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RESULTS OF HYDRAULIC TESTS IN WELLS DOE-1, 2, AND 3, SALT VALLEY, GRAND COUNTY, UTAH

By F. E. Rush, I. M. Hart, M. S. Whitfield, T. F. Giles, and T. E. D'Epagnier

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SYSTEM OF MEASUREMENT UNITS

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

Metric unit	Multiply by	To obtain inch-pound unit
centimeter (cm)	3.937×10^{-1}	inch (in)
kilometer (km)	6.214×10^{-1}	mile (mi)
meter (m)	3.281	foot (ft)
Celsius (°C)	1.8°C + 32	Fahrenheit (°F)
meter per day (m/d)	3.281	foot per day (ft/d)
meter squared per day (m^2/d)	1.076×10^{1}	foot squared per day (ft^2/d)
milligram per liter (mg/L)	1.0[1/]	part per million (ppm)
microgram per liter (µg/L)	1.0[1/]	part per billion (ppb)
kilogram per square centimeter (kg/cm^2)	1.422×10^{1}	pound per square inch (lb/in^2)
liter per second (L/s)	1.585×10^{1}	gallon per minute (gal/min)
liter (L)	2.642×10^{-1}	gallon (gal)
millidarcy	2.725×10^{-3}	foot per day (ft/d)

[1/] Approximate.

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ABSTRACT

Three exploratory wells were drilled for geological, geophysical, and hydrological purposes in Salt Valley, Grand County, Utah. Cap rock, salt, and interbeds of the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age were penetrated. The observed depth below land surface of the cap rock-salt interface ranges from 163 meters (m) to 191 meters. Approximately the upper 100 meters of cap rock were unsaturated by ground water. Within the saturated part of the cap rock, hydraulic heads generally decrease with depth and southwestward. Ion concentrations generally increase with depth in the saturated cap rock.

Hydraulic conductivity of cap rock, as determined from pumping tests, may be on the order of 5×10^{-3} meters per day; as a result, ground-water flow rates in the cap rock are probably very low. A carbon 14 specific activity for cap rock water yielded an uncorrected "age" of greater than 36,000 years. Salt and interbeds have hydraulic conductivities probably less than 1×10^{-4} meters per day.

INTRODUCTION

General Statement

The U.S. Geological Survey has been conducting investigations, funded by the U.S. Department of Energy, related to the isolation of high-level radioactive wastes. These investigations have included geological, geophysical, and hydrological studies to locate suitable environments for waste storage and to develop new techniques for site exploration and evaluation. As part of the investigations, this report presents hydrologic information on the Salt Valley Anticline of the Paradox Basin.

Purpose and Scope

The purpose of drilling test wells was to generate site-specific data to make geological, geophysical, and hydrological judgments about the character of cap rock and salt core of the Paradox Member of the Hermosa Formation of Middle Pennsylvanian age in the Paradox Basin. This report presents hydrologic data, supporting geological and geophysical information, and hydrologic interpretations pertaining to the penetrated rocks.

Location

Three test wells are located in Salt Valley on the Salt Valley-Cache Valley Anticline (fig. 1). The site is in the SE¼NE¼NW¼, sec. 5, T. 23 S., R. 20 E., Salt Lake base line and meridian, about 30 km northwest of Moab, in Grand County, Utah. The site is about 25 km northwest of the Colorado River and 35 km east of the Green River, both large regional streams (fig. 1). Detailed descriptions of the wells' locales follow; figure 2 shows the relation of the well locations to quarter-section corners and to the cliffs bordering the floor of Salt Valley.

The location of wells from the north quarter-section corner of section 5, T. 23 S., R. 20 E. is: (1) well 1 is 221 m south and 13 m west; (2) well 2 is 292 m south and 184 m west; and (3) well 3 is 354 m south and 47 m west. The locations of wells 2 and 3 from well 1 are: (1) well 2 is 185 m S. 68° W.; and (2) well 3 is 137 m S. 15° W. The distance between wells 2 and 3 is 150 m.

Table 1 lists altitudes at the wells (to an accuracy of ±0.15 m).

