1996 and May 1996 to November 1997 (table 6) by inserting discharge and drawdown values recorded at the same elapsed time in the three hydraulic tests into the following equation:

$$P_2 = \frac{Q_1 \times P_1 \times S_1}{Q_2 \times S_1} \qquad (1)$$

where

P_1 = the proportion of flow determined for a hydrogeologic interval during the hydraulic test in June 1995;

P_2 = the proportion of flow determined for a hydrogeologic interval during a hydraulic test in either February 1996 or May 1996 to November 1997;

Q_1 = the average discharge during the hydraulic test in June 1995;

Q_2 = the average discharge during a hydraulic test in February 1996 or May 1996 to November 1997;

S_1 = the drawdown in a hydrogeologic interval during the hydraulic test in June 1995; and

S_2 = the drawdown in a hydrogeologic interval during a hydraulic test in either February 1996 or May 1996 to November 1997.

In the three hydraulic tests discussed in this report, the Lower Bullfrog interval consistently contributed about 70 percent of the flow from observation wells to the pumping well at the C-hole complex; the Upper Tram interval consistently contributed about 20 percent of this flow; and all other intervals combined contributed about 10 percent of the total flow. To analyze the drawdown in any hydrogeologic interval, the total discharge from UE-25 c #3 was first multiplied by the percentage of flow contributed by the interval being analyzed, to avoid calculating erroneously large values of transmissivity and storativity (both of which are directly proportional to discharge).

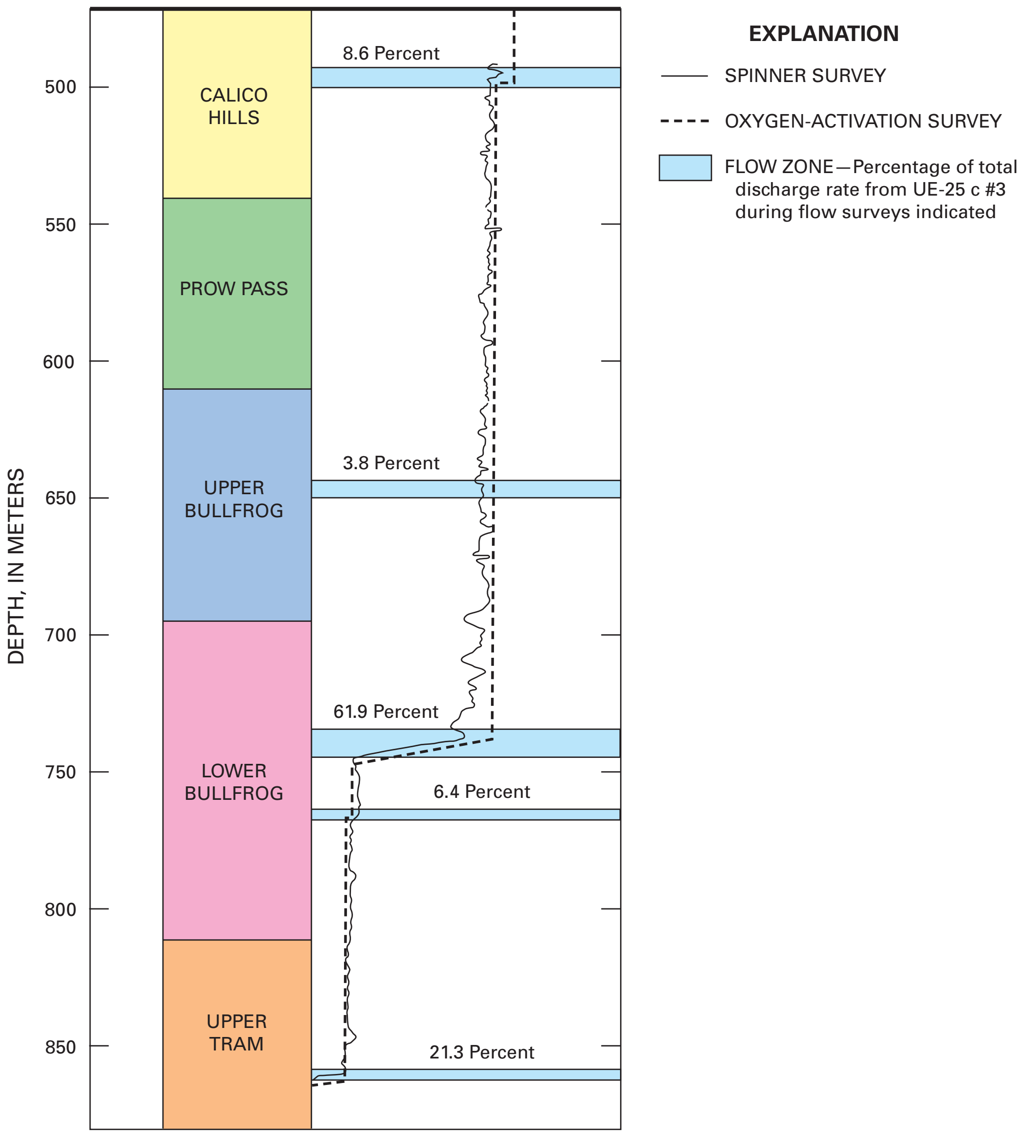


Figure 10. Flow surveys in UE-25 c #3 during the hydraulic test in June 1995.

Monitoring Network

Borehole UE-25 c #3 was selected as the pumping well for all hydraulic tests conducted from 1995 to 1997, based on evaluation of two hydraulic tests conducted in 1984. Boreholes UE-25 c #1 and UE-25 c #2 were used as observation wells for the hydraulic tests conducted in June 1995 and February 1996. Boreholes UE-25 c #1, UE-25 c #2, UE-25 ONC-1, USW H-4, UE-25 WT #14, UE-25 WT #3, and UE-25 p #1 were used as observation wells for the hydraulic test conducted from May 1996 to November 1997. Recording barometers were located at the C-hole complex during all hydraulic tests; a barometer located at borehole UE-25 ONC-1 also was used during the third hydraulic test.

Borehole UE-25 c #3 is 900.4 m deep. The borehole is cased and grouted to a depth of 417.0 m. During the hydraulic test in June 1995, UE-25 c #3 did not contain packers and was open from the Calico Hills to the Lower Tram interval. After packers were emplaced in August 1995, manipulation of the packers, well screens, and slotted casing allowed hydraulic communication with the Lower Bullfrog and Upper Tram intervals during hydraulic and tracer tests in February and March 1996 and with the Lower Bullfrog interval from May 1996 to December 1997.

Table 6. Interval discharges 5,800 minutes after pumping started, hydraulic tests in UE-25 c #3, June 1995 to November 1997

[Flow proportion for the Bullfrog-Tram interval shown in June 1995 is the sum of values for the Lower Bullfrog and Upper Tram intervals; L/s, liters per second; cm, centimeters; %, percentage; E, estimated; N/A, not applicable]

Hydrogeologic unit	June 1995			February 1996			May 1996 to November 1997		
	Discharge (L/s)	Drawdown (cm)	Flow %	Discharge (L/s)	Drawdown (cm)	Flow %	Discharge (L/s)	Drawdown (cm)	Flow %
				UE-25 c #1					
Calico Hills	22.5	No data	3.8	8.45	No data	0.5E	9.72	No data	1.1E
Prow Pass	22.5	43.0	2.9	8.45	14.0	2.5	9.72	14.9	2.3
Upper Bullfrog	22.5	52.1	3.9	8.45	21.6	4.3	9.72	19.2	3.3
Lower Bullfrog	22.5	49.7	68.3	8.45	No data	No data	9.72	21.0	66.8
Bullfrog-Tram	22.5	No data	89.4	8.45	19.5	92.7	9.72	N/A	N/A
Upper Tram	22.5	No data	21.1	8.45	No data	No data	9.72	No data	26.5
Lower Tram	22.5	No data	trace	8.45	No data	trace	9.72	No data	trace
				UE-25 c #2					
Calico Hills	22.5	351.7	3.8	8.45	16.4	0.5	9.72	43.0	1.1
Prow Pass	22.5	75.6	2.9	8.45	14.6	1.5	9.72	22.2	2.0
Upper Bullfrog	22.5	62.2	3.9	8.45	25.0	4.2	9.72	26.5	3.8
Lower Bullfrog	22.5	49.4	68.3	8.45	No data	No data	9.72	21.9	70.2
Bullfrog-Tram	22.5	No data	89.4	8.45	21.0	93.8	9.72	N/A	N/A
Upper Tram	22.5	283.2	21.1	8.45	No data	No data	9.72	No data	22.9
Lower Tram	22.5	239.6	trace	8.45	No data	trace	9.72	No data	trace

Borehole UE-25 c #2 is 30.4 m from UE-25 c #3 at the land surface and 910.1 m deep. It is cased and grouted to a depth of 416.0 m. Five dual-mandrel packers, suspended on 7.30-cm-diameter tubing, were emplaced in the borehole to isolate hydrogeologic intervals throughout the period of testing discussed in this report. Manipulation of packers and well screens allowed hydraulic communication with all six hydrogeologic intervals shown in figure 4 in June 1995, with the Lower Bullfrog and Upper Tram intervals in February and March 1996, and with the Lower Bullfrog interval from May 1996 to December 1997.

Borehole UE-25 c #1 is 68.4 m from UE-25 c #3 at the land surface and is 897.6 m deep. It is cased and grouted to a depth of 417.9 m. Five dual-mandrel packers, suspended on 7.30-cm-diameter tubing, were emplaced in the borehole to isolate hydrogeologic intervals throughout the period of testing discussed in this report. Manipulation of packers and well screens allowed hydraulic communication with the Calico Hills, Prow Pass, Upper Bullfrog, and Lower Bullfrog intervals in June 1995, with the Lower Bullfrog and Upper Tram intervals in February and March 1996, and with the Lower Bullfrog interval from May 1996 to December 1997.

Borehole UE-25 ONC-1 (Nye County Nuclear Waste Repository Project Office, written commun., 1995) is 842.8 m from borehole UE-25 c #3 at the land surface and is 469.4 m deep (about 36.3 m below the water level in the borehole). The borehole is telescoped downward and has a diameter of about 13 cm in the saturated zone. Seven packers inflated between the bottom of casing and a depth of 410 m separate the unsaturated and saturated zones; another packer emplaced at a depth of 452 m divides the saturated zone into two intervals. The upper of the saturated-zone intervals is open in the Calico Hills Formation and Prow Pass Tuff; the lower of these intervals is open in the Prow Pass Tuff. Absolute transducers, installed in all packed-off intervals, transmitted total (atmospheric and hydraulic) pressures to a data logger every 15 to 20 minutes during this study. Data from the lowermost transducer, which is at a depth of 458 m, were converted to pressure heads for analysis.

Borehole USW H-4, which is 2,245 m from borehole UE-25 c #3 at the land surface, is 1,219 m deep (Graves and others, 1997). The borehole diameter is 37.5 cm to a depth of 564 m and 22.2 cm below 564 m. Casing extends to a depth of 561 m; it is perforated below the water level, which was at an average depth of 518.3 m from 1985 to 1995. A packer emplaced at a depth of 1,181 m separates the Prow Pass, Bullfrog, and Tram Tuffs and the upper part of the Lithic Ridge Tuff from the lower part of the Lithic Ridge Tuff in the borehole. A 48-mm-diameter piezometer tube is installed in the upper part of the borehole, and a 62-mm-diameter piezometer tube is installed in the lower part of the borehole. Differential transducers emplaced in the two monitored intervals transmitted hydraulic pressures to a data logger every 15 minutes during this study. Only the data from the upper interval were used.

Borehole UE-25 WT #14, which is 2,249 m from borehole UE-25 c #3 at the land surface, is 399 m deep (Graves and others, 1997). The borehole has a diameter of 22.2 cm below the water table, which was at an average depth of 346.4 m from 1985 to 1995. The borehole is cased to a depth of 37 m and is open in the Topopah Spring Tuff and Calico Hills Formation. A 62-mm-diameter piezometer tube is installed in the borehole. A differential transducer emplaced in the piezometer tube transmitted hydraulic pressures to a data logger every 15 minutes during this study.

Borehole UE-25 WT #3, which is 3,526 m from borehole UE-25 c #3 at the land surface, is 348 m deep (Graves and others, 1997). The borehole has a diameter of 22.2 cm below the water table, which was at an average depth of 300.5 m from 1985 to 1995. The borehole is cased to a depth of 12 m and is open in the Bullfrog Tuff. A 62-mm-diameter piezometer tube is installed in the borehole. A differential transducer emplaced in the piezometer tube transmitted hydraulic pressures to a data logger every 15 minutes during this study.

Borehole UE-25 p #1, which is 630 m from borehole UE-25 c #3 at the land surface, is 1,805 m deep (Graves and others, 1997). The borehole diameter decreases from 37.5 to 15.6 cm with depth. Casing and cement emplaced to a depth of 1,297 m isolate Miocene tuffaceous rocks in the upper part of the borehole from Paleozoic carbonate rocks in the lower part of the borehole. The water-level altitude for the Paleozoic carbonate rocks in UE-25 p #1 is monitored through a 38-mm-diameter piezometer tube. The average depth to water in the piezometer tube was 361.8 m from 1985 to 1995. A differential transducer emplaced in the piezometer tube transmitted hydraulic pressures to a data logger every 60 minutes during this study.

Other boreholes beyond the immediate vicinity of the C-holes, which are part of a larger monitoring network for Yucca Mountain (Graves and others, 1997), were monitored periodically (generally monthly) during the hydraulic and tracer tests.

Description of Tests

A hydraulic test was conducted in June 1995 to determine hydraulic properties of the six hydrogeologic intervals at the C-hole complex that are shown in figure 4. The six intervals were isolated by packers in boreholes UE-25 c #1 and UE-25 c #2. Well screens opened in the packed-off intervals of the observation wells allowed hydraulic communication with the pumping well, UE-25 c #3, which was uncased and contained no packers to isolate intervals. Because of malfunctioning transducers, analyzable data were obtained only from the Prow Pass, Upper Bullfrog, and Lower Bullfrog intervals of UE-25 c #1 and the Calico Hills, Prow Pass, Upper Bullfrog, and Lower Bullfrog intervals of UE-25 c #2.

The hydraulic test started on June 12 at 14:23:59 and ended after 5,803 minutes (4.03 days) on June 16 at 15:06:53. Recovery was monitored until June 29, by which time it appeared to be complete in all intervals. At an average discharge rate of 22.5 L/s, drawdown in UE-25 c #3 rapidly increased to more than 10 m and reached a maximum of 10.9 m (fig. 11). The pumping in UE-25 c #3 produced drawdown ranging from 43.0 to 52.1 cm in intervals of UE-25 c #1 (fig. 12) and from 49.4 to 352 cm in intervals of UE-25 c #2 (fig. 13).

The most permeable interval identified in the hydraulic test conducted in June 1995, the Lower Bullfrog interval, was chosen for subsequently planned tracer tests at the C-hole complex to increase the chance of successful transport of tracers between the injection and recovery wells. Because the transducer in the Lower Bullfrog interval of UE-25 c #3 was not working, the packers between the Lower Bullfrog and Upper Tram intervals in all three of the C-holes were deflated, and the combined Lower Bullfrog and Upper Tram intervals (shown in figure 4 as the Bullfrog-Tram interval) became the test interval for the next series of tests.

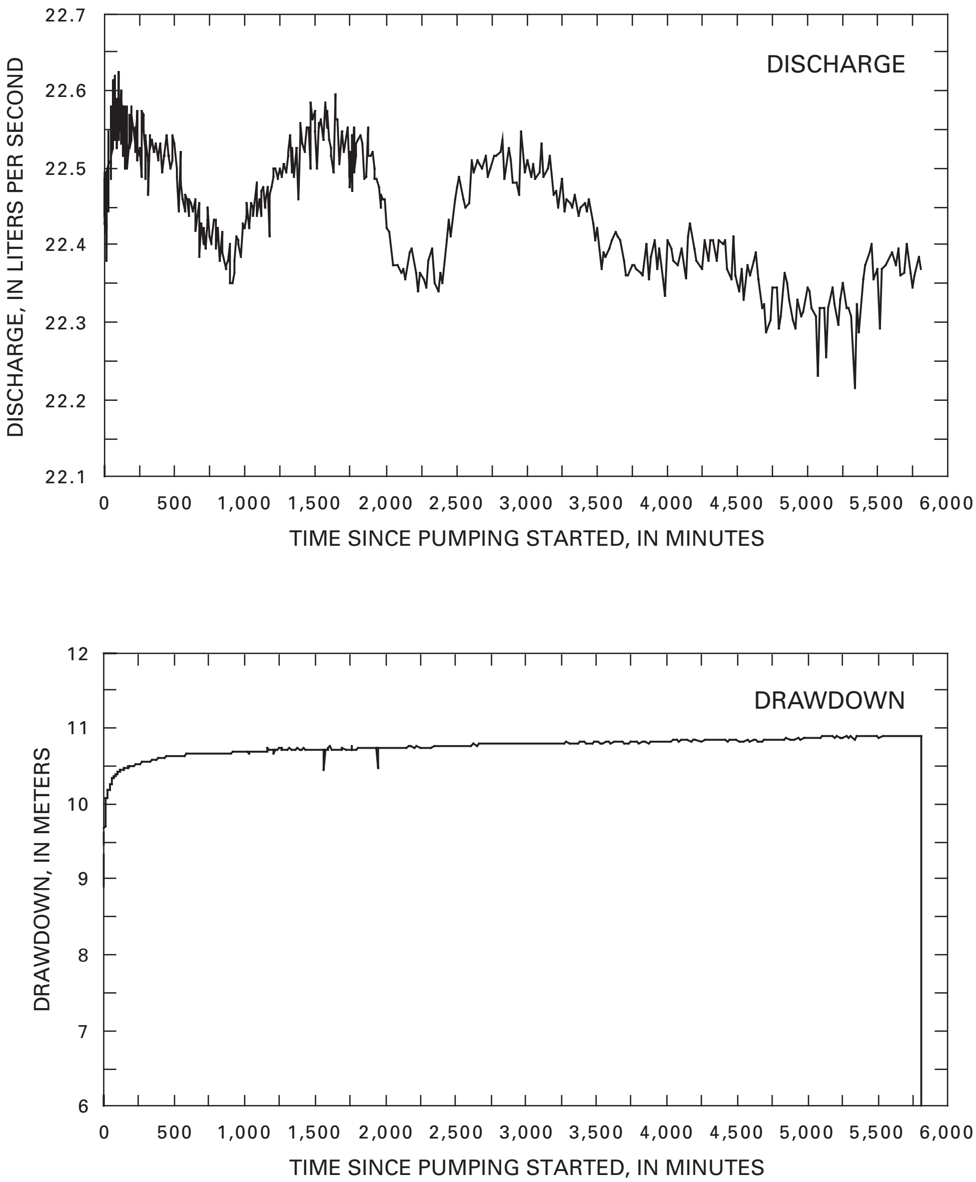


Figure 11. UE-25 c #3 discharge and drawdown, June 12–16, 1995.

After testing pump performance in January 1996 and allowing water levels in the C-holes to recover, pumping to establish a steep, quasi-steady-state hydraulic gradient between UE-25 c #2 (the injection well) and UE-25 c #3 (the recovery well) for a conservative tracer test began on February 8, 1996, at 13:54:45. Tracer injection occurred on February 13 at 10:18:22. The tracer injection disturbed the hydraulic pressure in the injection interval for 750 minutes and effectively terminated the analyzable drawdown record. The 6,984 minutes of drawdown recorded between the start of pumping and the injection of tracer were analyzed as a hydraulic test.

During the hydraulic test in February 1996, operation of the pump outside of its optimal performance range caused the discharge to decrease steadily, despite an adjustment of the pump speed on February 12, 5,640 minutes after pumping started. Prior to this adjustment, discharge decreased from 8.78 to 8.21 L/s. Adjusting the pump speed restored the discharge to 8.75 L/s, but it immediately began to decrease and was 8.57 L/s when the tracer test started on February 13 (fig. 14). Although average discharge after adjusting the pump speed was 0.10 L/s larger than before this adjustment, deviation from the average discharge of 8.49 L/s was just 3 percent of the mean for the entire period of pumping.

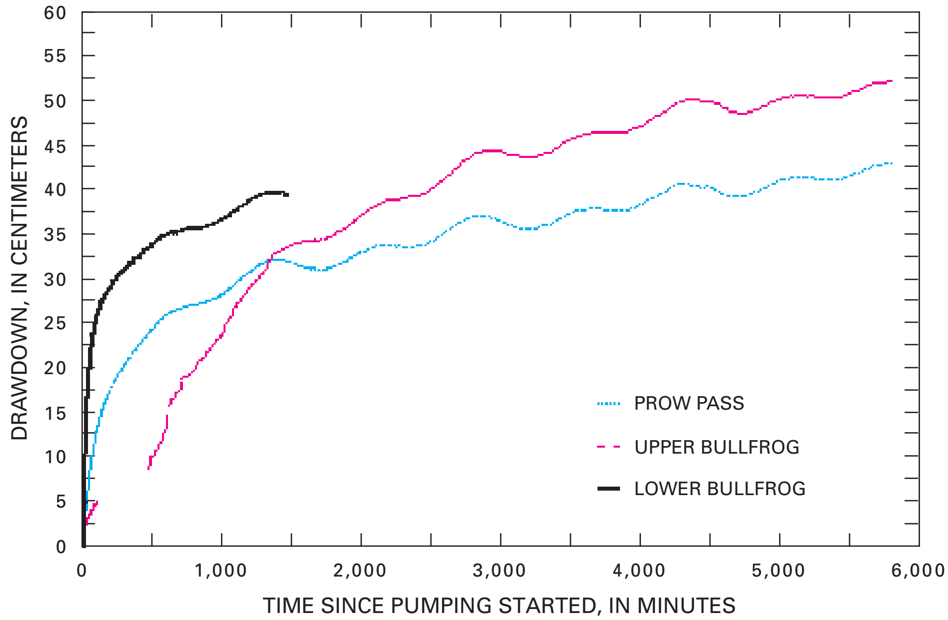


Figure 12. UE-25 c #1 drawdown, June 12–16, 1995.

As shown in figure 14, the pumping produced as much as 2.86 m of drawdown in the Bullfrog-Tram interval of UE-25 c #3 (96 percent of which occurred in the first 10 minutes). Adjustment of the pump speed caused a steplike increase of 0.19 m in UE-25 c #3 drawdown, but it had no discernible effect on drawdown in the other C-holes. Although oscillatory, drawdown in UE-25 c #1 steadily increased and ranged from 14.3 to 22.1 cm in the Prow Pass, Upper Bullfrog, and Bullfrog-Tram intervals (fig. 15). Although oscillatory, drawdown in UE-25 c #2 steadily increased and ranged from 14.9 to 25.3 cm in the Calico Hills, Prow Pass, Upper Bullfrog, and Bullfrog-Tram intervals (fig. 16). Steady increases in observation-well drawdown, together with small deviation from the average discharge, enabled the observation-

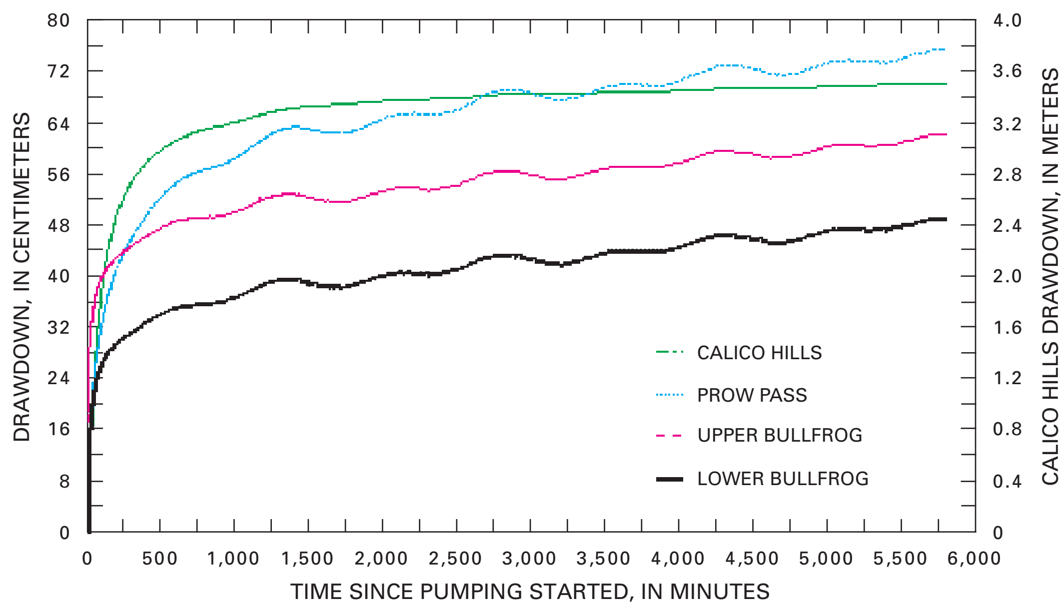


Figure 13. UE-25 c #2 drawdown, June 12–16, 1995.

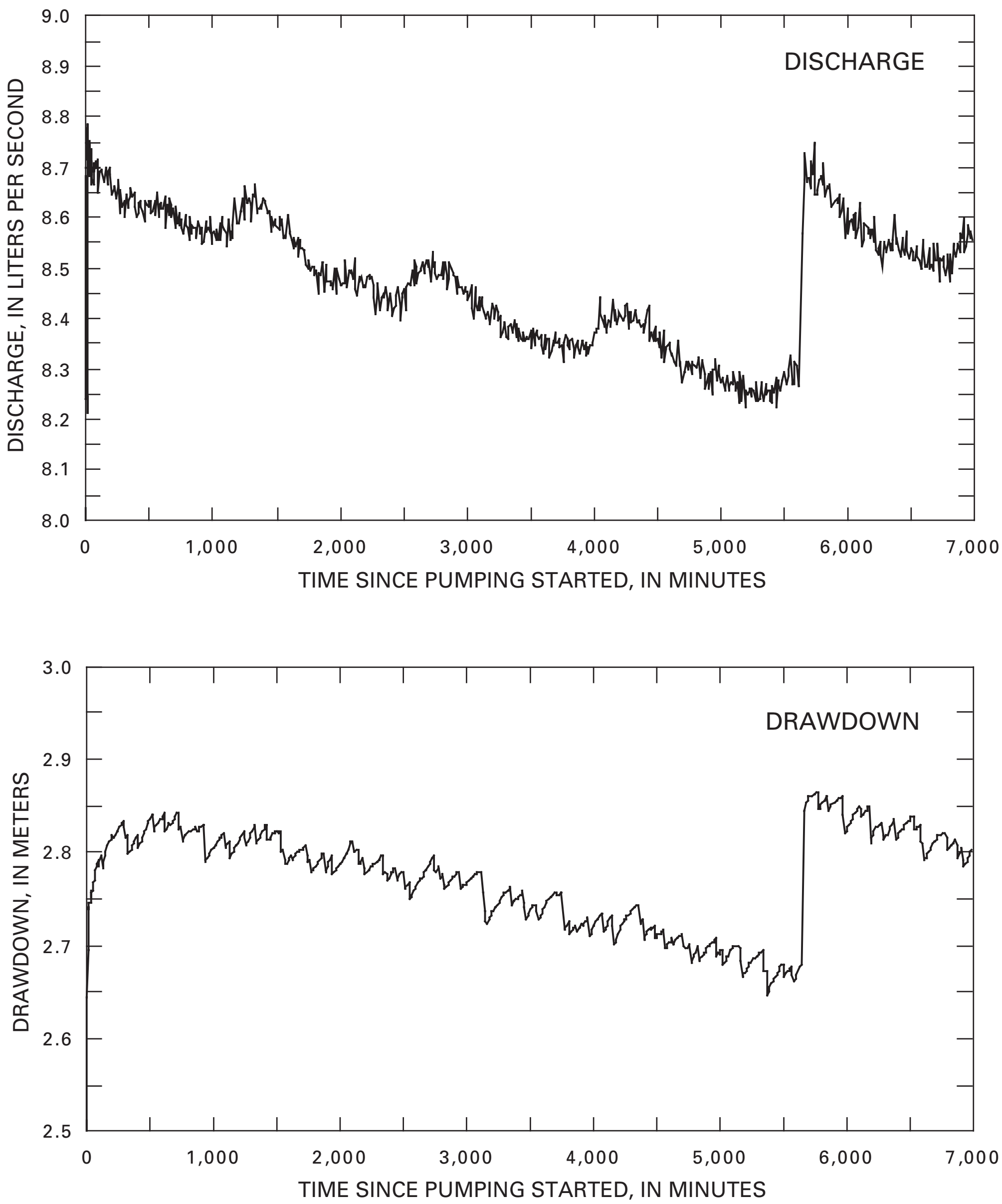


Figure 14. UE-25 c #3 discharge and drawdown, February 8–13, 1996.

well drawdown to be considered a single-cycle response to pumping for the entire period before tracer injection.

After the tracer test in the Bullfrog-Tram interval ended in March 1996, a new transducer was installed in the Lower Bullfrog interval of UE-25 c #3, and packers in the borehole were reconfigured. Subsequently, it was possible to conduct hydraulic and tracer tests in just the Lower Bullfrog interval. With nearly continuous pumping, a series of tracer tests was conducted in this interval by the USGS and Los Alamos National Laboratory from May 1996 to November 1997.

Pumping in UE-25 c #3 to establish a steep, quasi-steady-state hydraulic gradient for tracer tests in the Lower Bullfrog interval began May 8, 1996, at 11:16:57. From May 24, 1996, to March 26, 1997, the pump shut off 11 times because of problems with the generators that provided power to the pump. On March 26, 1997, at about 17:52, the pump shut off because of generator problems, which were not resolved until May 8, 1997. Problems with the power supply caused

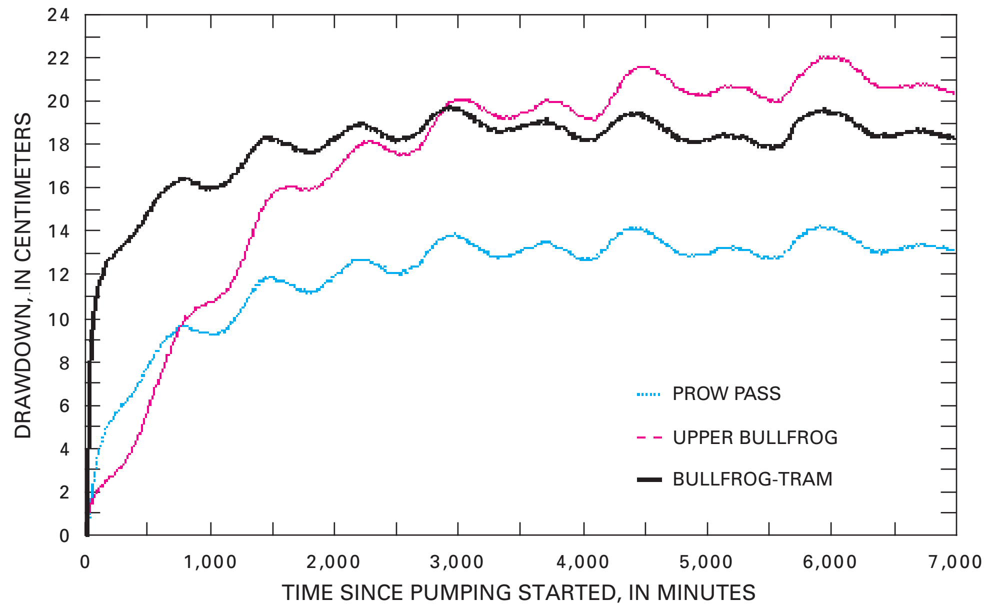


Figure 15. UE-25 c #1 drawdown, February 8–13, 1996.

the pump to shut off for 30 seconds seven times between May 30 and September 29, 1997 and at least once a day between October 15 and November 12, 1997. Pumping was terminated on November 12, 1997, at 15:59:50, 553.24 days after pumping started, and recovery was monitored until December 31, 1997.

Discharge between May 8, 1996 and March 26,1997 initially oscillated between 9.6 and 9.8 L/s, eventually stabilized at about 9.4 L/s, and averaged 9.53 L/s (fig. 17). After the generators were restored to service on May 8,1997, discharge decreased steadily from 9.3 to 8.9 L/s and averaged 9.01 L/s. The volume of water withdrawn between May 8, 1996 and November 12, 1997 was 440.2 million L, which is equivalent to an average discharge of 9.21 L/s.

As in previous hydraulic tests, drawdown in the pumped well was large and reached steady-state rapidly (fig. 17). Drawdown in the Lower Bullfrog

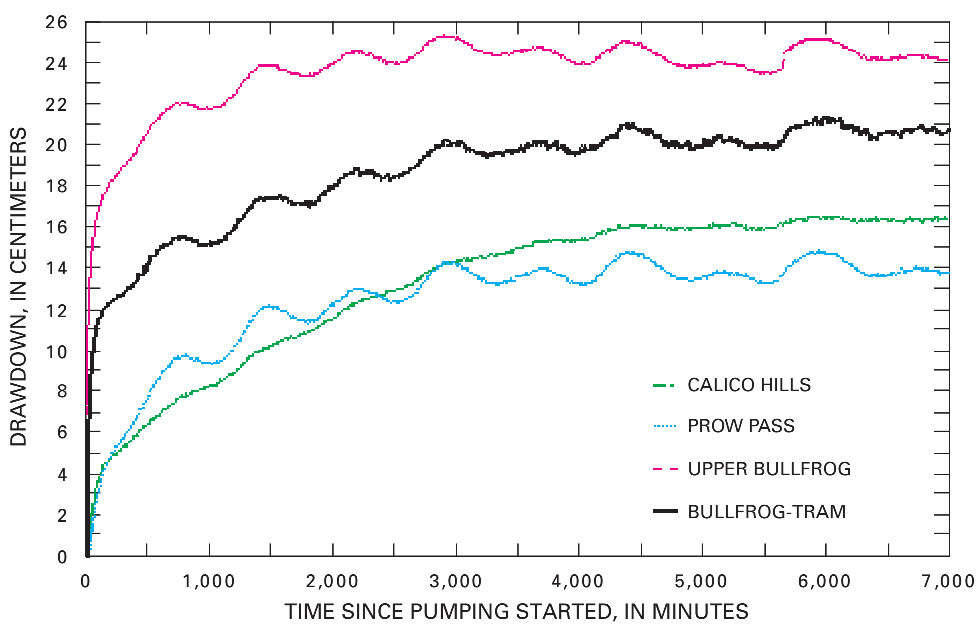


Figure 16. UE-25 c #2 drawdown, February 8–13, 1996.

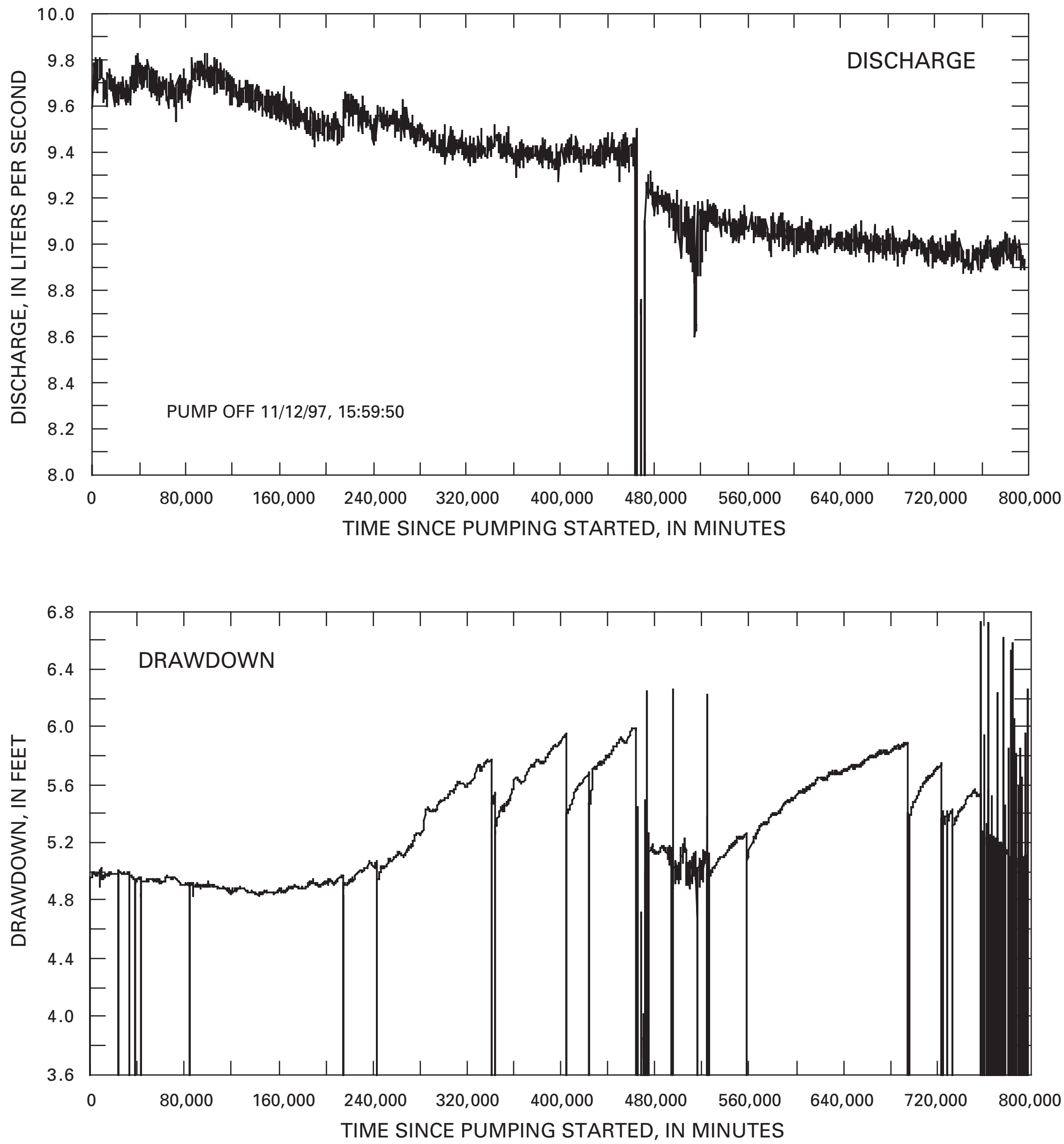


Figure 17. UE-25 c #3 discharge and drawdown, May 8, 1996, to November 12, 1997.

interval of UE-25 c #3 reached 4.8 m in 60 minutes and remained at 4.85–5.0 m until October 16, 1996, 232,000 minutes after pumping started. For unknown reasons, drawdown began increasing steadily after 232,000 minutes of pumping and was 5.98 m on March 26, 1997, 464,000 minutes after pumping started. After March 26, the frequent pump shutoffs kept drawdown below 5.9 m, except during the process of restarting the pump. Pump shutoffs typically caused rapid and complete or nearly complete recovery in UE-25 c #3, but these effects were reversed just as rapidly when the pump was restarted. Tracer test operations affected drawdown in the pumped well minimally. Recovery from pumping on December 12, 1997, 42,965 minutes after pumping stopped, was 99 percent of antecedent drawdown.

The prolonged period of unsteady pump discharge after March 26, 1997, effectively ended the drawdown record that could be analyzed as a hydraulic test for all observation wells except UE-25 ONC-1. The analyzable drawdown record from May 8, 1996, to March 26, 1997, is 464,134 minutes (322.32 days) long. With 11 downtimes ranging from 2 to 185 minutes, the pump was off for 649 minutes (about 0.1 percent of the time) during this period.

Drawdown in response to pumping the Lower Bullfrog interval of UE-25 c #3 is known to have occurred in the Prow Pass, Upper Bullfrog, and Lower Bullfrog intervals of UE-25 c #1 and in the Calico Hills, Prow Pass, Upper Bullfrog, and Lower Bullfrog intervals of UE-25 c #2. Drawdown in all intervals of these boreholes generally increased steadily but was very oscillatory. Peak drawdown by March 26, 1997, ranged from about 36 to 42 cm in intervals of UE-25 c #1 (fig. 18) and from about 35 to 51 cm in intervals of UE-25 c #2 (fig. 19).

Disruptions of drawdown in the Lower Bullfrog and other intervals of UE-25 c #1 and UE-25 c #2 occurred from pump shutoffs 11 times between May 1996 and March 1997. Pump shutoffs (most of the unlabeled downward spikes in figures 18 and 19) generally resulted in 20–50 percent recovery of water levels. However, these effects dissipated 50 to

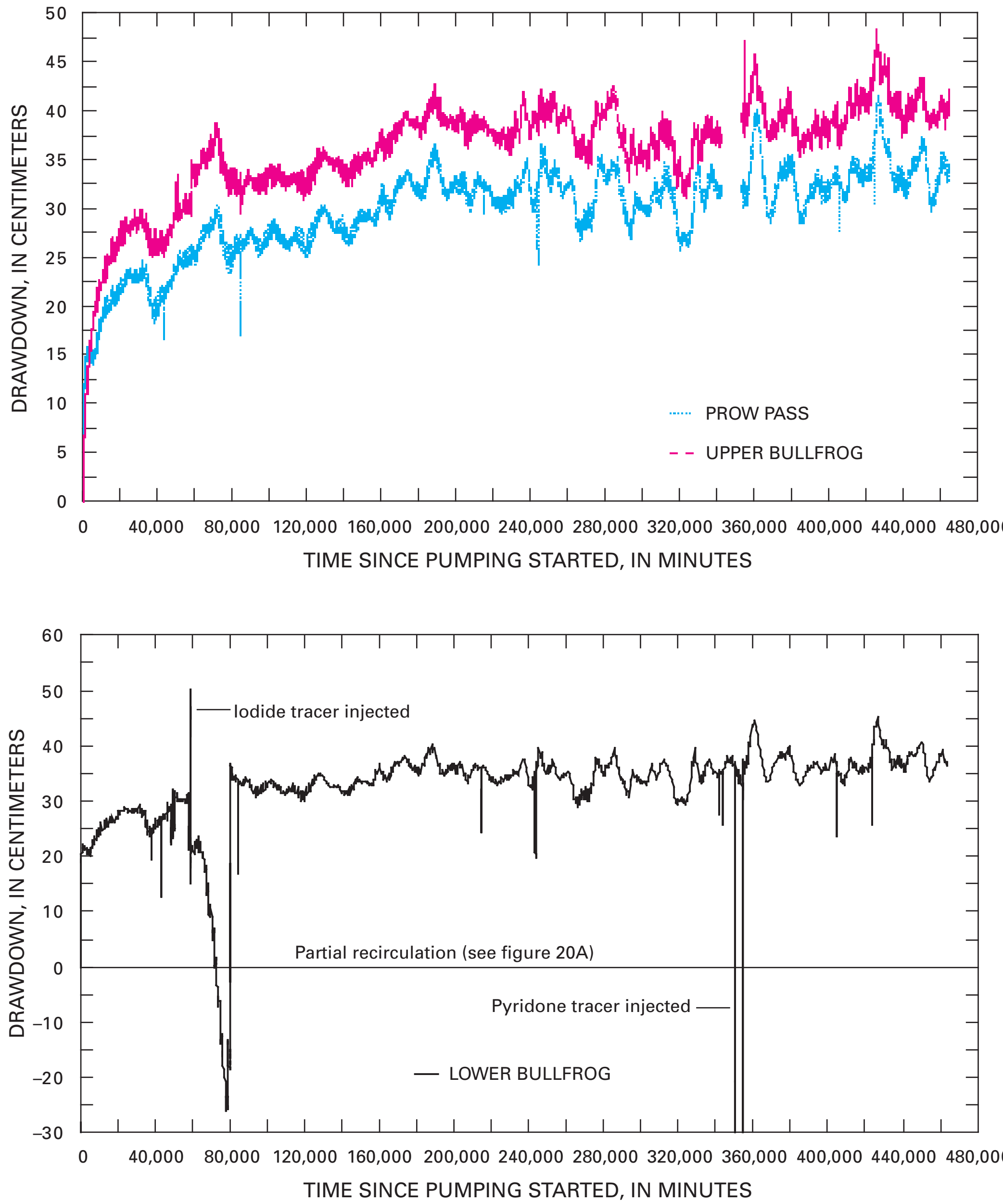


Figure 18. UE-25 c #1 drawdown, May 8, 1996, to March 26, 1997.