Table 1.--*Altitude of wells*

[Meters above mean sea level]

Well	Land-surface datum	Braden Head flange (permanent datum)	Rotary Kelly Bushing (RKB)
DOE-1	1,468.6	1,468.8	1,472.3
DOE-2	1,463.3	1,463.6	1,467.1
DOE-3	1,467.0	1,467.3	1,470.8

DRILLING PROGRAM

The drilling phase of the project involved drilling two shallow test wells to depths of nearly 400 m, wells DOE-1 and 2, and a deep well to 1,238 m, well DOE-3. The shallow wells were drilled primarily to generate geological, geophysical, and hydrological information about the cap rock. The deep well was drilled primarily to obtain continuous lithologic cores of the cap rock, salt, and interbeds. Construction characteristics of the wells are summarized in table 2.

Drilling was performed by the Brinkerhoff Drilling Co. Arranging for support service, such as mud, packers, and geophysical well-logging, was the responsibility of Woodward-Clyde Consultants.

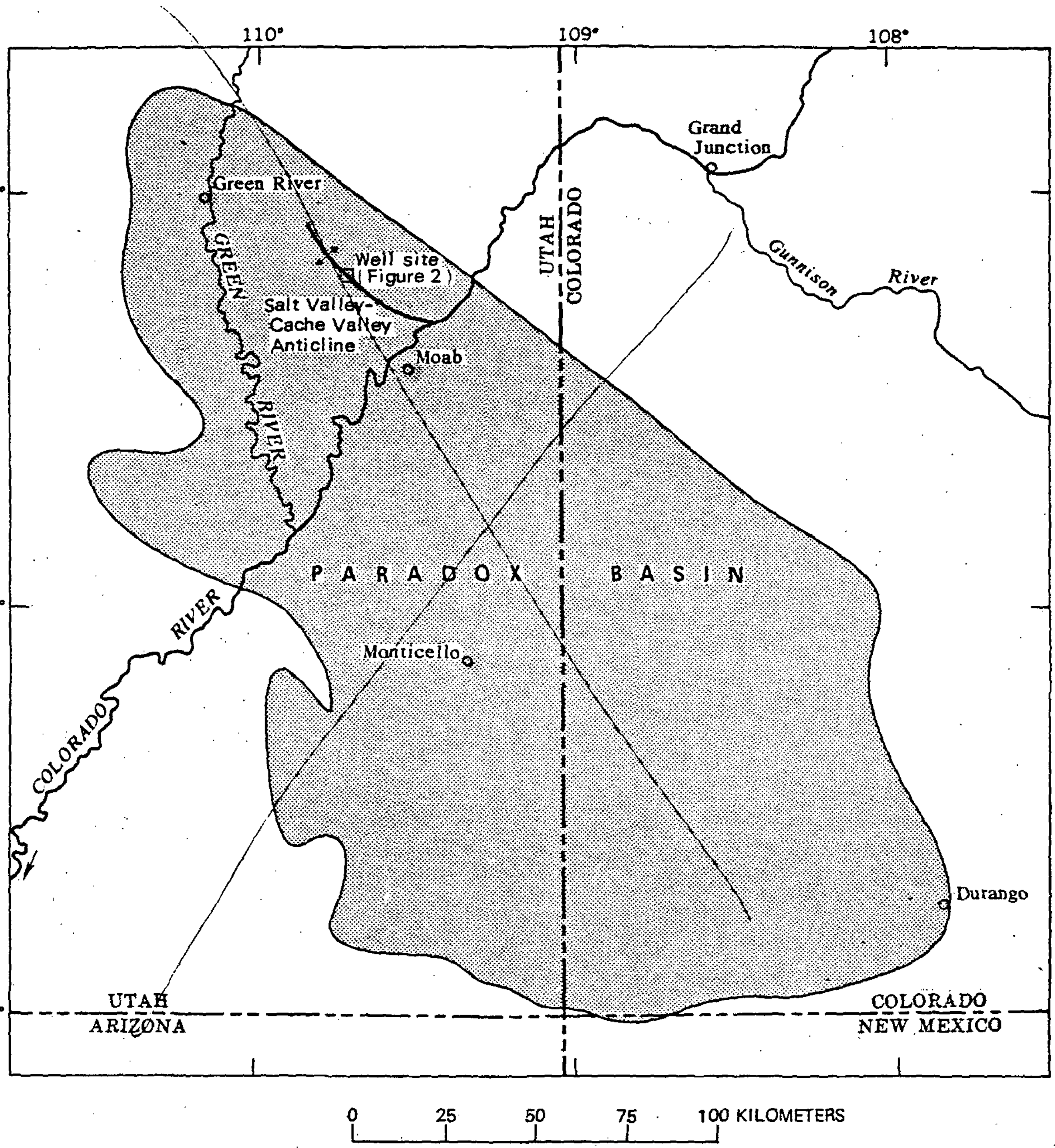

Figure 1.--Location of the test-well site in the Paradox Basin of Utah and Colorado.