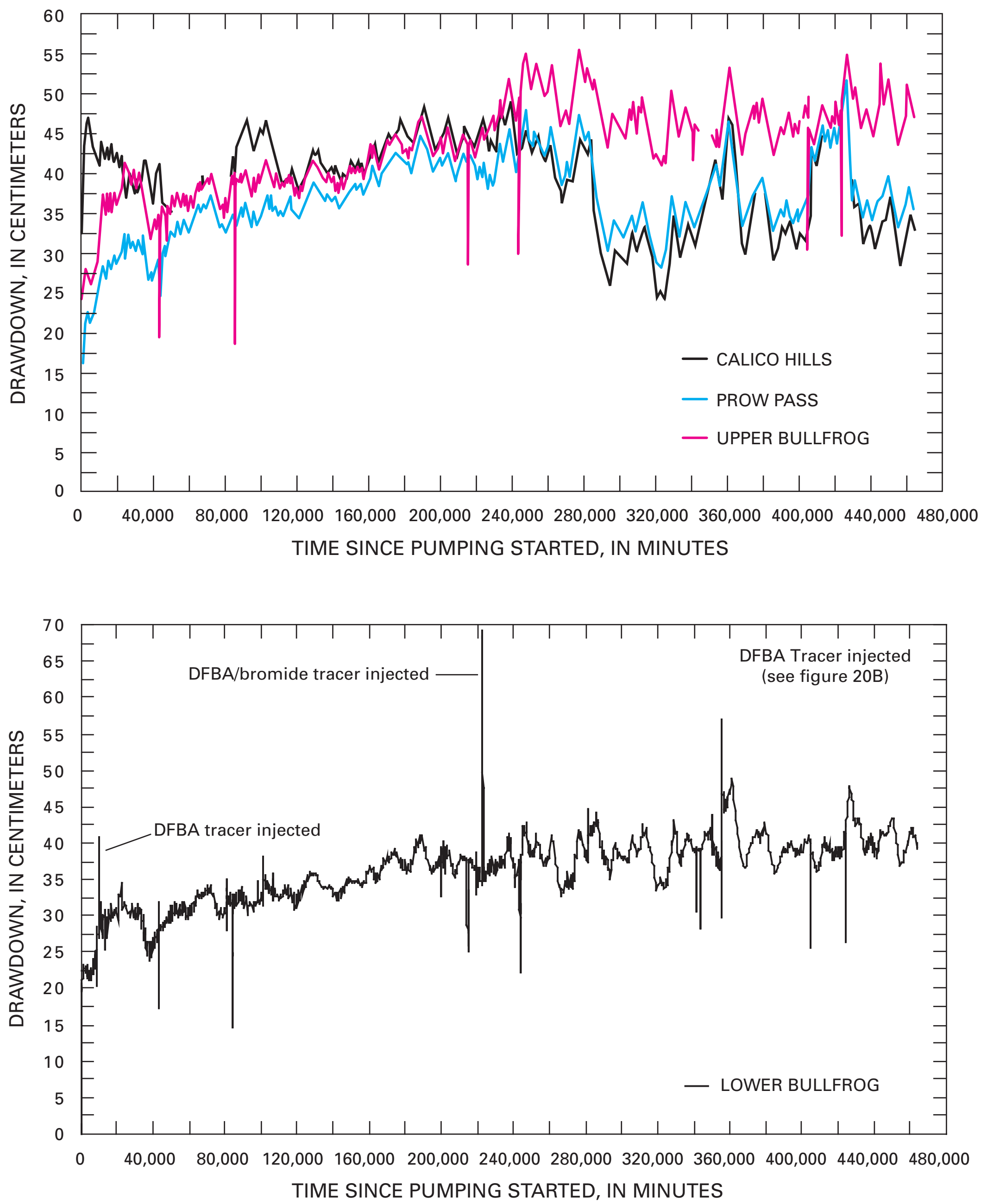


Figure 19. UE-25 c #2 drawdown, May 8, 1996, to March 26, 1997.

500 minutes after the pump was restarted and did not affect analysis of the drawdown.

Recirculation of water during tracer tests conducted between May and November 1996 generally caused small decreases in drawdown in the Lower Bullfrog interval of UE-25 c #1 or decreases followed by increases in drawdown in the Lower Bullfrog interval of UE-25 c #2 at the start and end of recirculation, that generally lasted 70 to 560 minutes. However, recirculation of water in UE-25 c #1 from June 17 to July 3, 1996, to facilitate transport of the sodium iodide tracer between the injection and recovery wells caused drawdown in the Lower Bullfrog interval of UE-25 c #1 to decrease in steps for 23,350 minutes (figs. 18 and 20A). Pumping water into UE-25 c #1 faster than it could drain probably caused the drawdown to decrease. Periodic increases in the injection pump rate caused this decrease to occur in steps.

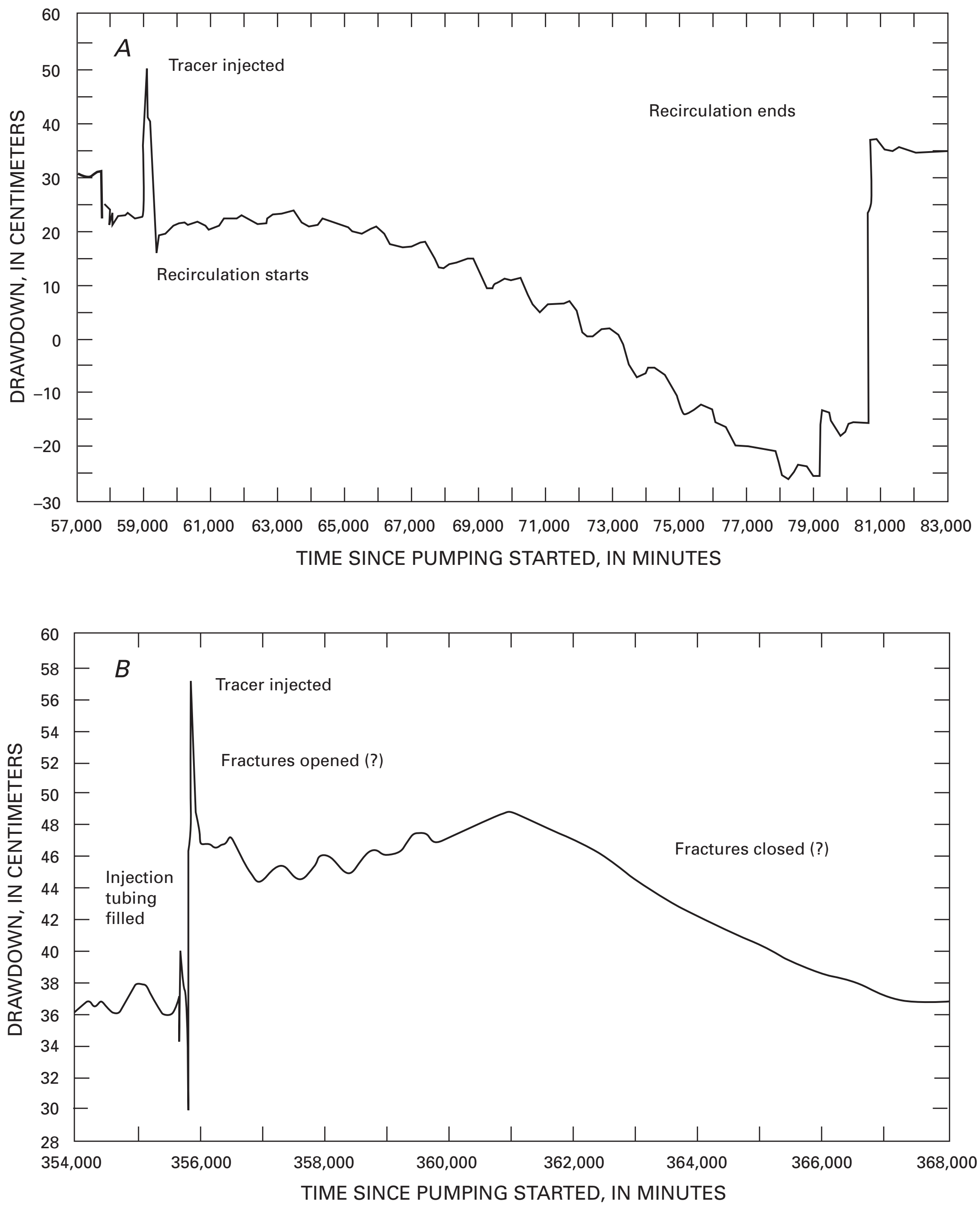


Figure 20. Disturbance of drawdown in Lower Bullfrog interval of UE-25 c #1 and UE-25 c #2 by tracer tests in 1996 and 1997: *A*, Sodium-iodide tracer test in UE-25 c #1, June 17 to July 5, 1996; *B*, 2,6-DFBA tracer test in UE-25 c #2, January 9 to 18, 1997 (2,6-DFBA, 2,6-difluorobenzoic acid).

Tracer injection during four tests that were conducted between May 1996 and November 1997 caused increased drawdown in the Lower Bullfrog interval of UE-25 c #1 or UE-25 c #2, that generally lasted 180 to 750 minutes. However, following injection of 2,6 difluorobenzoic acid tracer into UE-25 c #2 on January 10, 1997, drawdown in the Lower Bullfrog interval of UE-25 c #2 remained high for 8,360 minutes (figs. 19 and 20B). Increased drawdown could have resulted from opening fractures within an unknown (probably small) radius of the injection well because enlarged fractures would have allowed water to drain from the well faster. Lowered hydraulic heads associated with the dense injectate as it slowly drained from UE-25 c #2 also could have produced the observed water-level changes in UE-25 c #2.

Hypotheses regarding disturbances from tracer-test operations are not testable and, therefore, are presented only for consideration. It is important to note that (1) tracer-test operations conducted in one borehole generally did not affect drawdown in other boreholes; and (2) disturbances from tracer-test operations did not affect analyses of drawdown in UE-25 c #1 and UE-25 c #2.

Events of unknown origin caused hydraulic heads in the Lower Bullfrog interval of UE-25 c #1 and UE-25 c #2 to rise 5 to 8 cm from June 1 to 11, 1996 (a period of 14,800 minutes), and from November 6 to 14, 1996 (a period of 11,900 minutes). Because six observation wells within 3.5 km of UE-25 c #3 showed similar rises in hydraulic head, the events that produced these disturbances were not local in scale. No earthquakes were recorded in the vicinity of the Nevada Test Site at the time of these disturbances (U.S. Geological Survey National Earthquake Information Center, oral commun., 1997). Whatever the origin, the unknown events did not affect analyses of drawdown data.

Shutting off the pump in UE-25 c #3 on November 12, 1997, caused erratic responses in the Lower Bullfrog intervals of UE-25 c #2 and UE-25 c #1 that are not analyzable. Recovery in the Lower Bullfrog interval of UE-25 c #1 reached a plateau from 8,000 to 38,500 minutes after pumping stopped, after which it began increasing cyclically. On December 29, 1997, 67,000 minutes after pumping stopped, recovery in the Lower Bullfrog interval of UE-25 c #1 was about 95 percent of the antecedent drawdown (fig. 21). The transducer in the Lower Bullfrog interval of UE-25 c #2 was removed on December 9, 1997, at a time when readings from the transducer were erratic, and recovery was only about 70 percent of the antecedent drawdown.

Pumping in the Lower Bullfrog interval of UE-25 c #3 from May 1996 to March 1997 caused drawdown in all four of the observation wells beyond the C-hole complex that are completed in Miocene tuffaceous rocks. As in UE-25 c #1 and UE-25 c #2, drawdown in the four outlying observation wells was very oscillatory. Drawdown in these wells was not affected by pump shutoffs or tracer test operations.

Drawdown in UE-25 ONC-1, the nearest observation well to the C-holes, was detected 200 minutes after pumping started and increased steadily thereafter (fig. 22). Peak drawdown by March 26, 1997, was about 28 to 30 cm. Peak drawdown when pumping ended on November 12, 1997, was about 36 to 37 cm. Recovery in UE-25 ONC-1 followed a pattern similar to the Lower Bullfrog interval in UE-25 c #1 (fig. 21). On December 29, 1997, 67,500 minutes after pumping stopped, recovery in UE-25 ONC-1 was about 76 percent of the antecedent drawdown.

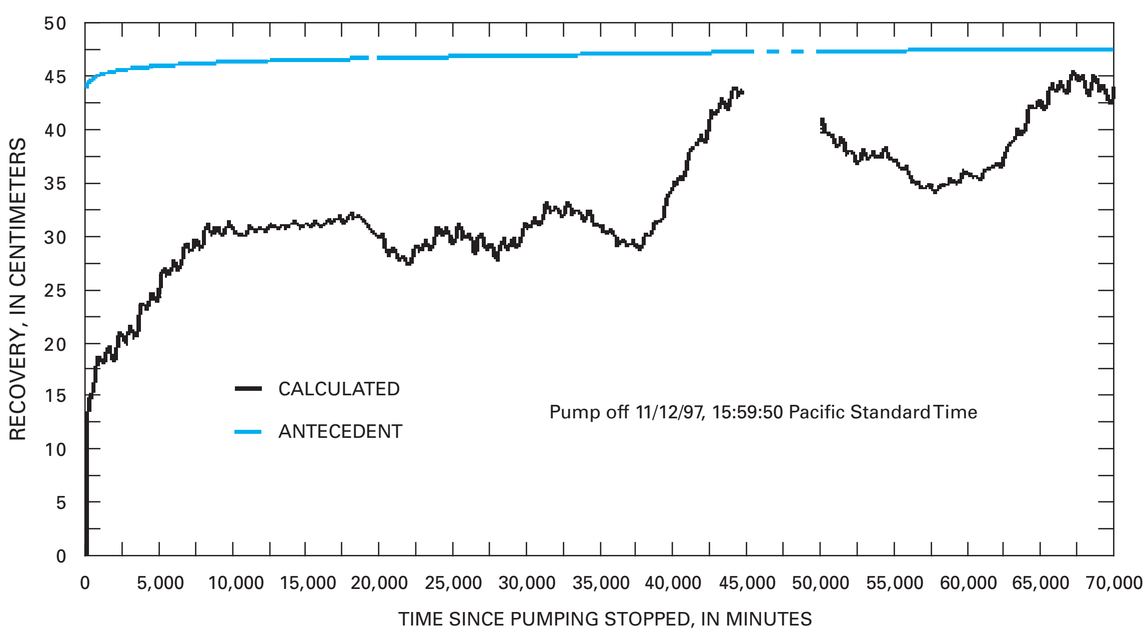


Figure 21. UE-25 c #1 Lower Bullfrog recovery, November 12 to December 31, 1997.

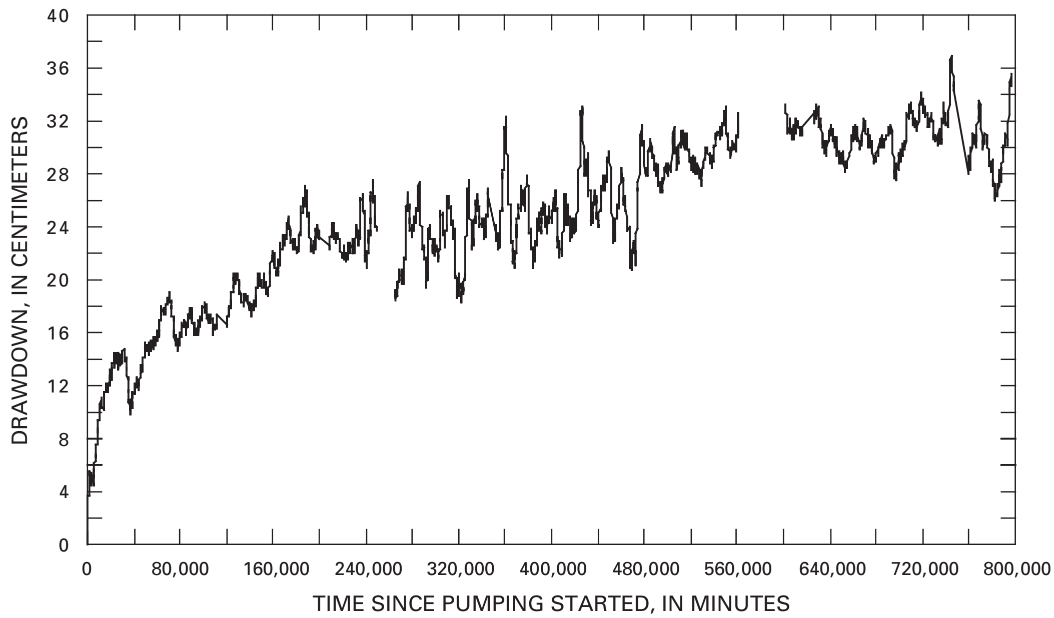


Figure 22. Drawdown in UE-25 ONC-1, May 8, 1996, to November 12, 1997.

Borehole UE-25 WT #3, the farthest observation well from the C-holes, responded similarly to the C-holes and UE-25 ONC-1 to the pumping in UE-25 c #3 that began on May 8, 1996. Drawdown in UE-25 WT #3 was detected 9,130 minutes after pumping started (fig. 23). Peak drawdown by March 26, 1997, was about 14 to 16 cm. Drawdown in UE-25 WT #3 was more oscillatory than in the other observation wells after 240,000 minutes of pumping, possibly because (1) UE-25 WT #3 was much farther from the pumping well than the other observation wells and affected by environmental stresses that did not extend to the other wells; and (2) pumping-related water-level changes in UE-25 WT #3 were much smaller than in

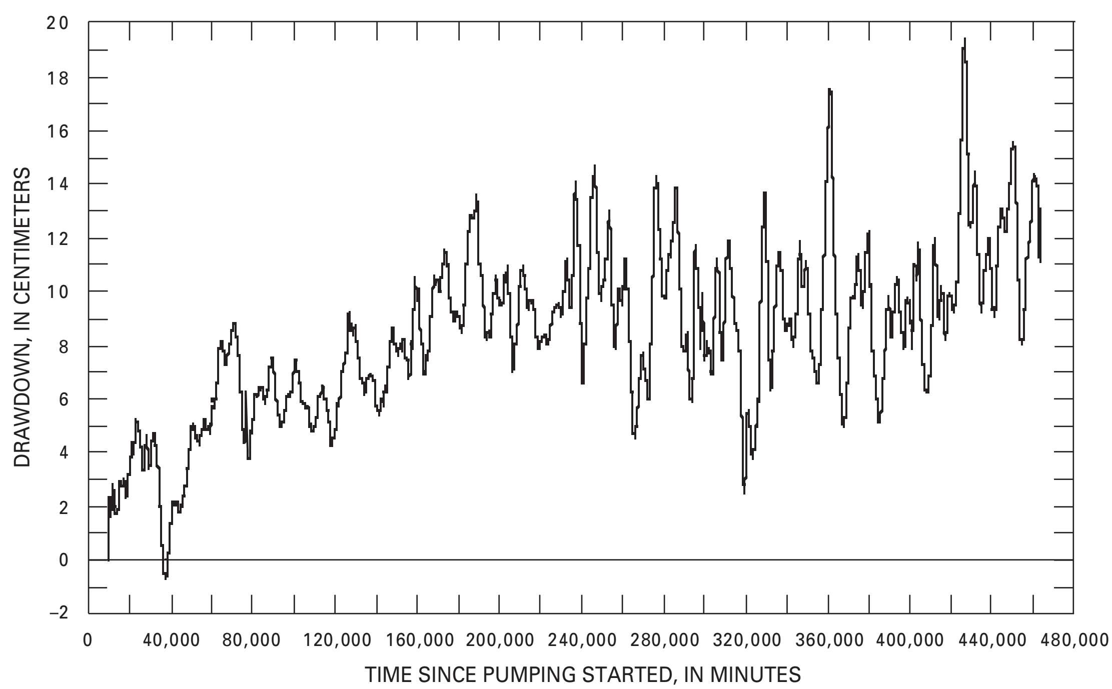


Figure 23. Drawdown in UE-25 WT #3, May 8, 1996 to March 26, 1997.

the other observation wells and, therefore, harder to separate from barometric and Earth-tide effects.

Unlike other observation wells monitored during the hydraulic test that began in May 1996, USW H-4 and UE-25 WT #14 exhibited steady-state drawdown as pumping progressed (fig. 24). Drawdown in both boreholes was delayed for about 5,000 minutes after pumping started, although very small, oscillatory water-level changes, possibly caused by borehole-storage release, occurred during this time. Between 5,000 and 72,000 minutes after pumping started, drawdown increased steadily in response to pumping. Drawdown in USW H-4 peaked at about 22 cm; drawdown in UE-25 WT #14 peaked at about 15 cm. After about 72,000 minutes of pumping, fluxes from recharge boundaries prevented further drawdown. As in a hydraulic test of the Tram interval in UE-25 c #1 conducted in 1984 (Geldon, 1996), recharge boundaries affecting USW H-4 and UE-25 WT #14 are inferred to be faults present near the

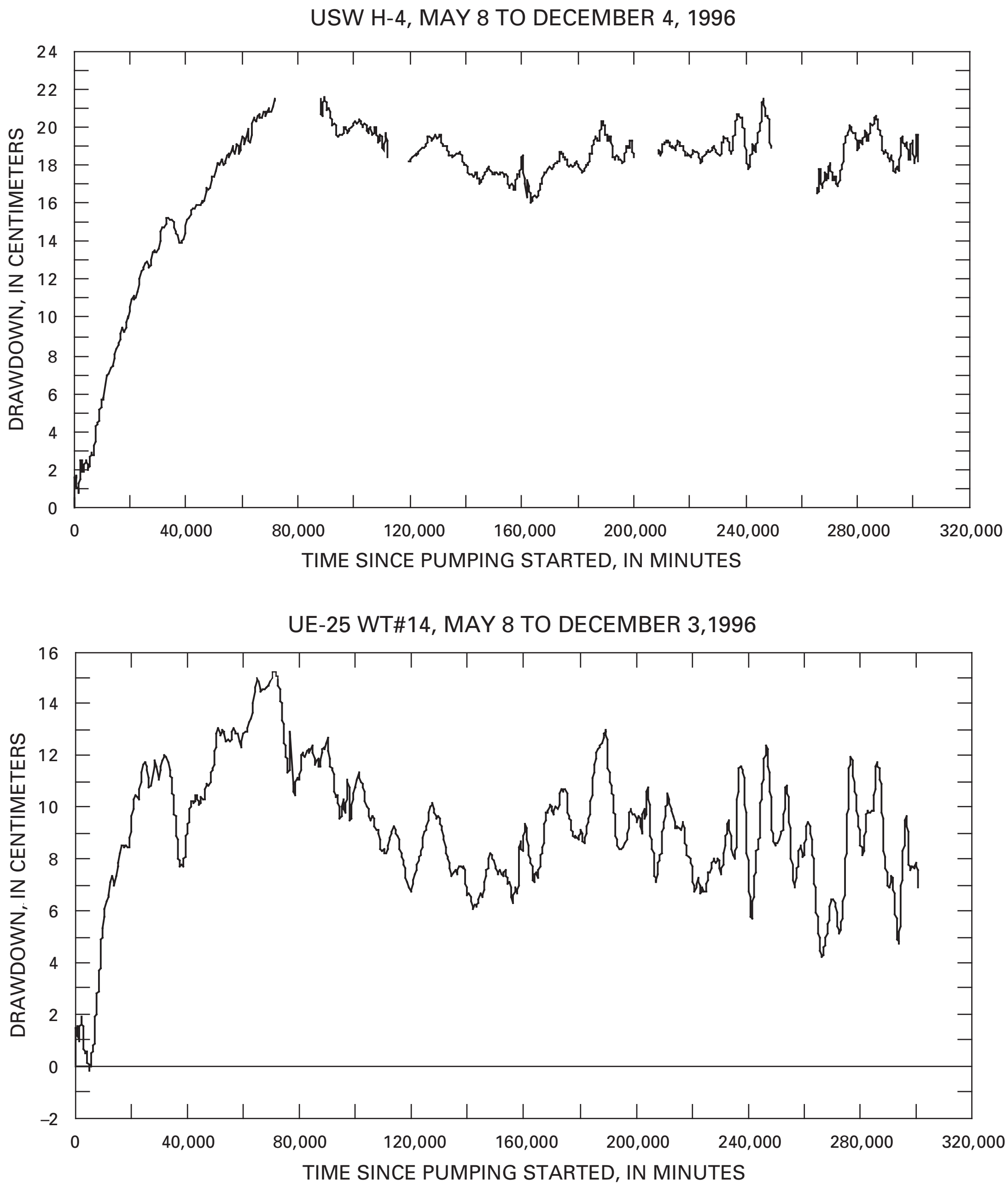


Figure 24. Drawdown in USW H-4 and UE-25 WT #14, May 8, 1996, to December 4, 1996.

observation wells. Numerous faults are located near USW H-4 (Day and others, 1998), and several segments of the Paintbrush Canyon Fault are located near UE-25 WT #14 (Dickerson and Drake, 1998). Conversely, there are no known changes in stratigraphy or lithology between the C-holes and either USW H-4 or UE-25 WT #14 that might be interpreted to create a hydraulic boundary.

Water-level declines observed in several other routinely monitored boreholes at Yucca Mountain from May 1996 to November 1997 are believed to be related to pumping at the C-hole complex (Graves, 2000). In boreholes in which declines were observed, the maximum declines ranged from 0.1 to 0.4 m (table 7). Water-level declines of about 0.2 m were observed in a borehole (USW WT-11) more than 8 km from the C-hole complex. Water levels in all of the boreholes returned to prepumping levels after pumping at the C-holes ceased.

HYDRAULIC PROPERTIES

Hydraulic tests conducted at the C-hole complex from 1995 to 1997 revealed much about the ability of hydrogeologic intervals in the C-holes and the Miocene tuffaceous rocks in the vicinity to store and transmit water. However, it must be emphasized that hydraulic properties computed from these tests pertain only to the structural setting in which the tests were conducted. The Lower Bullfrog interval is the most permeable interval in the C-holes because it is located in these boreholes where two intersecting faults have caused intense fracturing. The Calico Hills interval is the least permeable interval in the C-holes because it is the farthest interval vertically from faults that intersect these boreholes. In a different structural setting, the Lower Bullfrog, Calico Hills, and other intervals of the Miocene tuffaceous rocks could have different hydraulic properties than indicated at the C-hole complex. For example, the Bullfrog Tuff yielded very little of the water produced from the Miocene tuffaceous rocks during a tracejector flow survey of UE-25 p #1 (Craig and Robison, 1984), and the Calico Hills Formation yielded 32 percent of the water produced from the Miocene tuffaceous rocks during a tracejector flow survey of UE-25 b #1 (Lahoud and others, 1984). Cross-hole hydraulic tests at several sites on Yucca Mountain would enable extrapolation of hydraulic properties of the Miocene tuffaceous rocks beyond the immediate vicinity of the C-hole complex.

Calico Hills Interval

The Calico Hills interval responded in most hydraulic tests, including one conducted from May to June 1984 (Geldon, 1996), as an unconfined aquifer. In four tests conducted from 1984 to 1997, the Calico Hills interval consistently was determined to be the least permeable interval in the C-holes (table 8). The hydraulic test in May and June 1984 indicated that the Calico Hills interval in UE-25 c #1 has transmissivity

Table 7. Maximum observed water-level declines related to C-holes testing, May 1996 to November 1997, in routinely monitored boreholes at Yucca Mountain (data from Graves, 2000)

Borehole	Geologic unit	Maximum water-level decline (meters)
USW WT-1	Calico Hills Formation, Bullfrog Tuff	0.3
USW WT-2	Prow Pass Tuff	0.4
UE-25 WT #4	Calico Hills Formation	0.2
USW WT-11	Topopah Springs Tuff, Calico Hills Formation	0.2
UE-25 WT #14	Topopah Springs Tuff, Calico Hills Formation	0.2
UE-25 WT #16	Calico Hills Formation	0.1
UE-25 b #1 upper interval	Calico Hills Formation, Prow Pass Tuff, Bullfrog Tuff, upper Tram Tuff	0.3
USW H-1 uppermost interval	Prow Pass Tuff	0.4
USW H-4 upper interval	Calico Hills Formation, Prow Pass Tuff, Bullfrog Tuff, Tram Tuff, upper Lithic Ridge Tuff	0.3

Table 8. Results of hydraulic tests in borehole UE-25 c #3, June 1995 to November 1997

[nd, no data; na, not applicable; est, estimated to be the same as values obtained from a hydraulic test in May 1984]

Starting date	06/12/95	02/08/96 UE-25 c #1	02/08/96 UE-25 c #1	05/08/96	05/08/96	06/12/95	02/08/96 UE-25 c #2	05/08/96	05/08/96
Calico Hills									
Analyzed data	None	None	na	None	na	Drawdown	Drawdown	Drawdown	na
Period of record (minutes)	na	na	na	na	na	5,800	7,000	464,100	na
Aquifer type	Unconfined	Unconfined	na	Unconfined	na	Unconfined	Confined	Unconfined	na
Transmissive thickness (meters)	60.4	60.4	na	60.4	na	45.4	45.4	45.4	na
Distance from pumping well (meters)	78.3	78.3	na	78.3	na	29.0	29.0	29.0	na
Average discharge (liters per second)	0.85	0.042	na	0.10	na	0.85	0.042	0.10	na
Transmissivity (meters squared per day)	9(est)	9(est)	na	9(est)	na	6	10	4	na
Horizontal hydraulic conductivity (meters per day)	0.2(est)	0.2(est)	na	0.2(est)	na	0.1	0.2	0.08	na
Vertical hydraulic conductivity (meters per day)	0.3(est)	0.3(est)	na	0.3(est)	na	nd	nd	0.01	na
Storativity (dimensionless)	nd	nd	na	nd	na	0.0002	0.0006	0.0003	na
Specific yield (dimensionless)	0.003(est)	0.003(est)	na	0.003(est)	na	nd	nd	0.4	na
Prow Pass									
Analyzed data	Drawdown	Drawdown	Drawdown	Drawdown	na	Drawdown	Drawdown	Drawdown	na
Period of record (minutes)	5,800	7,000	7,000	464,100	na	5,800	7,000	464,100	na
Aquifer type	Confined	Unconfined	Confined	Confined	na	Confined	Confined	Confined	na
Transmissive thickness (meters)	18.9	18.9	18.9	18.9	na	23.8	23.8	23.8	na
Distance from pumping well (meters)	81.1	81.1	81.1	81.1	na	28.6	28.6	28.6	na
Average discharge (liters per second)	0.65	0.21	0.21	0.22	na	0.65	0.13	0.19	na
Transmissivity (meters squared per day)	60	50	60	50	na	40	30	30	na
Horizontal hydraulic conductivity (meters per day)	3	3	3	3	na	2	1	1	na
Vertical hydraulic conductivity (meters per day)	nd	0.0001	nd	nd	na	nd	nd	nd	na
Storativity (dimensionless)	0.0003	0.0003	0.0004	0.0002	na	0.0004	0.003	0.0008	na
Specific yield (dimensionless)	nd	nd	nd	nd	na	nd	nd	nd	na
Upper Bullfrog									
Analyzed data	Recovery	Drawdown	na	Drawdown	na	Drawdown	Drawdown	Drawdown	na
Period of record (minutes)	5,700	7,000	na	464,100	na	5,800	7,000	464,100	na
Aquifer type	Confined	Unconfined	na	Fissure-block	na	Confined	Confined	Confined	na
Transmissive thickness (meters)	46.0	46.0	na	46.0	na	24.1	24.1	24.1	na
Distance from pumping well (meters)	83.2	83.2	na	82.3	na	28.6	28.6	28.6	na
Average discharge (liters per second)	0.88	0.37	na	0.32	na	0.88	0.36	0.36	na
Transmissivity (meters squared per day)	90	40	na	50	na	100	100	80	na
Horizontal hydraulic conductivity (meters per day)	2	0.8	na	1/.00002*	na	4	4	3	na
Vertical hydraulic conductivity (meters per day)	nd	0.5	na	nd	na	nd	nd	nd	na
Storativity (dimensionless)	0.00006	0.0009	na	0.0001/.0009*	na	0.00003	0.00002	0.00002	na
Specific yield (dimensionless)	nd	0.002	na	nd	na	nd	nd	nd	na

Table 8. Results of hydraulic tests in borehole UE-25 c #3, June 1995 to November 1997—Continued

[nd, no data; na, not applicable; est, estimated to be the same as values obtained from a hydraulic test in May 1984]

Starting date	06/12/95	02/08/96	02/08/96	05/08/96	05/08/96	06/12/95	02/08/96	05/08/96	05/08/96
		UE-25 c #1					UE-25 c #2		
					Bullfrog-Tram				
Analyzed data	na	Drawdown	na	na	na	na	Drawdown	na	na
Period of record (minutes)	na	7,000	na	na	na	na	7,000	na	na
Aquifer type	na	Confined	na	na	na	na	Confined	na	na
Transmissive thickness (meters)	na	112	na	na	na	na	51.2	na	na
Distance from pumping well (meters)	na	86.3	na	na	na	na	29	na	na
Average discharge (liters per second)	na	7.84	na	na	na	na	7.93	na	na
Transmissivity (meters squared per day)	na	2,500	na	na	na	na	2,500	na	na
Horizontal hydraulic conductivity (meters per day)	na	20	na	na	na	na	50	na	na
Vertical hydraulic conductivity (meters per day)	na	nd	na	na	na	na	nd	na	na
Storativity (dimensionless)	na	0.0003	na	na	na	na	0.002	na	na
Specific yield (dimensionless)	na	nd	na	na	na	na	nd	na	na
					Lower Bullfrog				
Analyzed data	Recovery	None	na	Drawdown	Drawdown	Drawdown	None	Drawdown	Drawdown
Period of record (minutes)	6,300	na	na	464,100	464,100	5,800	na	464,100	464,100
Aquifer type	Confined	Confined	na	Confined	Fissure-block	Confined	Confined	Confined	Fissure-block
Transmissive thickness (meters)	62.8	62.8	na	62.8	62.8	29.9	29.9	29.9	29.9
Distance from pumping well (meters)	85.6	85.6	na	85.6	85.6	29.3	29.3	29.3	29.3
Average discharge (liters per second)	15.3	nd	na	6.37	6.37	15.3	nd	6.69	6.69
Transmissivity (meters squared per day)	1,800	nd	na	1,600	1,300	1,900	nd	1,600	1,300
Horizontal hydraulic conductivity (meters per day)	30	nd	na	30	20/.0004*	60	nd	50	40/.001*
Vertical hydraulic conductivity (meters per day)	nd	nd	na	nd	nd	nd	nd	nd	nd
Storativity (dimensionless)	0.0004	nd	na	0.0002	0.0002/.002*	0.003	nd	0.001	0.002/.02*
Specific yield (dimensionless)	nd	nd	na	nd	nd	nd	nd	nd	nd
					Upper Tram				
Analyzed data	None	None	na	None	na	None	None	None	na
Period of record (minutes)	na	na	na	na	na	na	na	na	na
Aquifer type	Leaky	Leaky	na	Leaky	na	Leaky	Leaky	Leaky	na
Transmissive thickness (meters)	49.7	49.7	na	49.7	na	21.3	21.3	21.3	na
Distance from pumping well (meters)	86.9	86.9	na	86.9	na	29.6	29.6	29.6	na
Average discharge (liters per second)	4.74	nd	na	2.52	na	4.74	nd	2.18	na
Transmissivity (meters squared per day)	nd	nd	na	800	na	nd	nd	900	na
Horizontal hydraulic conductivity (meters per day)	nd	nd	na	20	na	nd	nd	40	na
Vertical hydraulic conductivity (meters per day)	nd	nd	na	nd	na	nd	nd	nd	na
Storativity (dimensionless)	nd	nd	na	0.0001	na	nd	nd	0.001	na
Specific yield (dimensionless)	nd	nd	na	nd	na	nd	nd	nd	na

* First number is for fractures; second, for matrix

of 9 m^2/d, horizontal hydraulic conductivity of 0.2 m/d, vertical hydraulic conductivity of 0.3 m/d, and a specific yield of 0.003 (Geldon, 1996). The hydraulic test in June 1995 indicated that the Calico Hills interval in UE-25 c #2 has transmissivity of 6 m^2/d, horizontal hydraulic conductivity of 0.1 m/d, and storativity of 0.0002. Hydraulic tests conducted in February 1996 and from May 1996 to November 1997 generally supported the previous analyses. A representative plot indicating a match between the data and one of the type curves of Neuman (1975) for an unconfined, anisotropic aquifer is shown in figure 25.

Prow Pass Interval

The Prow Pass interval generally responded to hydraulic tests as a confined aquifer (table 8). The hydraulic test in June 1995 indicated that the Prow Pass interval in UE-25 c #1 has transmissivity of 60 m^2/d, hydraulic conductivity of 3 m/d, and storativity of 0.0003. The same hydraulic test indicated that the Prow Pass interval in UE-25 c #2 has transmissivity of 40 m^2/d, hydraulic conductivity of 2 m/d, and storativity of 0.0004. Hydraulic tests conducted in February 1996 and from May 1996 to March 1997 generally supported the previous analyses. A representative plot indicating a match between the data and the type curve of Theis (1935) for a confined aquifer is shown in figure 26.

Upper Bullfrog Interval

The Upper Bullfrog interval in UE-25 c #2 responded to all hydraulic tests as a confined aquifer (table 8). These tests consistently indicated transmissivity of 80 to 100 m^2/d, hydraulic conductivity of 3 to 4 m/d, and storativity of 0.00002 to 0.00003. A representative plot indicating a match between the data and the type curve of Theis (1935) for a confined aquifer is shown in figure 27.

The hydraulic test in June 1995 produced results for the Upper Bullfrog interval in UE-25 c #1 that were consistent with results for this interval in UE-25 c #2 (table 8). During longer tests conducted in

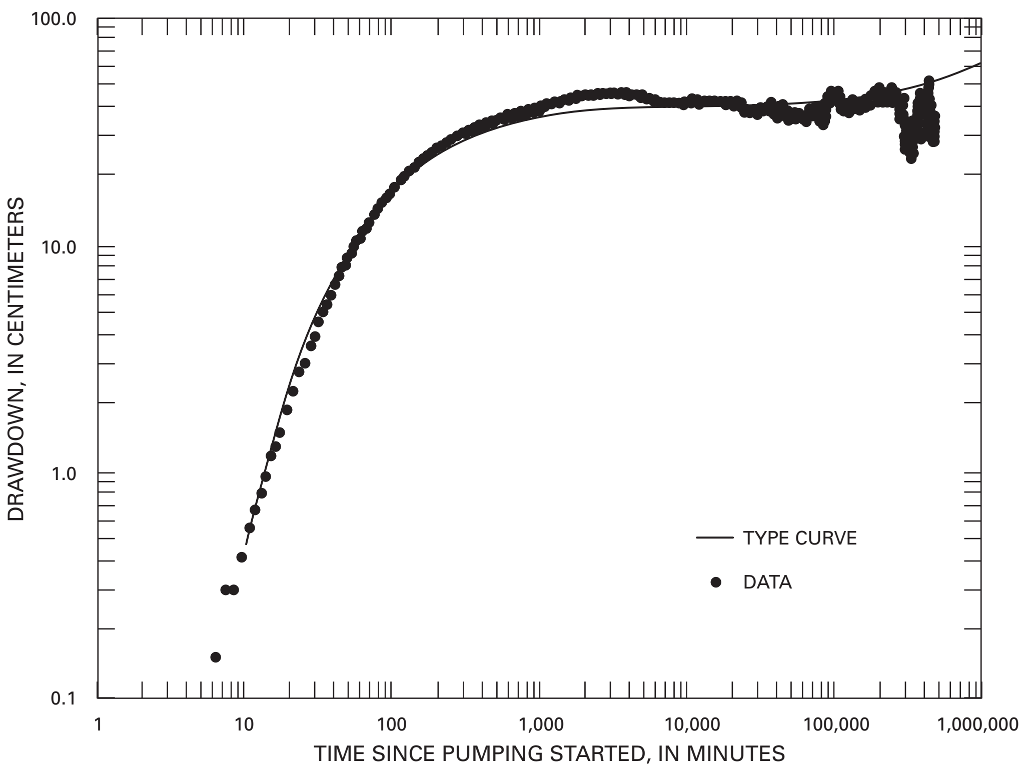


Figure 25. Analysis of drawdown in the Calico Hills interval of UE-25 c #2, May 8, 1996, to March 26, 1997 by the method of Neuman (1975).

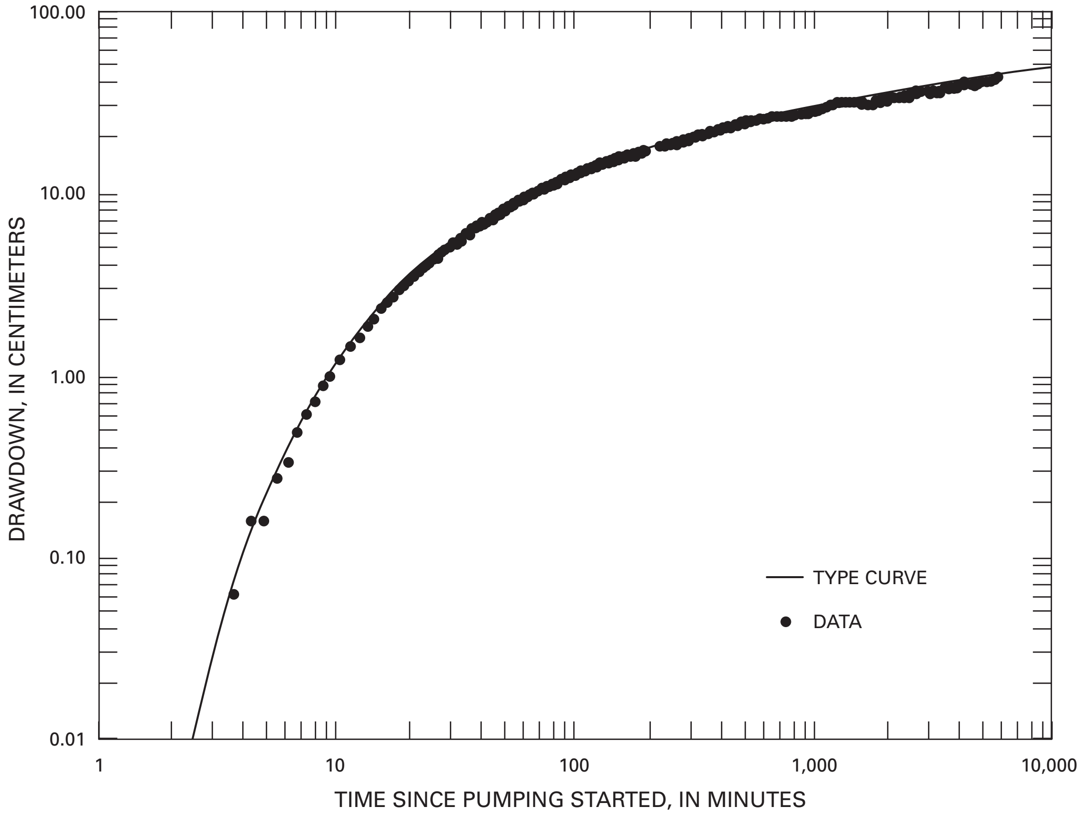


Figure 26. Analysis of drawdown in the Prow Pass interval of UE-25 c #1, June 12–16, 1995, by the method of Theis (1935).