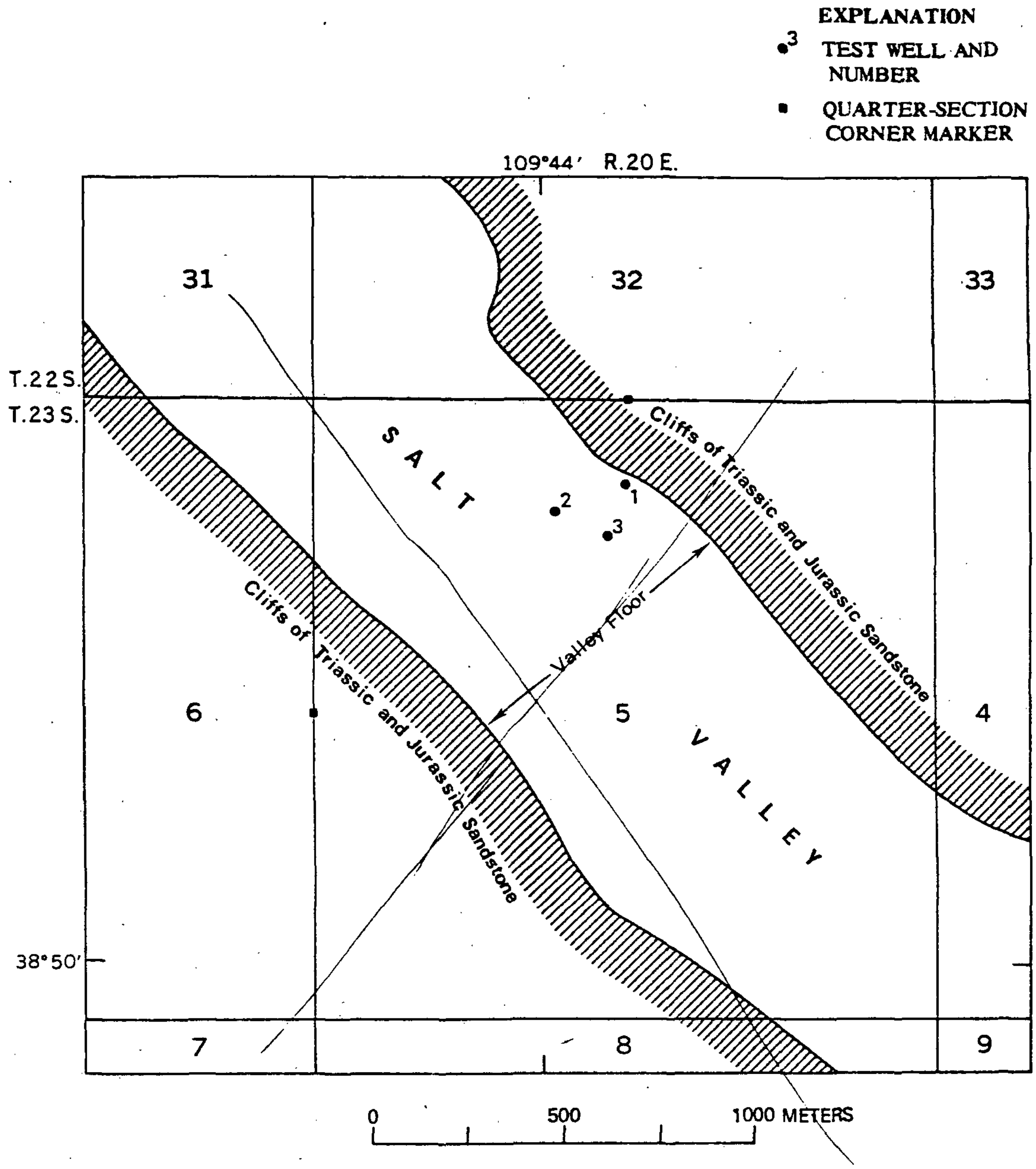

Figure 2.--Location of test wells in Salt Valley.