February 1996 and May 1996, sufficient time elapsed to reveal the effects of fractures on flow between the Upper Bullfrog interval in UE-25 c #1 and screened intervals in the pumping well. Analyses of drawdown complicated by downward flow through fractures indicated smaller values of transmissivity and hydraulic conductivity and larger values of storativity than analyses of drawdown in which the effects of fractures were not evident (table 8). Hydraulic properties determined from hydraulic tests conducted in 1996 and 1997 are considered less reliable than properties determined from the hydraulic test in June 1995 because the later tests were influenced substantially by screen placement in the observation and pumping wells.

Lower Bullfrog Interval

The undisturbed drawdown in the Lower Bullfrog interval of UE-25 c #1 and UE-25 c #2 during the hydraulic test conducted from May 1996 to November 1997 can be interpreted in several ways that were not evident from previous hydraulic tests of much shorter duration. Although previous tests indicated a confined-aquifer response, the test beginning in May 1996 progressed long enough for a double-humped drawdown curve characteristic of a fissure-block aquifer to develop. From 158,000 minutes after pumping started in May 1996 to the end of the analyzed record (464,100 minutes after pumping started), drawdown in UE-25 c #1 and UE-25 c #2 was more than could be anticipated on the basis of the earlier drawdown for long periods [using the equation of Theis (1935) to extrapolate drawdown]. The oscillatory pattern of drawdown in the C-holes after 158,000 minutes of pumping can be interpreted to indicate that the spreading cone of depression encompassed volumes of the Lower Bullfrog that alternately were less transmissive or as transmissive as the Lower Bullfrog in the C-holes.

Values of transmissivity computed for the Lower Bullfrog interval are significantly different depending on whether the interval is considered a confined aquifer or a fissure-block aquifer (table 8). In UE-25 c #1 and UE-25 c #2, transmissivity is 1,600 m^2/d if the Lower Bullfrog is analyzed as a confined aquifer (fig. 28) and 1,300 m^2/d if the Lower

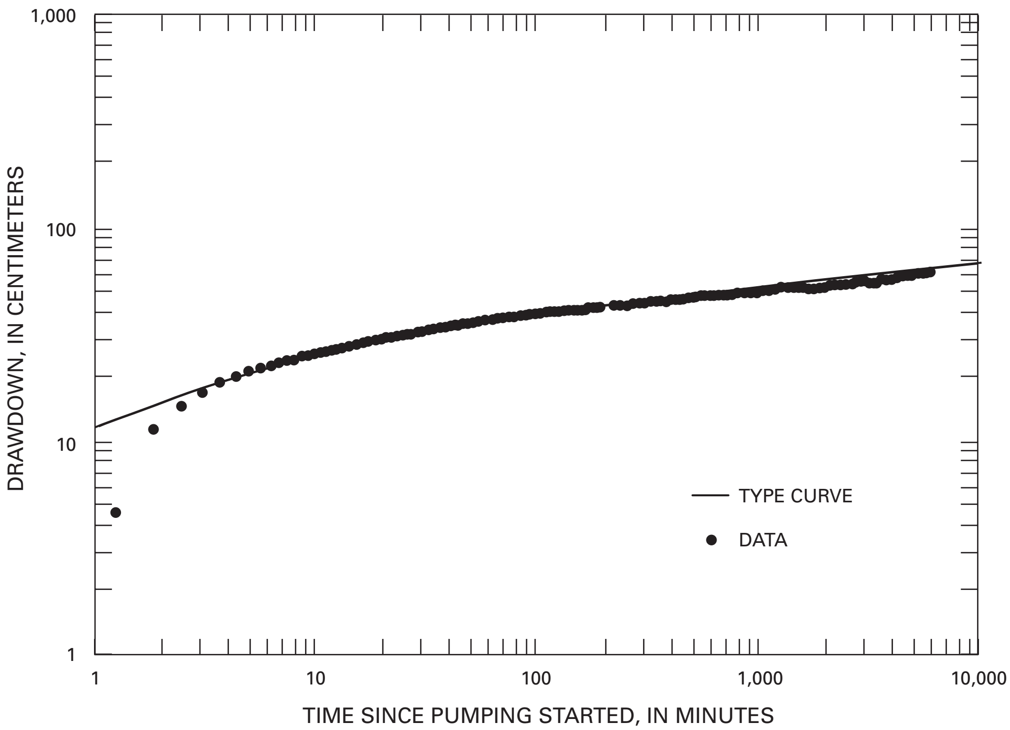


Figure 27. Analysis of drawdown in the Upper Bullfrog interval of UE-25 c #2, June 12–16, 1995, by the method of Theis (1935).

Bullfrog is analyzed as a fissure-block aquifer (fig. 29). Although the two analytical solutions produced equally plausible results, the fissure-block aquifer solution is consistent with a tracer test conducted from February to March 1996 that indicated dual porosity in the Bullfrog-Tram interval (Fahy, 1997). Also, the longer pumping required for the fissure-block aquifer response to develop, and the lower transmissivity value determined from this response, can be interpreted to confirm that less transmissive rocks were reached as the cone of depression spread to increasingly distant areas during the hydraulic test that began in May 1996.

Values of hydraulic conductivity and storativity are considerably larger in the rock mass between UE-25 c #2 and UE-25 c #3 than in the rock mass between UE-25 c #1 and UE-25 c #3. The hydraulic conductivity of the Lower Bullfrog interval is 50 m/d in UE-25 c #2 and 30 m/d in UE-25 c #1. The storativity of the Lower Bullfrog interval is 0.001 in UE-25 c #2 and 0.0002 in UE-25 c #1 (The hydraulic conductivity and storativity of the interval in both boreholes are about the same as that of the fractures in the interval in both boreholes).

Upper Tram Interval

The Upper Tram interval was known from hydraulic tests conducted in 1984 to respond to pumping as a leaky aquifer without confining-bed storage because of recharge from faults that intersect the C-holes in this interval (Geldon, 1996). Although hydraulic properties of the Upper Tram (UT) interval could not be determined directly from hydraulic tests conducted during this study (because of transducer malfunction), they could be calculated by subtracting values of hydraulic properties determined for the Lower Bullfrog (LB) interval from those determined for the Bullfrog-Tram (BT) interval. The following equations were used:

$$T_{UT} = T_{BT} - T_{LB} \tag{2}$$

$$S_{UT} = S_{BT} - S_{LB} \tag{3}$$

$$K_{UT} = (K_{BT} \times b_{BT} - K_{LB} \times b_{LB}) / b_{UT} \tag{4}$$

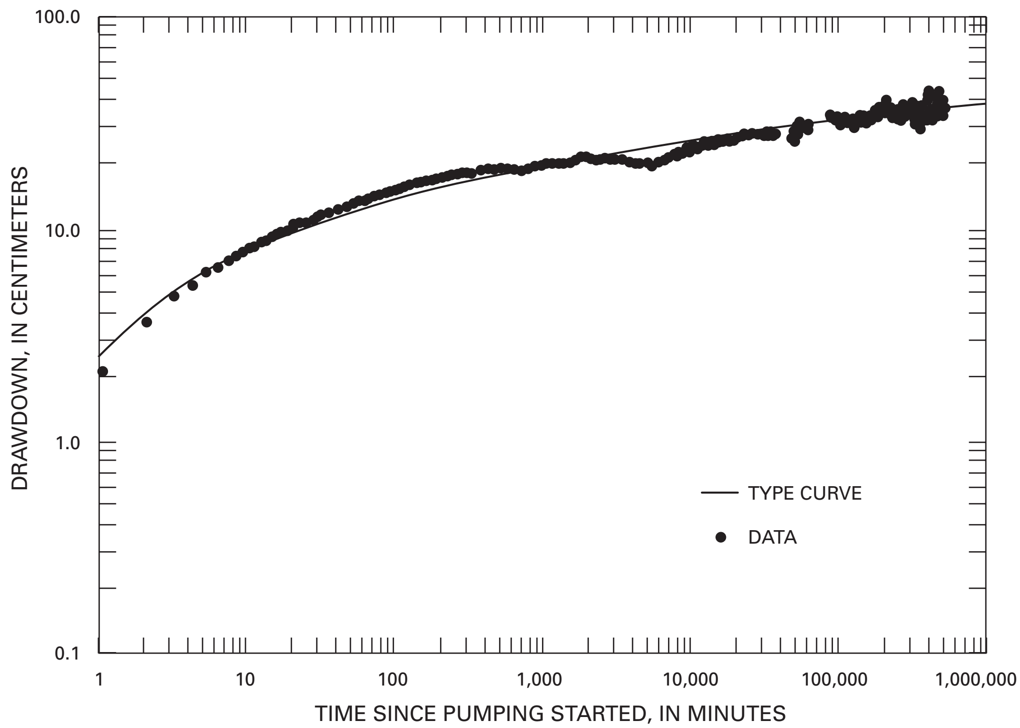


Figure 28. Analysis of drawdown in the Lower Bullfrog interval of UE-25 c #1, May 8, 1996, to March 26, 1997, by the method of Theis (1935).

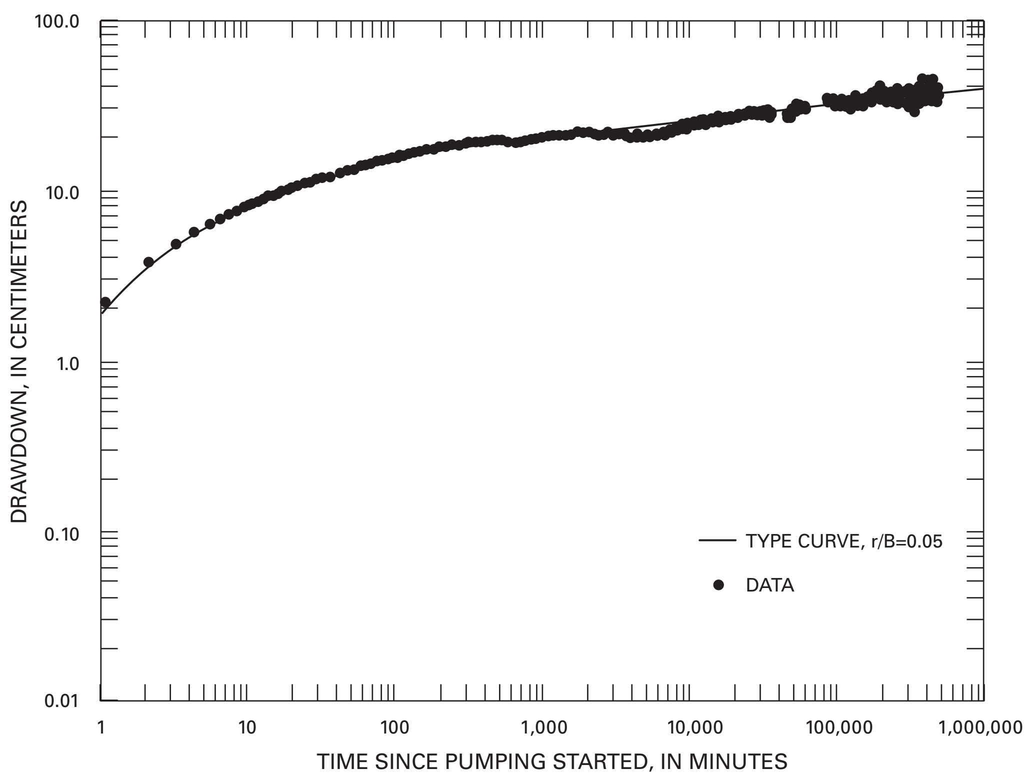


Figure 29. Analysis of drawdown in the Lower Bullfrog interval of UE-25 c #1, May 8, 1996, to March 26, 1997, by the method of Streltsova-Adams (1978).

where:

T = transmissivity (m^2/d);
S = storativity (dimensionless);
K = hydraulic conductivity (m/d); and
b = thickness (m).

Only hydraulic properties of the LB interval determined by the Theis (1935) solution were used in these calculations because hydraulic properties of the BT interval (which includes the Lower Bullfrog) were determined by this method. These calculations indicated transmissivity of 800 m^2/d, hydraulic conductivity of 20 m/d, and storativity of 0.0001 for the Upper Tram interval in UE-25 c #1 and transmissivity of 900 m^2/d, hydraulic conductivity of 40 m/d, and storativity of 0.001 for the Upper Tram interval in UE-25 c #2 (table 8).

Miocene Tuffaceous Rocks

Indicative of hydraulic connection through a highly developed fracture network, diverse intervals of the Miocene tuffaceous rocks in six observation wells responded to the pumping in UE-25 c #3 from May 1995 to November 1997 (table 9). The C-holes, UE-25 ONC-1, and USW H-4 appear to be connected hydraulically through a northwest-trending zone of discontinuous faults that extends from Bow Ridge to Antler Wash (Geldon and others, 1998). The Paintbrush Canyon and related faults that intersect UE-25 WT #14 and the C-holes probably enhance hydraulic connection between these boreholes. Hydraulic connection between the C-holes and UE-25 WT #3 probably is enabled both stratigraphically and structurally because these boreholes were open during hydraulic tests in the same geologic unit (the Bullfrog Tuff) and are cut by the same faults (the Paintbrush Canyon and related faults).

Analyses of the drawdown in individual observation wells (figs. 30–33) indicate hydraulic properties of the rock mass at the scale of the distance between these boreholes and UE-25 c #3 (table 9). Analyses of drawdown in multiple observation wells, either as a function of time (normalized by dividing by the square of the distance between the observation and pumping wells) or as a function of distance at a specified time, indicate hydraulic properties of the rock mass in which all of the included observation wells are located.

Despite being 843 m from UE-25 c #3, UE-25 ONC-1 responded to pumping after only 200 minutes, because it is in the same structural block as the C-holes (between the Bow Ridge and Paintbrush Canyon Faults) and is well connected by fractures related to northwest-trending faults. This fracture connection is reflected in a characteristic fissure-block aquifer response. From 200 to 2,000 minutes, flow from fractures caused drawdown to increase as a function of log time. From 2,000 to 6,000 minutes, as flow from the rock matrix into fractures occurred, drawdown remained relatively constant. After 6,000 minutes, drawdown increased again as a function of log time as flow from both the fractures and matrix occurred. Drawdown conformed to the type curve of Streltsova-Adams (1978) for $\eta = 10$ and $r/B = 1.0$ (fig. 30). Transmissivity computed from the type-curve match equals 1,000 m^2/d. If the transmissive thickness between the C-hole complex and UE-25 ONC-1 is assumed to vary linearly between known thicknesses in UE-25 c #2 and USW H-4, then it can be estimated to be about 193 m in UE-25 ONC-1. Dividing transmissivity by the estimated transmissive thickness indicates a fracture hydraulic conductivity of 5 m/d. In comparison, the hydraulic conductivity of the matrix (table 9) is insignificant. Computed storativity for the fractures in UE-25 ONC-1 is 0.001, which is one-tenth of the computed storativity of the matrix.

Located 2,245 m from UE-25 c #3, borehole USW H-4 took 5,000 minutes to respond to pumping. From 5,000 to 72,000 minutes after pumping started, drawdown in USW H-4 conformed to the type curve of Theis (1935) for a confined aquifer (fig. 31). After 72,000 minutes, drawdown became relatively constant in response to the recharge effect of nearby fault boundary. The preboundary drawdown indicated transmissivity of 700 m^2/d and storativity of 0.002 (table 9). Dividing transmissivity by the transmissive thickness obtained from a flow survey (Whitfield and others, 1984) indicated a hydraulic conductivity value of 2 m/d. The location of the recharge boundary could not be ascertained because only USW H-4 was affected by this boundary, and the analytical solution to determine the location of a boundary (Lohman, 1972) requires that at least two wells be affected by the same boundary.

Located 2,249 m from UE-25 c #3, borehole UE-25 WT #14 took 5,250 minutes to respond to pumping. From 5,250 to 9,000 minutes, a transition from borehole-storage release to release of water from the aquifer occurred. From 9,000 to 72,000 minutes

Table 9. Hydraulic properties computed from observation well responses to pumping in UE-25 c #3, May 1995 to November 1997

[est, estimated]

Borehole	UE-25 c #2	UE-25 c #2	UE-25 c #1	UE-25 c #1
Starting date of hydraulic test	05/22/95	05/08/96	05/22/95	05/08/96
Period of record (minutes)	14,400	464,100	11,400	464,100
Analyzed data	Drawdown	Drawdown	Recovery	Drawdown
Geologic units in monitored interval	Calico Hills to Tram	Calico Hills to Tram	Calico Hills to Tram	Calico Hills to Tram
Aquifer type	Unconfined	Variable	Unconfined	Variable
Transmissive thickness (meters)	165	144	252	238
Distance from pumping well (meters)	29.0	29.0	82.6	82.9
Average discharge (liters per second)	17.9	9.53	17.9	9.53
Transmissivity (meters squared per day)	2,100	2,400–2,600	1,800	2,200–2,600
Horizontal hydraulic conductivity (meters per day)	13	16–18	7	9–11
Vertical hydraulic conductivity (meters per day)	1.7	Unknown	0.3	Unknown
Storativity (dimensionless)	0.003	0.003–.004	0.001	0.002
Specific yield (dimensionless)	0.2	Unknown	0.01	Unknown

Borehole	UE-25 ONC-1	USW H-4	UE-25 WT #14	UE-25 WT #3
Starting date of hydraulic test	05/08/96	05/08/96	05/08/96	05/08/96
Period of record (minutes)	796,700	72,000	72,000	463,500
Analyzed data	Drawdown	Drawdown	Drawdown	Drawdown
Geologic units in monitored interval	Prow Pass	Prow Pass to Lithic Ridge	Topopah Spring and Calico Hills	Bullfrog
Aquifer type	Fissure-block	Confined	Confined	Confined
Transmissive thickness (meters)	193 (est)	276	Unknown	47.5 (est)
Distance from pumping well (meters)	843	2,245	2,249	3,526
Average discharge (liters per second)	9.21	9.72	9.72	9.59
Transmissivity (meters squared per day)	1,000	700	1,300	2,600
Horizontal hydraulic conductivity (meters per day)	5/.002*	2	Unknown	56
Storativity (dimensionless)	0.001/.01*	0.002	0.002	0.002

* First number is for fractures; second, for matrix (Values of transmissivity and hydraulic conductivity listed for UE-25 ONC-1 and USW H-4 differ from those obtained from a hydraulic test conducted from May 22 to June 1, 1995, but the values determined from the longer test beginning in May 1996 are considered more reliable).

after pumping started, drawdown in UE-25 WT #14 conformed to the type curve of Theis (1935) for a confined aquifer (fig. 32). After 72,000 minutes, drawdown became very oscillatory, but broad oscillations in the data deviated about a relatively constant value. The late-time data are interpreted to be a less-than-ideal response to a recharge boundary. The preboundary drawdown indicates transmissivity of 1,300 m^2/d and storativity of 0.002 (table 9). Hydraulic conductivity and the location of the boundary could not be determined because of insufficient data.

Located 3,526 m from UE-25 c #3, borehole UE-25 WT #3 took 9,130 minutes to respond to pumping. Thereafter, drawdown in UE-25 WT #3 was very oscillatory, but it could be fit to the type curve of Theis (1935) for a confined aquifer (fig. 33). This solution indicated transmissivity of 2,600 m^2/d and

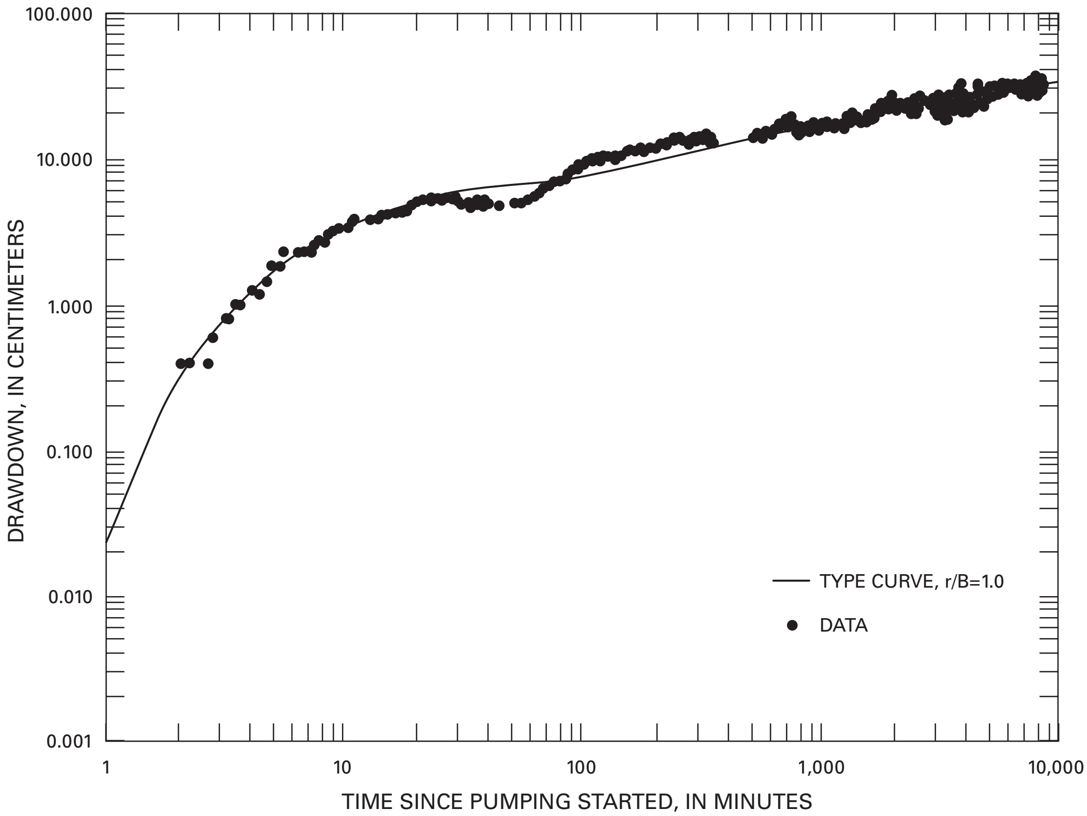


Figure 30. Analysis of drawdown in UE-25 ONC-1, May 8, 1996, to November 12, 1997, by the method of Streltsova-Adams (1978).

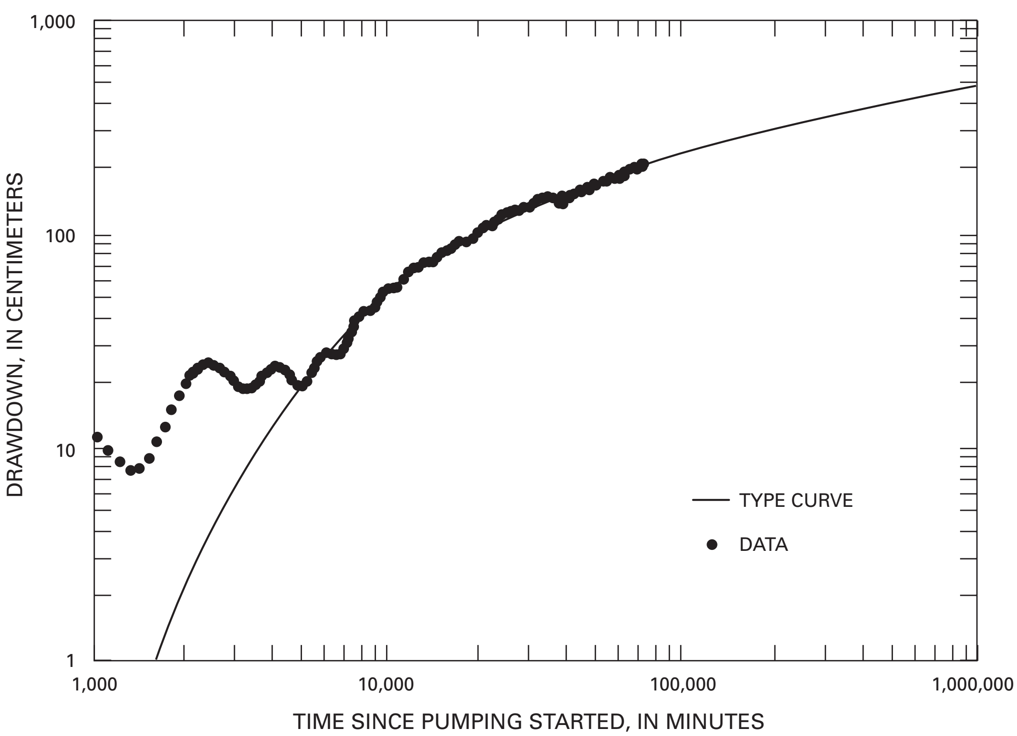


Figure 31. Analysis of drawdown in USW H-4, May 8 to June 27, 1996, by the method of Theis (1935).

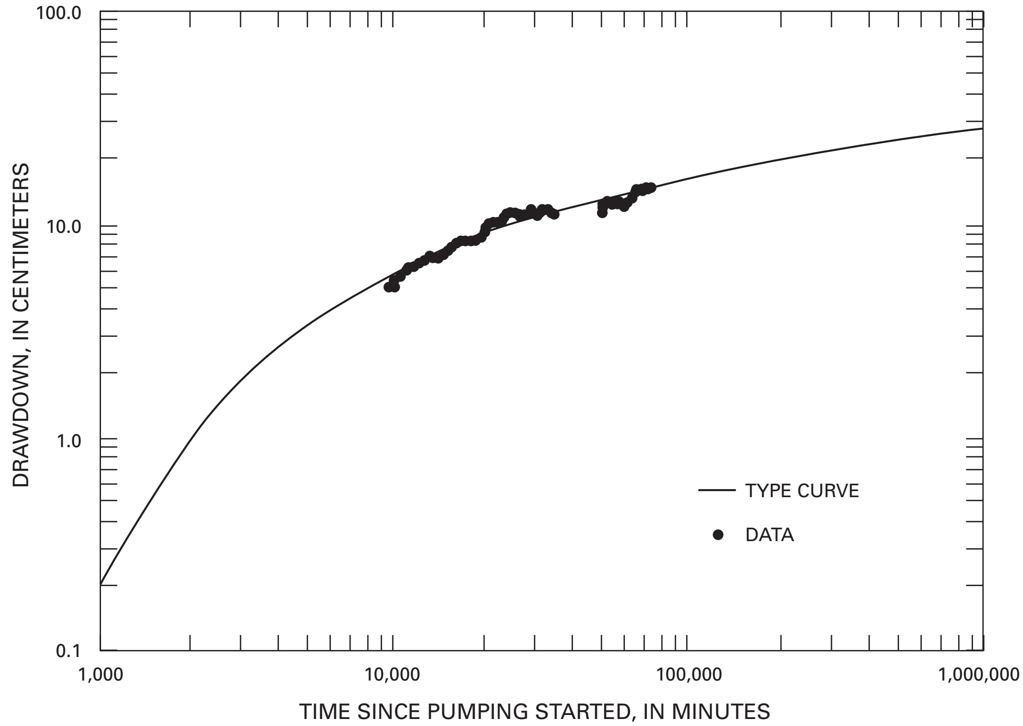


Figure 32. Analysis of drawdown in UE-25 WT #14, May 8 to June 27, 1996, by the method of Theis (1935).

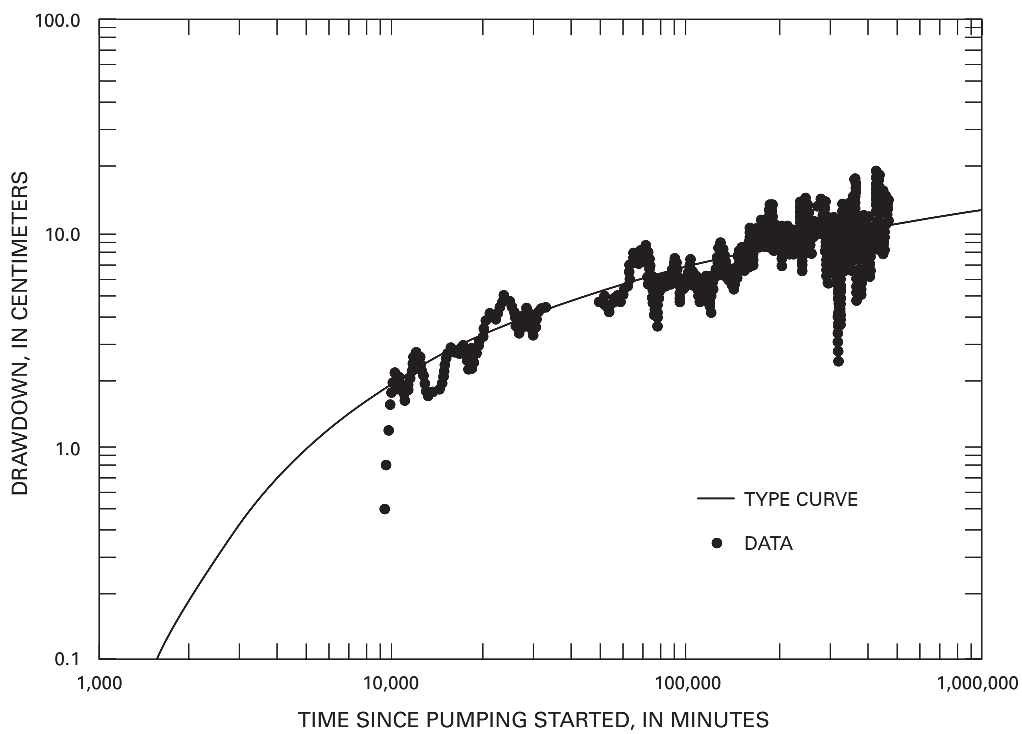


Figure 33. Analysis of drawdown in UE-25 WT #3, May 8, 1996, to March 26, 1997, by the method of Theis (1935).

storativity of 0.002 (table 9). Dividing transmissivity by the length of the open interval in UE-25 WT #3, 47.5 m, indicated a hydraulic conductivity value of 56 m/d. Actual hydraulic conductivity probably is smaller than the calculated value because the thickness of transmissive rock between the C-hole complex and UE-25 WT #3 probably exceeds the length of the open interval.

The transmissivity of the Miocene tuffaceous rocks appears to decrease northwestward in the area containing the observation wells used in the hydraulic test that began in May 1996. Depending on the analytical solutions used, transmissivity could be interpreted to decrease from 2,600 m^2/d in the vicinity of UE-25 WT #3 to about 2,000 m^2/d in the vicinity of the C-holes. The transmissivity of the Miocene tuffaceous rocks is 1,300 m^2/d in the vicinity of UE-25 WT #14, 1,000 m^2/d in the vicinity of UE-25 ONC-1, and 700 m^2/d in the vicinity of USW H-4.

The hydraulic conductivity distribution of the Miocene tuffaceous rocks in the vicinity of the C-holes is believed to be structurally controlled. Hydraulic conductivity in UE-25 c #2 decreases from 20–60 m/d in the Upper Tram and Lower Bullfrog intervals to 0.08–0.2 m/d in the Calico Hills interval as the vertical distance from faults that intersect the borehole increases (table 8). The average hydraulic conductivity of the Miocene tuffaceous rocks in UE-25 c #2 is twice that in UE-25 c #1 (table 9), possibly because UE-25 c #2 is located nearer to the subsurface intersection of the northerly trending Paintbrush Canyon or Midway Valley Fault and a northwest-trending fault (shown in figure 2) that underlies the gap through the northern part of Bow Ridge. If spatial relations between faults and hydraulic conductivity at the C-hole complex are combined with values of hydraulic conductivity determined from analyses of drawdown in UE-25 ONC-1, UE-25 WT #3, and USW H-4 (table 9), then a general distribution of hydraulic conductivity for the Miocene tuffaceous rocks in the vicinity of the C-holes can be inferred. This inferred general distribution is shown in figure 34.

In the 21-km^2 area encompassed by observation wells used in hydraulic tests at the C-hole complex from 1995 to 1997, the storativity of Miocene tuffaceous rocks in these observation wells uniformly is 0.001 to 0.003 (table 9). Analysis of the drawdown in observation wells not affected by boundaries as a function of the time divided by the square of the distance from the pumping well (fig. 35) indicates that the average storativity of the Miocene tuffaceous rocks in the area encompassed by the observation wells is 0.002. This same analysis indicates that the average transmissivity of the Miocene tuffaceous rocks in this area is 2,200 m^2/d. Being able to derive a single analytical solution for UE-25 c #1, UE-25 c #2, UE-25 ONC-1, and UE-25 WT #3 confirms that the Miocene tuffaceous rocks in the structural block delimited by the Paintbrush Canyon, Bow Ridge, and Dune Wash Faults, at least as far north as lower Midway Valley, are a single aquifer in which flow is influenced by the same structural, stratigraphic, and climatic factors.

Plots of drawdown in observation wells as a function of distance 30,000, 100,000, 200,000, 305,000, and 463,000 minutes after pumping started in May 1996 (drawdown at 30,000 and 463,000 minutes shown in figure 36) confirm the ovoid pattern of drawdown aligned with faults extending from Bow Ridge to Antler Wash that was detected during the hydraulic test conducted from May 22 to June 1, 1995 (Geldon and others, 1998). Analyzed by the method of Cooper and Jacob (1946), plots of drawdown as a function of distance (fig. 37) indicate values of transmissivity ranging from 2,100 to 2,600 m^2/d and values of storativity ranging from 0.0005 to 0.002 (table 10). In comparison, analysis of drawdown in observation wells as a function of distance 14,000 minutes after pumping started in May 1995 indicated transmissivity of 2,300 m^2/d and storativity of 0.003 (Geldon and others, 1998). Distance-drawdown and time-drawdown analyses discussed in this section converge on the same solutions.

During the four hydraulic tests conducted at the C-hole complex from 1995 to 1997, drawdown occurred in all monitored intervals of the C-holes and other observation wells, regardless of the geologic interval being pumped. This hydraulic connection across geologic and lithostratigraphic contacts is believed to result from interconnected faults, fractures, and intervals with large matrix permeability. The Miocene tuffaceous rocks appear to respond to pumping as a single aquifer in the Yucca Mountain area. This conclusion is supported by being able to use the drawdown from observation wells completed in different Miocene geologic units in single analytical solutions of drawdown as a function of time or distance, and the widespread observed water-level declines related to pumping. The Paintbrush Canyon

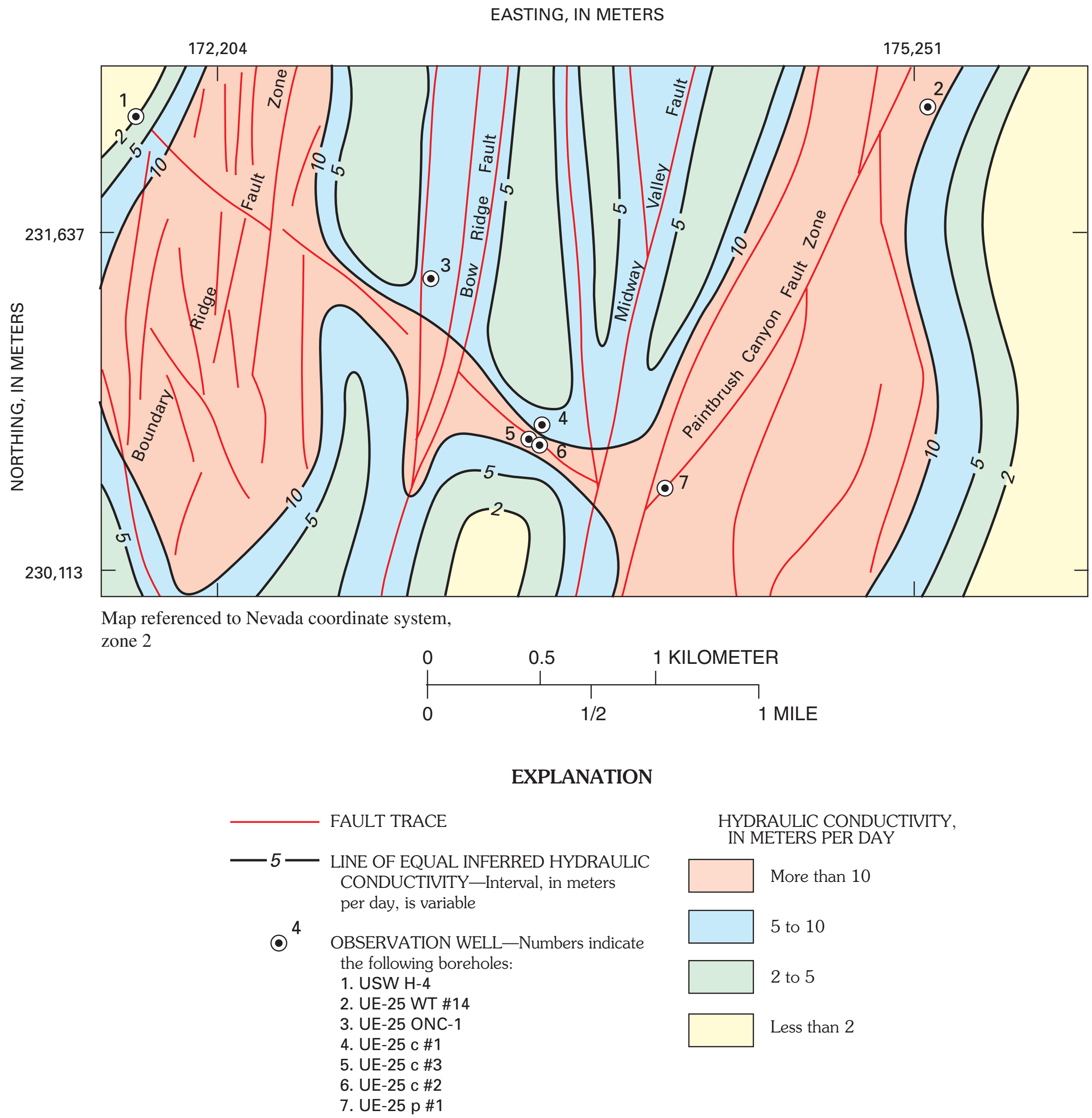


Figure 34. Inferred distribution of hydraulic conductivity of Miocene tuffaceous rocks in the vicinity of the C-holes.

Fault appears to be an effective recharge boundary within the aquifer because the effects of pumping were minimal or not observed east of this feature. Designation of separate aquifers and confining units within the Miocene tuffaceous rocks, therefore, may not be appropriate in this area.

Paleozoic Carbonate Rocks

Borehole UE-25 p #1 was monitored during hydraulic tests in 1995 and 1996 to evaluate hydraulic connection between the Miocene tuffaceous rocks and Paleozoic carbonate rocks in the vicinity of the C-holes, which previously had been indicated by hydraulic head measurements in UE-25 p #1 and borehole flow surveys in the C-holes. Measurements as UE-25 p #1 was being drilled in 1983 indicated a 22-m difference in hydraulic heads for the Paleozoic carbonate rocks and Miocene tuffaceous rocks in UE-25 p #1 (Craig and Robison, 1984), which indicated a potential for water to flow from the lower to the upper hydrogeologic unit. Flow surveys conducted in the C-holes in 1991 indicated upward flow in the

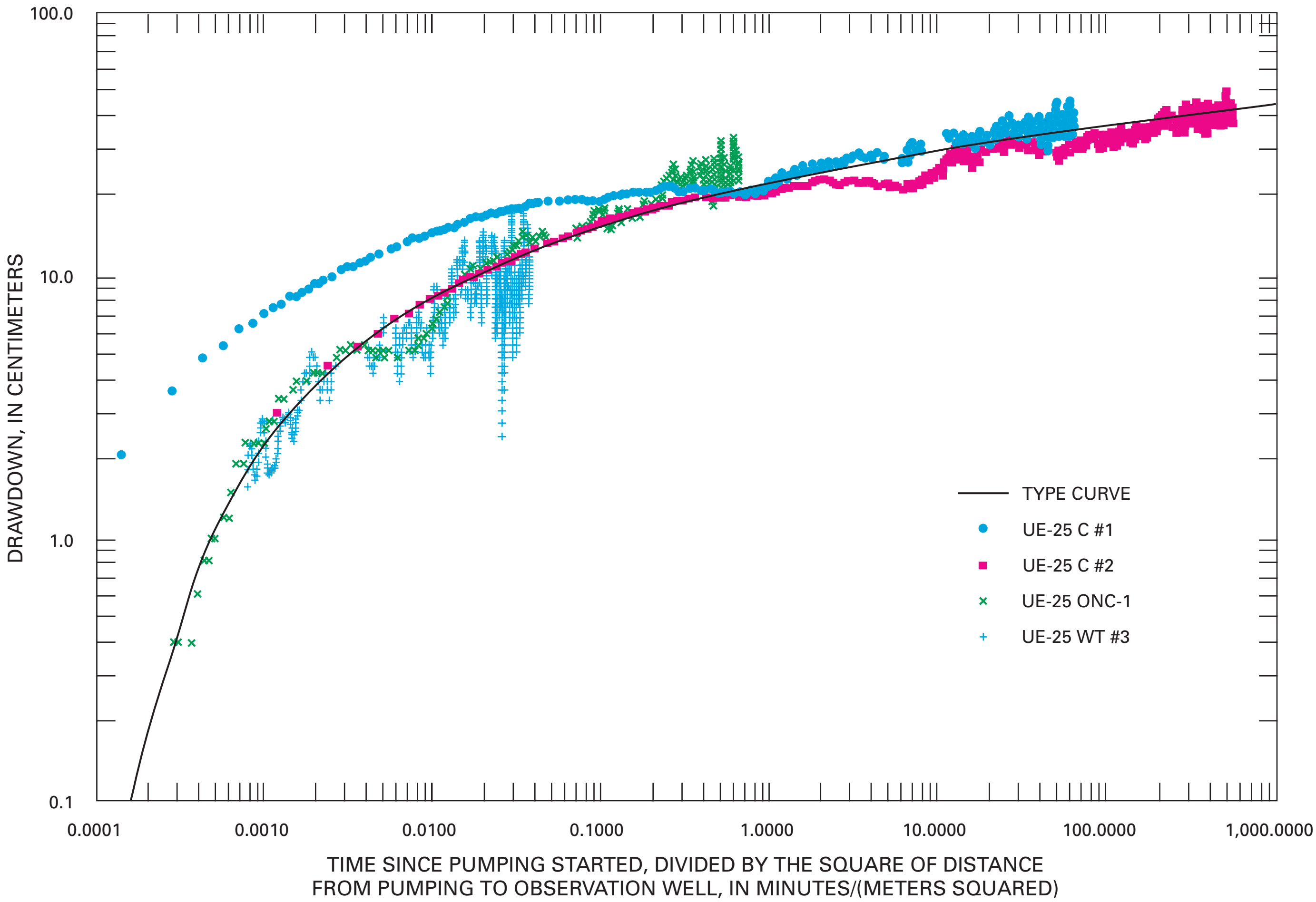


Figure 35. Analysis of drawdown in observation wells as a function of time divided by the square of the distance from the pumping well 322 days after pumping started in UE-25 c #3 on May 8, 1996.

lower parts of these boreholes (Geldon, 1996), which most likely originated in the Paleozoic carbonate rocks because the intervening tuffaceous rocks generally are considered a confining unit (Luckey and others, 1996).