Table 2.--*Construction characteristics of the test wells*

Construction characteristics	Well		
	DOE-1	DOE-2	DOE-3
Started drilling below surface casing (1978)---	July 27	August 13	August 25
Well completed (1978)-----	August 12	August 24	November 5
Surface casing:			
Diameter (cm)-----------	34.0	34.0	50.8
Depth interval (m)------	0-26	0-25	0-26
Main casing:			
Diameter (cm)-----------	24.4	24.4	34.0
Depth interval (m)------	0-228	0-203	0-226
Open hole interval (m)----	228-TD	203-TD	226-TD
Total depth drilled (m)---	389	370	1,238
Open-hole bit size (cm)---	22.2	22.2	22.2

Geologists, geophysicists, and hydrologists of the U.S. Geological Survey selected cores from well DOE-3 for laboratory analysis to determine permeability, porosity, and mineralogic and structural characteristics of the salt and associated interbeds. Results from these tests were not available for this report.

Several major problems developed with drilling and hydraulic testing of these three wells. To detect first moisture in the cap rock and not seal off fractures, dry air and air mist were used as drilling fluids instead of mud in the upper part of wells DOE-1 and 2. The absence of drilling mud to exert pressure against the well wall allowed considerable caving of the cap rock in the two shallow test wells. Well DOE-3 was drilled with salt water and heavy mud, which reduced caving but prevented detecting the occurrence of formation moisture. Caving also occurred during the swabbing of well DOE-1 and during the pumping test for well DOE-2. This resulted in a fluctuating yield and turbid water. The collapse of material while pumping well DOE-2 resulted in pump damage, limiting the time of drawdown tests. The use of drilling fluids is summarized in table 3.

Dangerous concentrations of hydrogen sulfide were produced while testing the cap rock below a depth of 153 m in well DOE-2. Local concentration of this gas in the atmosphere reached 30,000 parts per million (ppm), and commonly maintained a level between 800 and 1,000 ppm while the well was being pumped.

Table 3.--*Drilling fluids used in wells*

[Does not include fluids used for drilling surface-casing interval]

Drilling fluid	Well-depth interval below land surface (m)		
	DOE-1	DOE-2	DOE-3
Air (dry)	26-161	25-115	--------
Air mist	161-208	115-168 213-370	--------
Saltwater	-------	-------	228-270
Saltwater gel	208-389	168-213	26-228 270-1,238

During the drilling of well DOE-3, it was necessary to use a heavy drilling mud with a weight between 1.2 and 1.5 kilograms per liter (kg/L), because some of the shale interbeds were expected to contain methane and other gases. Core recovery below the cap rock was good, but the steeply dipping interbeds in the salt commonly caused the core barrel to jam. A high chloride concentration (between 250,000 and 300,000 mg/L) had to be maintained while drilling some beds to prevent highly soluble potash minerals from being dissolved while the core was being cut. Use of heavy mineralized mud, however, created problems associated with the hydraulic testing and sampling of interbeds. The hydraulic head of the drilling mud was greater than the head within the beds, and any permeable zones were probably sealed off. Swabbing with a clear brine was necessary to attempt to clean the walls of the wells prior to testing. Due to caving of the cap rock and lack of water-yielding ability of the interbeds, the water-sampling and water-analysis program was greatly restricted.

The geophysical logs made in the wells are listed in table 4. Two sets of logs were made for each well: one for the upper zone before casing, the other for the uncased, lower zone.

GEOHYDROLOGIC UNITS

The Paradox Basin is part of the Colorado Plateau, as defined by Fenneman (1946). According to Hite and Lohman (1973, p. 4), this basin is not a definable physiographic feature, but rather is defined as the area of southeastern Utah and southwestern Colorado that is underlain by a sequence of Pennsylvanian evaporites, mostly halite. In the general area of the well site, evaporites are overlain by a thick sequence of continental sediments, mostly arkosic sandstone and conglomerate.

Table 4.--*Geophysical logs for test wells DOE-1, 2, and 3*

[Logs made by Birdwell Division, Seismograph Services Corp.]

Potential------	Spontaneous potential (well DOE-3 only)
Resistivity----	Induction Conductivity
Acoustic-------	Velocity 3-D variable density Seisviewer
Nuclear--------	Gamma Neutron Density
Temperature----	Temperature
Mechanical-----	Directional inclinometer Caliper

Due to salt flowage, about 16 diapiric and nondiapiric salt anticlines and domes have formed in the northeastern part of the basin (Hite and Cater, 1972). Salt cores of some of these anticlines are 3,000 m or more thick. The younger, overlying rocks are arched in anticlinal form trending northwestward. The anticlines are commonly breached by erosion, forming flat-floored valleys along their axes, such as Salt Valley.

Cap rock overlies the salt core under the floor of Salt Valley. The cap rock is composed mostly of collapsed beds of shale, gypsum, limestone, dolomite, and sandstone that were formerly interbeds within the salt sequence; this material remains after salt dissolution in the upper part of the salt core. Structure of both cap rock and the salt core is very complex. Thickness of the cap rock beneath the floor of Salt Valley probably is within the range of 150 to 300 m. The salt core probably reaches a thickness of about 3,000 m in some areas along the anticlinal axis.

Lithologic units drilled in well DOE-1 are summarized in table 5 and figure 3. Intervals are principally based on geophysical well logs. As indicated in the table, depth to the cap rock-salt interface is 191 m.

Within the salt sequence, four relatively thin interbeds were encountered, having an aggregate thickness of 27 m. This is about 15 percent of the salt sequence penetrated during drilling.

In well DOE-2, the cap rock-salt interface is at a depth of 163 m, or an altitude of 1,300 m. No interbeds were encountered, with the possible exception of two thin interbeds of questionable identification. The interbeds, if present, are at depths of 167 and 214 m in figure 4; each is less than 3 m thick, and would be less than 3 percent of the penetrated salt sequence.

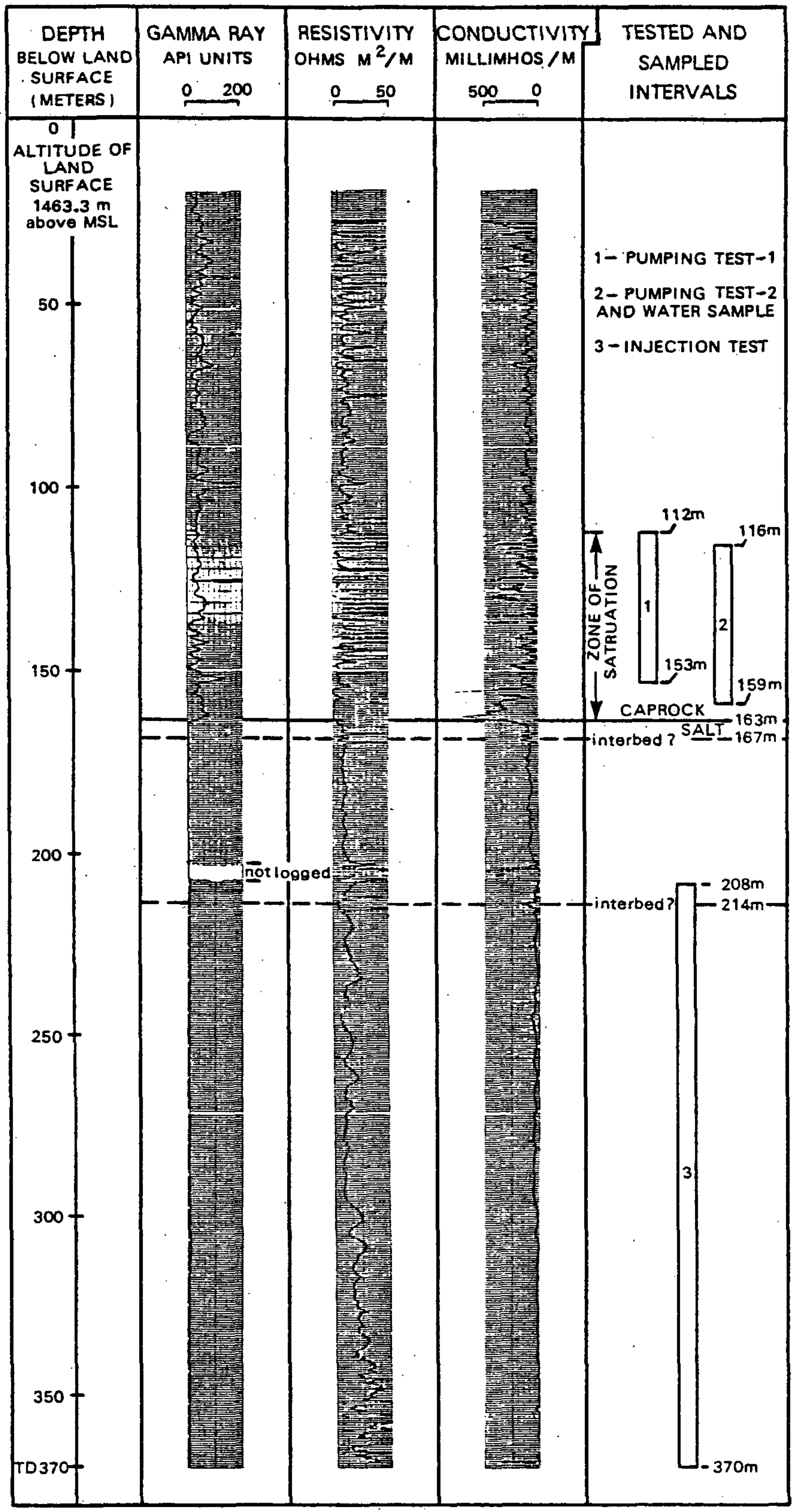

Figure 4.--Geophysical logs, general lithology, and tested intervals for well DOE-2.