Although UE-25 p #1 was monitored for 14,400 minutes after pumping started in May 1995 (Geldon and others, 1998) and 256,200 minutes after pumping started in May 1996 (fig. 38), drawdown in the Paleozoic carbonate rocks was not detected. This lack of drawdown could indicate that the water being pumped was drawn laterally from the Miocene tuffaceous rocks. Alternatively, the water could have been drawn upward from the Paleozoic carbonate rocks without causing drawdown in the underlying aquifer if the Paleozoic rocks have a large storage capacity. Hydraulic connection between the Miocene tuffaceous rocks and Paleozoic carbonate rocks could not be confirmed or refuted by monitoring water levels in UE-25 p #1 during this study.

Analytical Uncertainty

Analytical methods used in this study to determine hydraulic properties rely on assumptions about the type of aquifer, some of which are violated in nearly all applications. These violations are tolerated to simplify the flow system being analyzed, but they create unquantifiable uncertainty in computed hydraulic properties. For example, all methods assume that the aquifer is a porous medium. However, the influence of fractures is fundamental to conceptualizing the flow of water in Miocene tuffaceous rocks at and near the C-hole complex. The solution to this conundrum is to consider fractures to be so interconnected that the Miocene tuffaceous rocks respond to

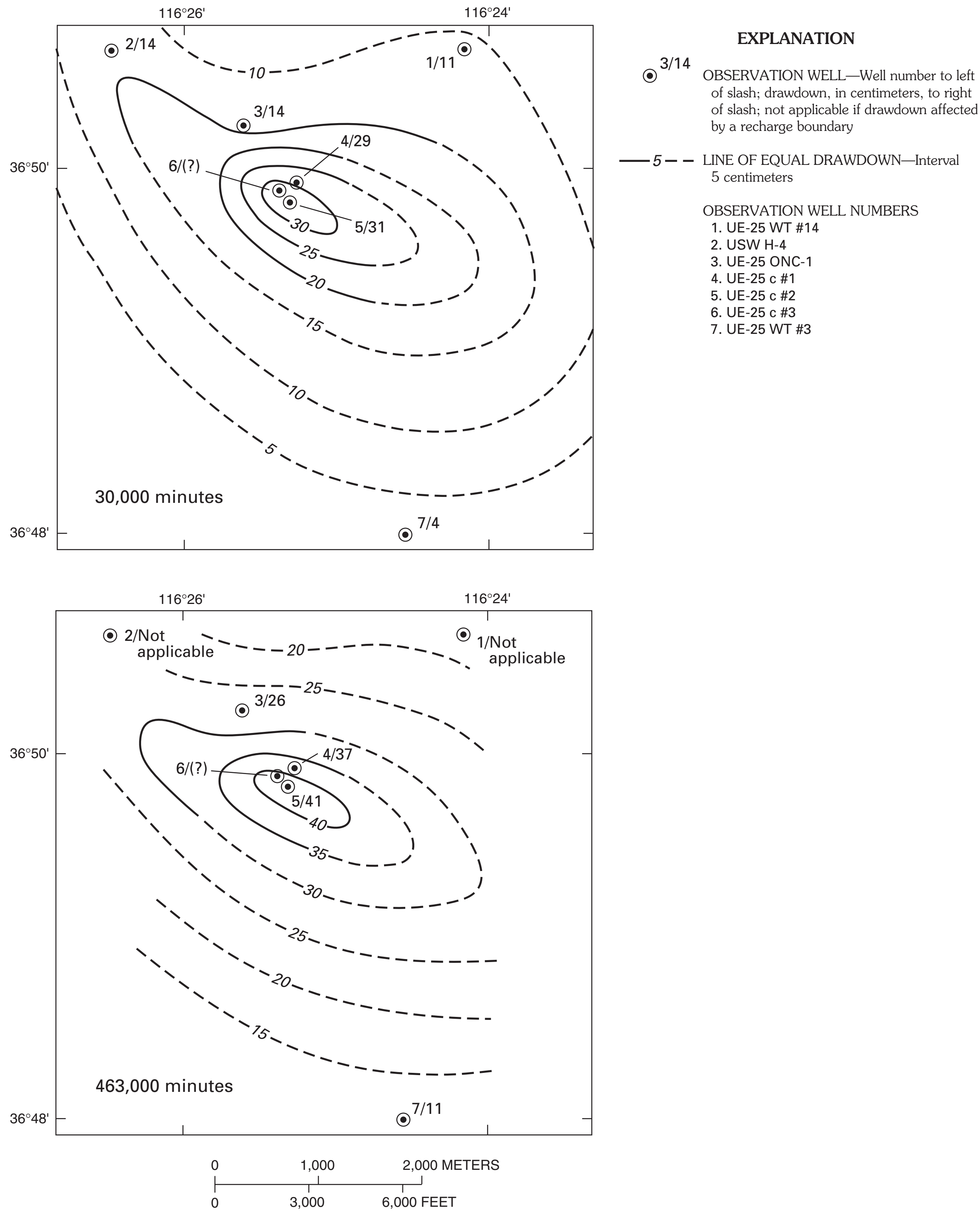


Figure 36. Distribution of drawdown in observation wells 30,000 minutes (20.8 days) and 463,000 minutes (321.5 days) after pumping started in UE-25 c #3 on May 8, 1996.

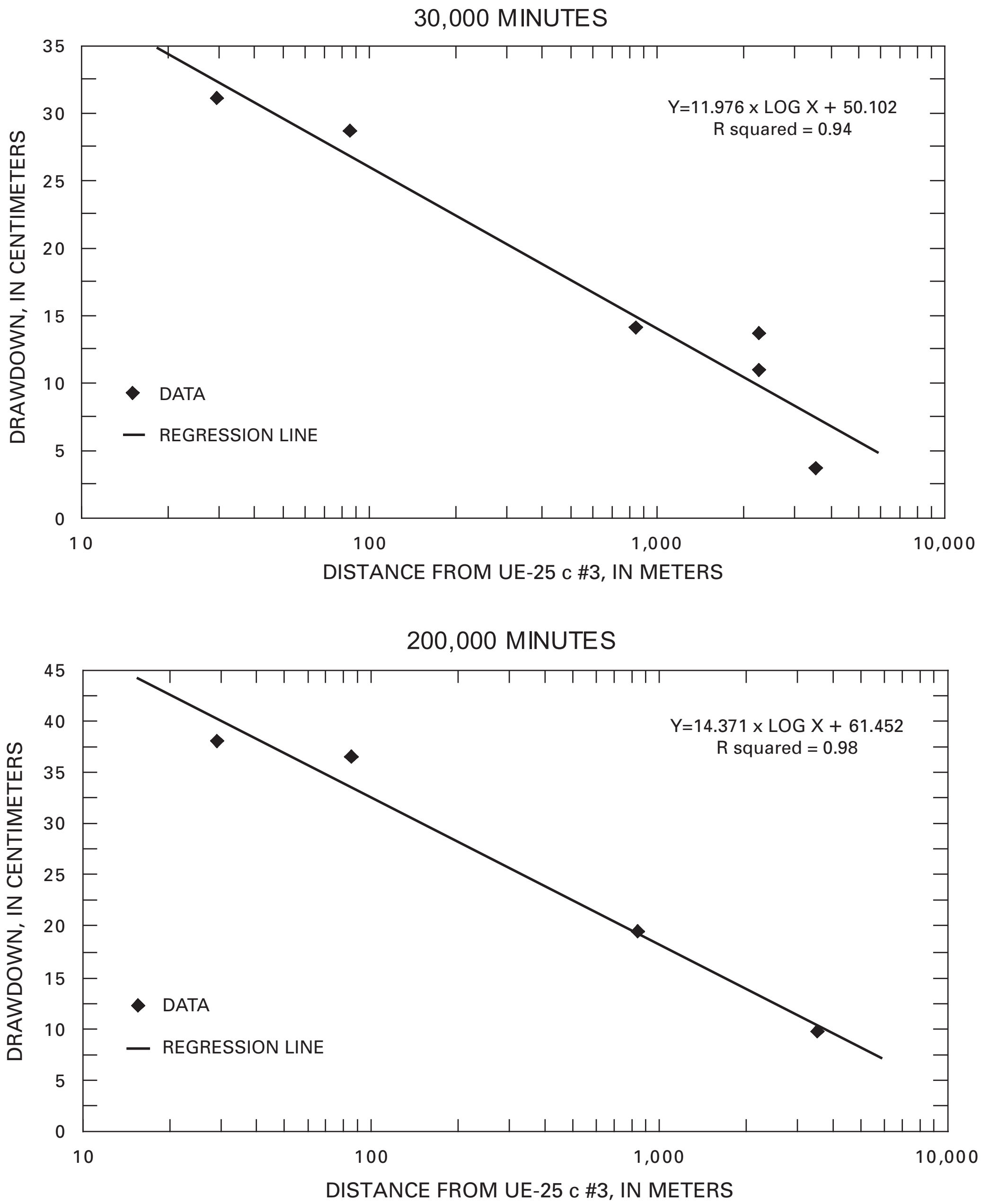
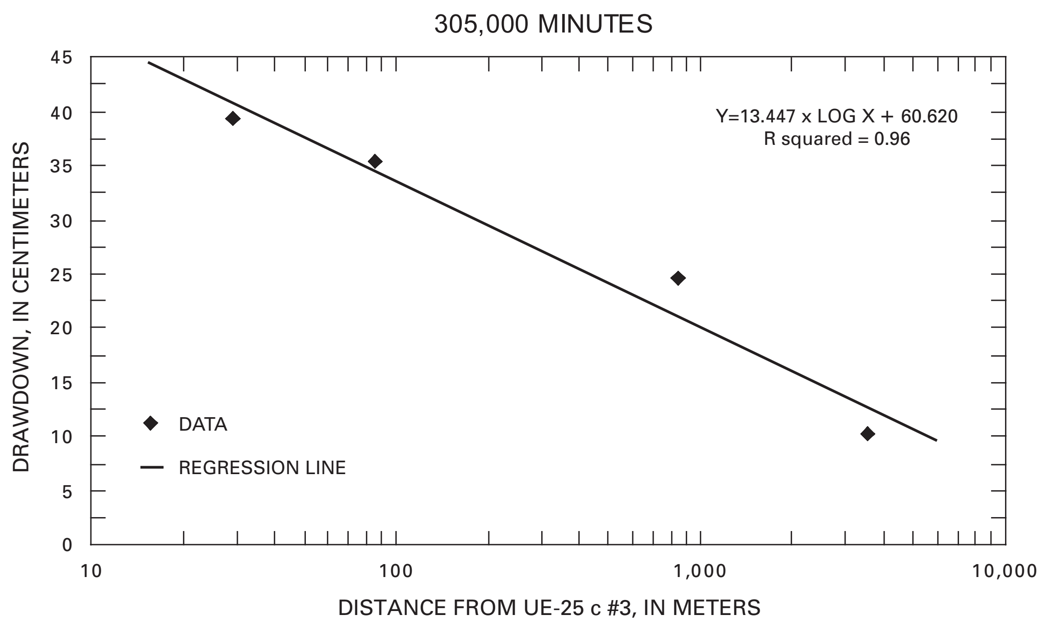


Figure 37. Analyses of drawdown in observation wells as a function of distance from the pumping well 30,000, 200,000, 305,000, and 463,000 minutes after pumping started in UE-25 c #3 on May 8, 1996.



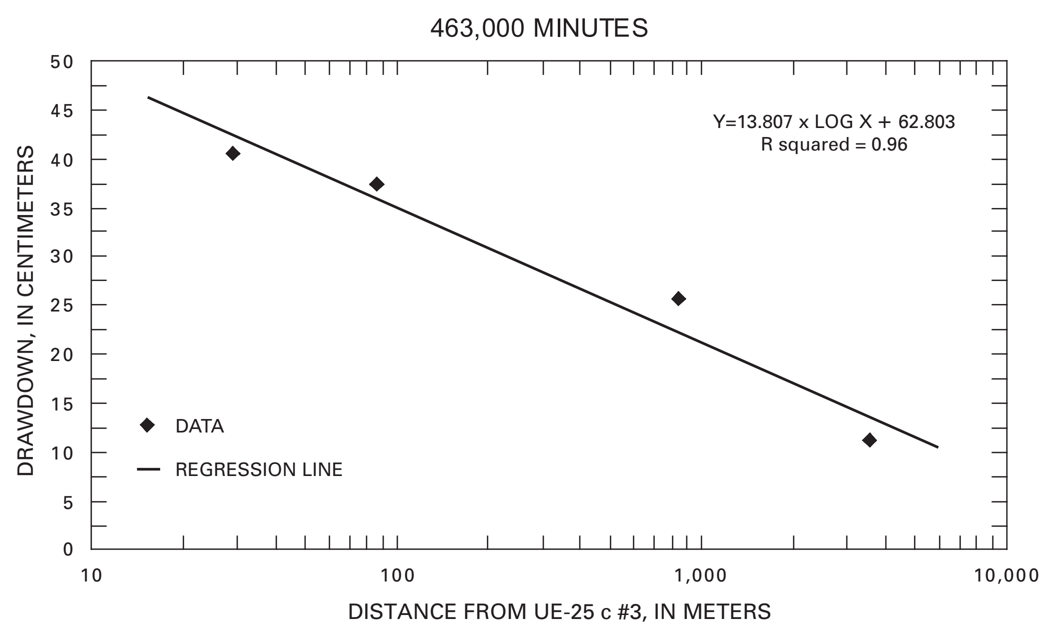


Figure 37. Analyses of drawdown in observation wells as a function of distance from the pumping well 30,000, 200,000, 305,000, and 463,000 minutes after pumping started in UE-25 c #3 on May 8, 1996—Continued.

Table 10. Hydraulic properties determined from drawdown in observation wells as a function of distance from the pumping well, hydraulic test in UE-25 c #3, May 1996 to November 1997

Time since pumping started, in minutes	Transmissivity, in meters squared per day	Storativity
30,000	2,600	0.0005
100,000	2,500	0.0009
200,000	2,100	0.002
305,000	2,300	0.001
402,000	2,200	0.001
463,000	2,200	0.001

pumping as "an equivalent porous medium." This rationalization seems to be justified by the way in which plots of drawdown or recovery of water levels in wells successfully conform to type curves derived for porous media.

Another fundamental assumption that commonly is violated is that flow to the pumping well is derived from an aquifer of infinite extent. The many faults in the area of the C-holes functioning as either recharge or barrier boundaries make the concept of an infinite aquifer unsupportable. Generally constraining observation wells between faults bounding the block in which the C-holes are located minimized boundary effects but did not eliminate them. Drawdown in USW H-4 and UE-25 WT #14 obviously was affected by recharge boundaries during the hydraulic test that began in May 1996.

All of the analytical methods used in this study assume radial flow to the pumping well. The flow from intervals other than the one being pumped that was detected during hydraulic tests in February 1996 and May 1996 to November 1997 indicates that flow during these tests actually was three-dimensional or spherical. Ignoring the vertical component of flow seems to have been justified by the generally good agreement between results of the hydraulic test in June 1995, in which flow between observation and pumping wells was radial, and results for most intervals monitored in subsequent tests. Nevertheless, there is some inaccuracy involved in analyzing the flow from unscreened intervals above or below the pumped interval by techniques developed only for analyzing flow from the pumped interval.

The most commonly applied analytical method in this study, that of Theis (1935), assumes flow from an infinite, homogeneous, isotropic, confined aquifer. Transected by numerous faults and variably welded, the Miocene tuffaceous rocks in the vicinity of the C-holes are neither homogeneous nor isotropic. As a result, hydraulic gradients toward the pumping well vary directionally, a situation that is ignored by the mathematics of the Theis (1935) solution. Disregarding a nonuniform hydraulic gradient seemingly

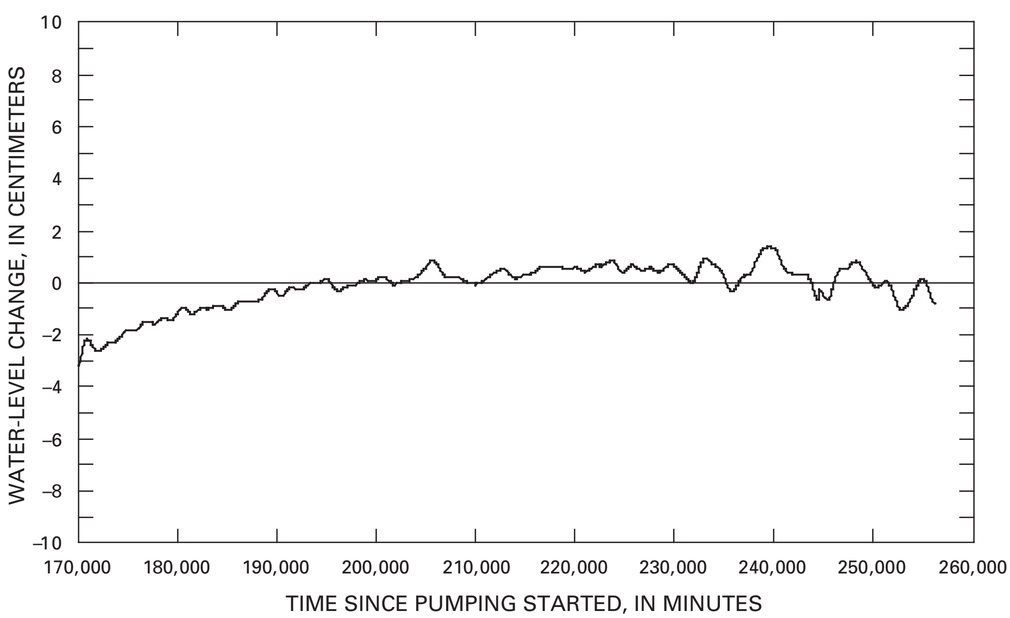


Figure 38. Water-level changes in UE-25 p #1, September 3 to November 2, 1996.

would result in inaccurate computations of hydraulic properties. Consistent calculations of hydraulic properties for individual intervals and the composite section of Miocene tuffaceous rocks from test to test, from well to well, or when multiple observation wells are used in a time-drawdown or distance-drawdown analysis indicates that either errors are being made consistently, or calculated values approximate actual values of hydraulic properties, despite simplification of structural and lithologic complexities.

All of the analytical techniques used in this study required input parameters that had to be determined or approximated for hydrogeologic intervals or boreholes in which drawdown was monitored. Included in these parameters are the distance of the interval or borehole from the pumping well, the transmissive thickness of the interval or borehole, the barometric efficiency of the interval or borehole, the proportion of flow from a hydrogeologic interval, and the fracture spacing within a hydrogeologic interval. Errors in deriving any of these input parameters could have changed calculated hydraulic properties considerably.

Values of transmissivity and storativity determined in this study are believed to be accurate to one significant figure, but reported values of hydraulic conductivity are more uncertain. Hydraulic conductivity can be calculated from the known thickness of transmissive intervals within a test interval, the entire thickness of the test interval, or an assumed thickness of transmissive rock between the observation and pumping wells. Because the transmissive thickness was unknown, it was impossible to determine hydraulic conductivity in many analyses. Even where hydraulic conductivity could be determined, it was done without much confidence. For example, it is impossible to know whether the hydraulic conductivity of the Lower Bullfrog interval in UE-25 c #1 really is about half that in UE-25 c #2 or whether these calculated hydraulic conductivity values result solely from about the same transmissivity value in each borehole being divided by an assumed transmissive thickness that is twice as large in UE-25 c #1 than in UE-25 c #2.

Analytical uncertainty can be decreased with additional study of the Miocene tuffaceous rocks at Yucca Mountain. Hydraulic tests are needed in the Prow Pass or Upper Bullfrog interval of the C-holes to determine with more confidence hydraulic properties of poorly transmissive rocks. A hydraulic test in the Upper Tram interval of the C-holes would assess directly the influence of faults on ground-water flow. Cross-hole hydraulic tests, preceded by extensive hydrogeologic characterization, at several sites in the Yucca Mountain area would help determine lateral variations in hydraulic properties as a result of lithologically and structurally caused heterogeneity.

CHEMISTRY OF WATER SAMPLES COLLECTED DURING HYDRAULIC TESTS

Sampling of water from UE-25 c #3 was done periodically during the hydraulic and tracer tests conducted from May 1995 to November 1997 to monitor chemical and isotopic changes that may occur with long-term pumpage. Background chemistry of UE-25 c #3 water and changes in the water as a function of the volume pumped (average discharge multiplied by the time since pumping started) between May 1995 and October 1997 (table 11) are discussed briefly in this section. More extensive interpretation and discussion of this water chemistry are beyond the scope of this study.

Background Chemistry of UE-25 c #3 Water

Water pumped from UE-25 c #3 is a sodium-bicarbonate type, which except for large concentrations of lithium, bromide, and strontium is typical of water from the Miocene tuffaceous rocks (fig. 39). In contrast, water from the Paleozoic carbonate rocks is a calcium-magnesium-bicarbonate type (fig. 39).

The water from UE-25 c #3 is fresh, slightly alkaline, and warm. The water has a dissolved solids concentration of 219–234 mg/L and a specific conductance of 272–340 μS/cm. The pH of this water ranges from 7.7 to 7.9. The concentration of dissolved oxygen in water from a depth of 697 to 813 m was 3.5 mg/L on May 13, 1997 (Kenneth Covay, U.S. Geological Survey, written commun., 1997).