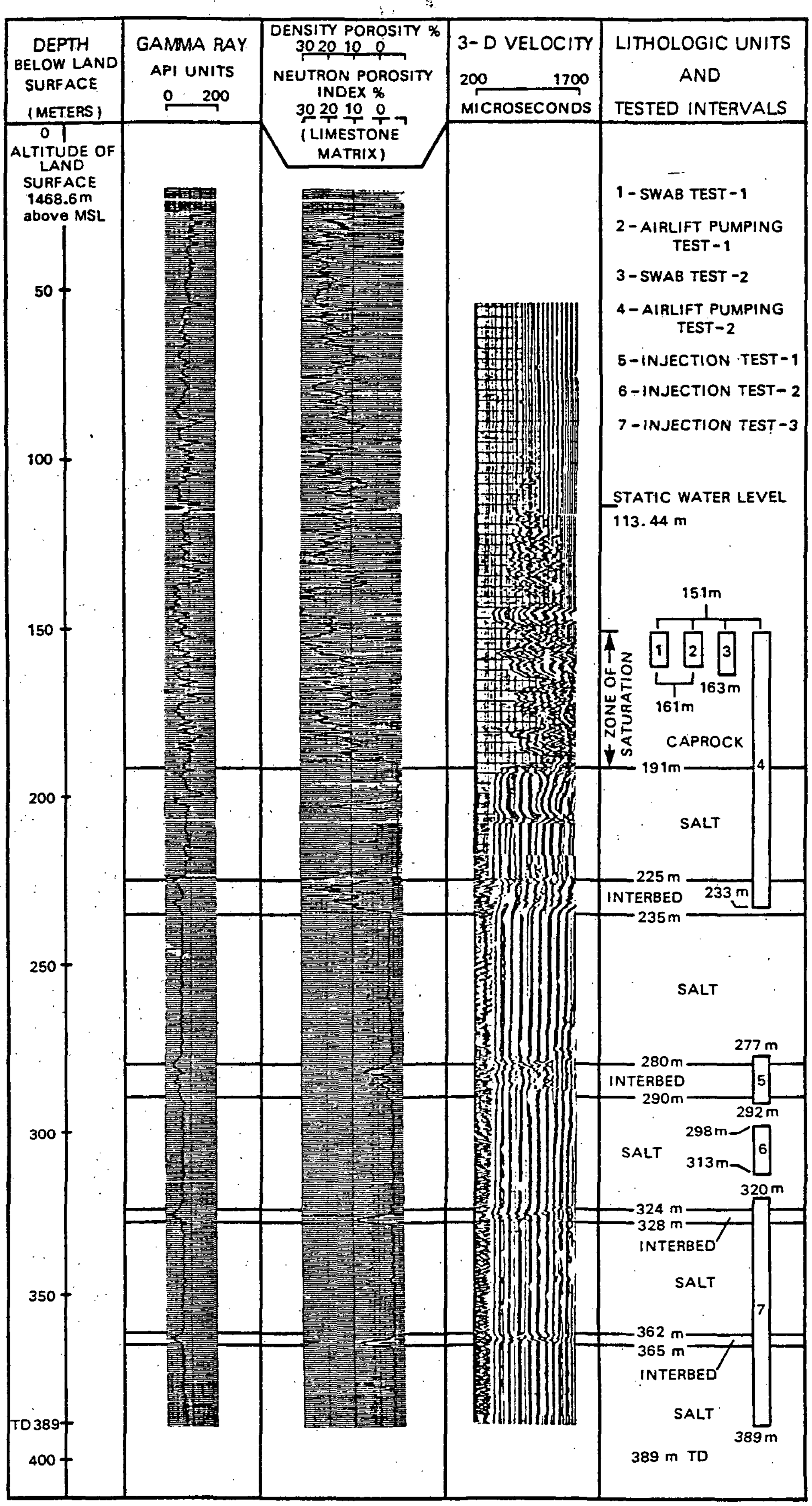

Figure 3.--Geophysical logs, general lithology, and tested intervals for well DOE-1.

Table 5.--*Summary of lithologic intervals encountered in drilling well DOE-1*

Lithology	Depth interval below land surface (m)	Altitude interval above mean sea level (m)	Thickness
Cap rock----	0-191	1,469-1,278	191
Salt--------	191-225	1,278-1,244	34
Interbed----	225-235	1,244-1,234	10
Salt--------	235-280	1,234-1,189	45
Interbed----	280-290	1,189-1,179	10
Salt--------	290-324	1,179-1,145	34
Interbed----	324-328	1,145-1,141	4
Salt--------	328-362	1,141-1,107	34
Interbed----	362-365	1,107-1,104	3
Salt--------	365-389	1,104-1,080	24[1/]

[1/]Lithologic unit not completely penetrated.

Table 6 and plate 1 (in pocket) are lithologic summaries for well DOE-3. The first salt bed was encountered at a depth of 165 m, about the same depth as in well DOE-2, both somewhat shallower than in well DOE-1. A total of 20 interbed intervals were encountered in the salt sequence; they ranged in thickness from 1 to 43 m. The aggregate thickness of the interbeds is 252 m, or 23 percent of the penetrated sequence. The salt units had thicknesses ranging from 4 to 265 m.

Four interbeds are overturned and repeated, as determined from the geophysical logs of well DOE-3 (table 6). This demonstrates the structural complexity of the salt core of the Salt Valley Anticline at this site.

HYDROLOGIC TESTING, MONITORING, AND SAMPLING

The first part of this section describes the procedures used during testing, monitoring, and sampling of Salt Valley test wells DOE-1, 2, and 3. Procedures described include pumping, swabbing, slug injecting, drill-stem testing, water-level measuring, water-quality sampling, air lifting, and discharge monitoring. The second part of this section discusses results of these procedures, presented for each of the test wells separately.

Table 6.--*Summary of lithologic intervals encountered in drilling well DOE-3*

Lithology	Depth interval below land surface (m)	Altitude interval above mean sea level (m)	Thickness	Remarks
Cap rock---	0- 165	1,467-1,302	165	
Salt-------	165- 430	1,302-1,037	265	
Interbed---	430- 448	1,037-1,019	18	
Salt-------	448- 494	1,019- 973	46	
Interbed---	494- 536	973- 931	42	
Salt-------	536- 559	931- 908	23	
Interbed---	559- 585	908- 882	26	
Salt-------	585- 634	882- 833	49	
Interbed---	634- 652	833- 815	18	
Salt-------	652- 657	815- 810	5	
Interbed---	657- 674	810- 793	17	
Salt-------	674- 753	793- 714	79	
Interbed---	753- 756	714- 711	3	
Salt-------	756- 775	711- 692	19	
Interbed---	775- 780	692- 687	5	This is an overturned equivalent of the next above interbed.
Salt-------	780- 824	687- 643	44	
Interbed---	824- 826	643- 641	2	
Salt-------	826- 877	641- 590	51	
Interbed---	877- 878	590- 589	1	
Salt-------	878- 914	589- 553	36	
Interbed---	914- 916	553- 551	2	
Salt-------	916- 966	551- 501	50	
Interbed----	966- 988	501- 479	22	
Salt-------	988-1,010	479- 457	22	
Interbed---	1,010-1,036	457- 431	26	This is an overturned equivalent of the next above interbed.
Salt-------	1,036-1,071	431- 396	35	
Interbed---	1,071-1,072	396- 395	1	
Salt-------	1,072-1,084	395- 383	12	
Interbed---	1,084-1,099	383- 368	15	
Salt-------	1,099-1,135	368- 332	36	
Interbed---	1,135-1,136	332- 331	1	
Salt-------	1,136-1,140	331- 327	4	
Interbed---	1,140-1,143	327- 324	3	
Salt-------	1,143-1,148	324- 319	5	
Interbed---	1,148-1,149	319- 318	1	
Salt-------	1,149-1,153	318- 314	4	