Changes in UE-25 c #3 Water Chemistry During Pumping

As the volume of water pumped from UE-25 c #3 increased during hydraulic and tracer tests

Table 11. Major ions, trace elements, and isotopes in water from UE-25 c #3, May 1995 to October 1997

[L/s, liters per second, °C, degrees Celsius; mg/L, milligrams per liter; ND, not detected]

Date	Time	Average discharge (L/s)	Time since pump on (minutes)	Volume pumped (kiloliters)	Field pH (Standard units)	Temperature (°C)
05/18/95	09:45:00	23.1	1,332	1,846	7.7	ND
05/22/95	16:00:00	17.8	62	66	7.7	41.4
05/23/95	11:30:00	17.7	1,232	1,310	7.7	41.4
05/31/95	17:00:00	17.9	13,082	14,050	7.7	40.3
12/04/96	13:00:00	9.59	302,563	174,100	7.8	38.3
02/19/97	10:00:00	9.55	413,263	236,800	7.8	40.2
06/12/97	09:25:00	9.29	575,948	321,000	7.9	40.0
10/21/97	09:30:00	9.22	764,593	423,000	7.8	39.8

Date	Time	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SiO_2 (mg/L)
05/18/95	09:45:00	11	0.31	55	1.9	55
05/22/95	16:00:00	11	0.30	58	1.9	60
05/23/95	11:30:00	11	0.30	57	1.9	58
05/31/95	17:00:00	11	0.30	56	1.9	57
12/04/96	13:00:00	12	0.32	51	1.9	52
02/19/97	10:00:00	12	0.31	54	2.0	53
06/12/97	09:25:00	12	0.30	53	2.1	52
10/21/97	09:30:00	12	0.32	54	2.0	52

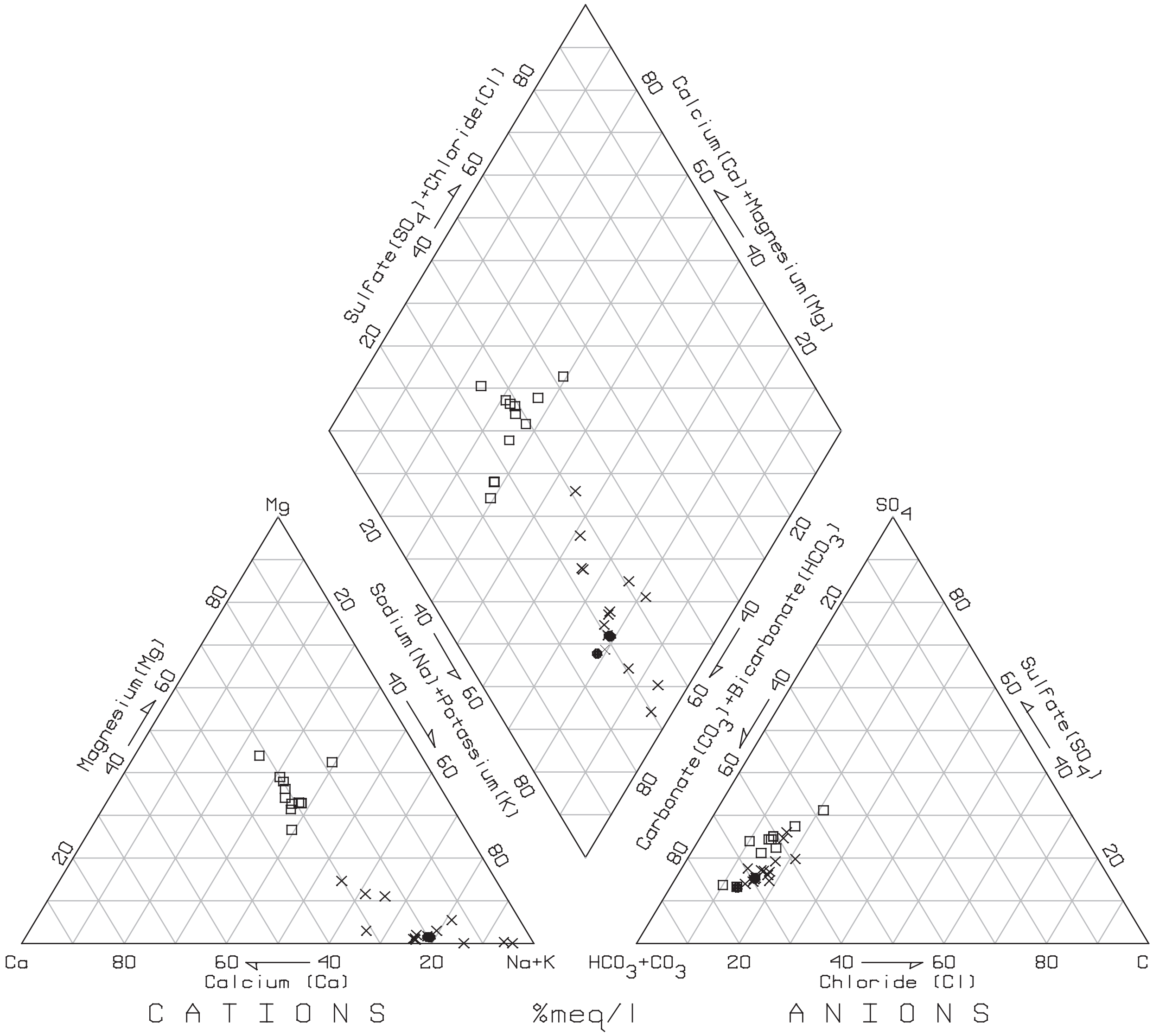
Date	Time	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	NO_2+NO_3 (mg/L)
05/18/95	09:45:00	140	20	6.7	2.2	1.2
05/22/95	16:00:00	140	19	6.4	2.2	ND
05/23/95	11:30:00	141	19	6.5	2.2	ND
05/31/95	17:00:00	175[1]	19	6.4	2.2	1.2
12/04/96	13:00:00	135	21	6.9	1.9	ND
02/19/97	10:00:00	135	20	6.3	2.1	ND
06/12/97	09:25:00	135	19	6.3	2.1	1.2
10/21/97	09:30:00	133	20	6.6	2.1	ND

Date	Time	Sr (mg/L)	Li (mg/L)	Al (mg/L)	Fe (mg/L)	Br (mg/L)
05/18/95	09:45:00	ND	ND	0.0070	0.100	0.060
05/22/95	16:00:00	0.042	0.100	ND	0.070	0.060
05/23/95	11:30:00	0.043	0.090	ND	0.030	0.060
05/31/95	17:00:00	0.044	0.080	ND	0.020	0.060
12/04/96	13:00:00	0.049	0.084	0.0065	0.010	0.64
02/19/97	10:00:00	0.048	0.082	<0.005	0.012	0.24
06/12/97	09:25:00	0.048	0.079	0.0036	0.0040	0.13
10/21/97	09:30:00	0.049	0.072	<0.005	0.0034	0.10

Date	Time	δ^2H (per mil)	$\delta^{18}O$ (per mil)	$\delta^{13}C$ (per mil)	$\delta^{87}Sr$ (per mil)	Dissolved solids (mg/L)
05/18/95	09:45:00	–100	–13.4	ND	ND	220
05/22/95	16:00:00	–99.3	–13.4	–6.5	0.96	227
05/23/95	11:30:00	–99.7	–13.4	–6.2	0.86	221
05/31/95	17:00:00	–99.8	–13.4	–6.5	0.83	226
12/04/96	13:00:00	–99.8	–13.4	–6.4	0.72	ND
02/19/97	10:00:00	–99.7	–13.4	–7.5	0.78	219
06/12/97	09:25:00	–99.6	–13.5	–7.6	ND	222
10/21/97	09:30:00	ND	ND	ND	0.78	234

Isotopic notation: Deuterium, oxygen, carbon, and strontium isotopic ratios are reported using the delta (δ) notation in units of parts per thousand. The delta notation is calculated as $\delta = [(R_{sample}/R_{standard}) - 1)]*1{,}000$ where R_{sample} can be $^2H/^1H$, $^{18}O/^{16}O$, $^{13}C/^{12}C$, or $^{87}Sr/^{86}Sr$, and $R_{standard}$, the appropriate isotope ratios of the reference standards. The standards are Vienna Standard Mean Ocean Water (VSMOW) for δ^2H and $\delta^{18}O$, Vienna PeeDee belemnite (VPDB) for $\delta^{13}C$, and the mean ocean water value for $\delta^{87}Sr$.

[1]Analyzed value probably is incorrect because it is much larger than values determined for other samples obtained from 1995 to 1997.



EXPLANATION

×	MIOCENE TUFFACEOUS ROCKS	Na+K	SODIUM + POTASSIUM
●	UE-25 c #3	Ca	CALCIUM
□	PALEOZOIC CARBONATE ROCKS	Mg	MAGNESIUM
% meq/l	PERCENT MILLIEQUIVALENTS PER LITER	Cl	CHLORIDE + FLUORIDE
		SO_4	SULFATE
		$HCO_3 + CO_3$	BICARBONATE + CARBONATE

Figure 39. Major ion chemistry of water from UE-25 c #3, Miocene tuffaceous rocks, and Paleozoic carbonate rocks, Yucca Mountain area (Data from McKinley and others, 1991; Perfect and others, 1995; U.S. Geological Survey, unpublished data).

conducted from 1995 to 1997, small changes occurred in some of the dissolved ion concentrations and in the isotope ratios. Calcium increased slightly from 11 to 12 mg/L whereas magnesium remained constant within analytical error. Concurrently, sodium decreased erratically and potassium increased. The net effect of these very slight variations is that the ratio of calcium plus magnesium to sodium plus potassium in the water increased slightly with increased pumpage. More significantly, the isotope parameters, δ^2H and

$\delta^{18}O$, remained constant whereas $\delta^{13}C$ increased slightly and $\delta^{87}Sr$ decreased considerably. These chemical and isotopic changes may indicate a change in the source of water with increased pumpage. The isotopic data are not supportive of an increasing component of water from carbonate rocks. The $\delta^{13}C$ ratio of carbonate water from UE-25 p #1 is –2.3 per mil (Stuckless and others, 1991) and the $\delta^{87}Sr$ ratio is +3.6 per mil (Zell Peterman, U.S. Geological Survey, written commun., 2002). These values cannot provide an end member for the trends shown in table 11 because the effects would be opposite of what is observed. Further, the $\delta^{2}H$ value for water from the carbonate rocks at UE-25 p #1 is –106 per mil, which is much smaller than the nearly constant and larger values for the UE-25 c #3 water (table 11). More likely, the small dissolved ion and isotopic variations simply reflect lateral variations in these parameters in the volcanic aquifer that are being sampled with increasing pumpage at UE-25 c #3. The variability in dissolved ions in the volcanic aquifer shown in figure 39 is more than sufficient to account for the small variability in dissolved ions in UE-25 c #3 with pumpage.

SUMMARY AND CONCLUSIONS

Four hydraulic tests were conducted by the U.S. Geological Survey in Miocene tuffaceous rocks at the C-hole complex at Yucca Mountain, Nevada, between May 1995 and November 1997. The C-hole complex consists of three orthogonally spaced boreholes that are 30.4 to 76.6 m apart at the land surface and about 900 m deep. The C-holes are located at the northern end of Bow Ridge, on the west side of Midway Valley. Below the water table, which is 400 to 402 m deep at the site, the C-holes penetrate the Calico Hills Formation, and the Prow Pass, Bullfrog, and Tram Tuffs of the Crater Flat Group. A northerly trending fault, believed to be either the Paintbrush Canyon or Midway Valley Fault, and an offsetting northwesterly trending fault intersect the C-holes at the bottom of the Bullfrog and top of the Tram Tuffs.

Borehole flow surveys, geophysical logs, and aquifer tests done between 1983 and 1995 identified six hydrogeologic intervals in the C-holes—the Calico Hills, Prow Pass, Upper Bullfrog, Lower Bullfrog, Upper Tram, and Lower Tram intervals. Flow within these intervals comes from diversely oriented fractures and the interstices of variably welded ash-flow, ash-fall, and reworked tuff. During hydraulic tests, the Lower Bullfrog interval contributed about 70 percent of the flow, the Upper Tram interval contributed about 20 percent of the flow, and all other intervals combined contributed about 10 percent of the flow. Because these hydrogeologic intervals are defined by spatially related faults and fracture zones, their existence and hydraulic properties cannot be extended beyond the immediate vicinity of the C-holes.

Hydraulic tests were conducted at the C-hole complex in May 1995, June 1995, February 1996, and May 1996 to November 1997. In all of these tests, borehole UE-25 c #3 was used as the pumping well, and boreholes UE-25 c #1 and UE-25 c #2 were used as observation wells.

During the first and last hydraulic tests, boreholes UE-25 ONC-1, USW H-4, UE-25 WT #14, UE-25 WT #3, and UE-25 p #1 also were used as observation wells. Borehole UE-25 ONC-1, which is 842.8 m from UE-25 c #3, is completed in the Prow Pass Tuff. Borehole USW H-4, which is 2,245 m from UE-25 c #3, is completed in the Prow Pass, Bullfrog, Tram, and Lithic Ridge Tuffs. Borehole UE-25 WT #14, which is 2,249 m from UE-25 c #3, is completed in the Topopah Spring Tuff and Calico Hills Formation. Borehole UE-25 WT #3, which is 3,526 m from UE-25 c #3, is completed in the Bullfrog Tuff. Borehole UE-25 p #1, which is 630 m from UE-25 c #3, is completed in Paleozoic carbonate rocks.

Hydraulic tests conducted at the C-hole complex from 1995 to 1997 were designed sequentially to determine: (1) hydraulic properties of the composite saturated-zone section in the C-holes; (2) hydraulic properties of the six hydrogeologic intervals in the C-holes; and (3) heterogeneity in the Miocene tuffaceous rocks, including the influence of faults, in the area encompassed by observation wells. Additionally, it was hoped that monitoring UE-25 p #1 might establish whether the tuffaceous rocks are connected hydraulically to the Paleozoic carbonate rocks, a regional aquifer. The Paleozoic rocks are estimated to be about 455 m below the C-holes.

The hydraulic test conducted in May 1995 is discussed briefly in this report and in more detail by Geldon and others (1998). During the test, which lasted 10.0 days, all of the C-holes were open from the bottom of casing to the bottom of the borehole. UE-25 c #3 was pumped at an average rate of 17.9 L/s. Drawdown in the pumping well was 7.76 m; drawdown in observation wells ranged from 0 to 42 cm.

The hydraulic test in June 1995 lasted 4.0 days. During the test, UE-25 c #3 was open from the bottom of casing to the bottom of the borehole. The six hydrogeologic intervals in UE-25 c #1 and UE-25 c #2 were isolated by packers and screened open to flow. UE-25 c #3 was pumped at an average rate of 22.5 L/s. Drawdown in the pumping well was 10.9 m; drawdown in intervals of UE-25 c #1 and UE-25 c #2 ranged from 43 to 352 cm.

The hydraulic test in February 1996 lasted 4.9 days. The six hydrogeologic intervals in the C-holes were isolated by packers. Well screens in these boreholes were opened in the Lower Bullfrog and Upper Tram intervals. However, all monitored intervals responded to pumping. UE-25 c #3 was pumped at an average rate of 8.49 L/s. Drawdown in the pumping well was 2.86 m; drawdown in intervals of UE-25 c #1 and UE-25 c #2 ranged from 14 to 25 cm.

The hydraulic test conducted from May 1996 to November 1997 lasted 553.2 days. The Lower Bullfrog interval was isolated by packers in the pumping well. Packers remained in place from the previous test in UE-25 c #1 and UE-25 c #2. Only the Lower Bullfrog interval was screened open in the C-holes, but all monitored intervals in these boreholes responded to pumping. UE-25 c #3 was pumped at an average rate of 9.21 L/s. Drawdown in the pumping well reached 5.98 m by March 26, 1997, but was kept below 5.9 m during the remainder of the test by frequent pump shutoffs caused by problems with generators used to supply power to the pump. Drawdown in all observation wells was very oscillatory. Peak drawdown by March 26, 1997, ranged from 35 to 51 cm in intervals of UE-25 c #1 and UE-25 c #2. Drawdown in UE-25 ONC-1 began 200 minutes after pumping started and reached 37 cm when pumping ended. Drawdown in UE-25 WT #3 began 9,130 minutes after pumping started and reached 16 cm when generator problems developed on March 26, 1997. Drawdown attributable to aquifer stress was detected in USW H-4 5,000 minutes after pumping started, peaked at 22 cm 67,000 minutes later, and became steady-state for the remainder of the test. Drawdown attributable to aquifer stress was detected in UE-25 WT #14 5,250 minutes after pumping started, peaked at 15 cm 67,000 minutes later, and became steady-state for the remainder of the test. Water-level declines, believed to be related to the C-hole pumping, were observed in other boreholes in the area. These declines were observed in boreholes that were more than 8 km from the C-hole complex. No drawdown was observed in UE-25 p #1.

In all hydraulic tests, large, rapid drawdown (and recovery) in the pumping well far exceeded what could have been predicted from hydraulic properties calculated from observation-well drawdown in the same tests. Most of this pumping-well drawdown probably can be attributed to frictional head loss or borehole-skin effects. Because the pumping-well drawdown largely is independent of aquifer properties, analyses of this drawdown result in misleadingly small values of transmissivity and hydraulic conductivity. Consequently, only drawdown and recovery in observation wells were used for analyses of hydraulic tests discussed in this report. Hydraulic tests at the C-hole complex imply that analyses of pumping-well drawdown throughout the Yucca Mountain area are not reliable.

Hydrogeologic intervals in the C-holes have layered heterogeneity. The Calico Hills interval is unconfined, the Prow Pass and Upper Bullfrog intervals are confined, the Lower Bullfrog interval is a fissure-block aquifer, and the Upper Tram interval receives flow from crosscutting faults in response to pumping. Transmissivity increases downhole from 4–10 m^2/d in the Calico Hills interval to 1,300–1,600 m^2/d in the Lower Bullfrog interval, although this trend is reversed near the bottom of the C-holes. In the Upper Tram interval, transmissivity is 800–900 m^2/d. Hydraulic conductivity increases downhole from 0.1–0.2 m/d in the Calico Hills interval to 20–50 m/d in the Lower Bullfrog and Upper Tram intervals. Storativity in UE-25 c #2 generally increases downhole from 0.0002–0.0004 in the Calico Hills and Prow Pass intervals to 0.001–0.002 in the Lower Bullfrog and Upper Tram intervals, although the storativity of the Upper Bullfrog interval is an order of magnitude smaller than in other intervals above the Lower Bullfrog. Storativity in the Prow Pass and Upper Bullfrog intervals in UE-25 c #1 is similar to that in UE-25 c #2, but the storativity of the Lower Bullfrog and Upper Tram intervals in UE-25 c #1 is about a tenth of that in UE-25 c #2. Vertical distributions of hydraulic properties in the C-holes are believed to represent the increasing influence of faults and related fractures toward the bottom of the boreholes.

Distributions of drawdown in the hydraulic tests conducted in May 1995 and from May 1996 to November 1997 were influenced strongly by northwesterly and northerly trending faults. Drawdown in UE-25 ONC-1 in the latter test showed a fissure-block aquifer response, possibly because of fractures related to a northwesterly trending zone of discontinuous faults that extends between Bow Ridge and Antler Wash. Drawdown in UE-24 WT #14 and USW H-4 during the same test reached steady-state after 72,000 minutes of pumping because of recharge from the Paintbrush Canyon Fault and a zone of northerly trending faults that transects Boundary Ridge.

Drawdown data from four wells monitored during the hydraulic test conducted from May 1996 to November 1997 matched to the type curve for a confined aquifer indicated transmissivity of 2,200 m^2/d and storativity of 0.002 for the Miocene tuffaceous rocks within a 21-km^2 area surrounding the C-holes. Plots of drawdown in observation wells as a function of their distance from the pumping well at various times during the same test indicated transmissivity of 2,100–2,600 m^2/d and storativity of 0.0005–0.002. Analyses of drawdown in the composite saturated-zone section of the C-holes in May 1995 and in outlying observation wells from May 1996 to November 1997 indicated that the transmissivity of the tuffaceous rocks decreases northwesterly from 2,600 m^2/d in UE-25 WT #3, to about 2,000 m^2/d in the C-holes, to 700 m^2/d in USW H-4.

The hydraulic conductivity of the Miocene tuffaceous rocks areally ranges from less than 2 to more than 10 m/d. It is largest where prominent, northerly trending faults are closely spaced or intersected by northwesterly trending faults. Relatively large hydraulic conductivity occurs beneath Fran Ridge, Bow Ridge, and Boundary Ridge. Hydraulic conductivity is smallest toward the crest of Yucca Mountain and Jackass Flats.

During the four hydraulic tests conducted at the C-hole complex from 1995 to 1997, drawdown occurred in all monitored intervals of the C-holes and other observation wells, regardless of the geologic interval being pumped. This hydraulic connection across geologic and lithostratigraphic contacts is believed to result from interconnected faults, fractures, and intervals with large matrix permeability. The Miocene tuffaceous rocks appear to respond to pumping as a single aquifer in the Yucca Mountain area. This conclusion is supported by being able to use the drawdown from observation wells completed in different Miocene geologic units in single analytical solutions of drawdown as a function of time or distance, and the widespread observed water-level declines related to pumping. The Paintbrush Canyon Fault appears to be an effective boundary within the aquifer because the effects of pumping were minimal or not observed east of this feature. Designation of separate aquifers and confining units within the Miocene tuffaceous rocks, therefore, may not be appropriate in this area.

Water pumped from UE-25 c #3 is a sodium-bicarbonate type, which except for large concentrations of lithium, bromide, and strontium is typical of water from the Miocene tuffaceous rocks. In contrast, water from the Paleozoic carbonate rocks is a calcium-magnesium-bicarbonate type. Samples of UE-25 c #3 water, analyzed from 1995 to 1997, seem to indicate that changes in the quality of the water pumped from that well are probably due solely to lateral variations in water quality within the tuffaceous rocks. The isotopic data are not supportive of an increasing component of carbonate aquifer water.

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