Table 6.--*Summary of lithologic intervals encountered in drilling well DOE-3*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above mean sea level (m)	Thickness	Remarks
Interbed---	1,153-1,156	314- 311	3	This is an overturned equivalent of the interbed in depth interval 1,140-1,143 m.
Salt-------	1,156-1,167	311- 300	11	
Interbed---	1,167-1,170	300- 297	3	
Salt-------	1,170-1,176	297- 291	6	
Interbed---	1,176-1,219	291- 248	43	The lower part of this interbed is the overturned equivalent of the upper part of this interbed.
Salt-------	1,219-1,238	248- 229	19+	

Procedures

Pumping

Aquifer transmissivity and hydraulic conductivity may be determined from analysis of pumping-test data by following standard methods (see, for example, Ferris and others, 1962). In the Salt Valley test wells, hole conditions were a major factor in limiting pumping tests. Caving and hole erosion, low transmissivities, and lack of observation wells reduced use of standard pumping-test procedures. However, use of the Theis formula (Ferris and others, 1962, p. 100-103) for recovery of a pumped well allowed some success in determining aquifer coefficients. This method requires a pre-pumping water level, a known rate and period of discharge, known thickness of the aquifer, and measurements of recovery of water level with time after pumping stops. Submersible pumps were used prior to setting the casing.

Swabbing

Swabbing a well may be desirable to accomplish several tasks involved with testing, monitoring, and sampling. During the drilling and testing program, swabbing was used to test for saturation, to determine general water-yielding ability of saturated materials, to clean and develop wells, and to collect water samples. In some cases, a test well did not yield sufficient water to sustain pumping tests. Swabbing the well and monitoring recovery, produced data that was used to determine aquifer coefficients or qualitative hydraulic characteristics. Often, to combat loss of circulation during drilling, mud or other materials are added to the drilling fluid. Swabbing is usually required to clean wells of these materials before testing for quantitative or qualitative characteristics (Blankennagel, 1967, p. 27). This cleaning and well development also precedes collection of water samples for chemical analysis.

Slug injection

The slug-injection test as a method of estimating transmissivity of an aquifer was introduced by Ferris and Knowles (1954) and modified by Cooper and others (1967) and Papadopulos and others (1973). The test consists of causing an instantaneous change in water level in a well by suddenly introducing a known volume of water and observing recovery of the water level with time. The slug test is one of the few available field-test methods for testing formations with low transmissivities, when yields are too low to permit pumping tests of even relatively short duration. Inflatable packers were used with this procedure to isolate testing zones.

Drill-stem tests

During the drilling of well DOE-3, many interbeds were encountered in the salt sequence. Past drilling experiences in the Paradox Basin indicate a potential for high-pressure natural gas zones in these beds. To collect hydraulic data for these zones and insure safety of personnel and equipment, drill-stem tests were made at each interbed. Although the drill-stem test is a conventional evaluation technique in petroleum exploration, it is rarely used as a tool by ground-water hydrologists. However, these tests can provide information on three critical properties of subsurface formations of interest to hydrologists as well as to the petroleum industry--pressure head, permeability, and water chemistry (Bredehoeft, 1965, and Hackbarth, 1978). During the drill-stem test, the interval to be tested is isolated in the hole by the use of packers attached to the drill string; it is allowed to yield fluid into the drilling pipe under the influence of head difference between formation and atmospheric pressures. Pressures are recorded throughout the test by recording gages contained within the drill string; a sample of formation fluid can be recovered at the end of the test, but in many cases may not be representative of formation fluid, due to contamination by drilling fluids.

Air lift

Samples of formation fluids were collected to provide water-chemistry data. Pumping, swabbing, drill-stem testing, and air-lifting were used to collect these samples. The first three methods have already been described. The air-lift method requires an air pipe inside an eductor, or pumping pipe. Air is circulated down the air pipe, forcing formation fluids up the eductor to the surface. On a rotary-drilling rig, normal circulation, downward through the drill-string and upward in the annulus, is convenient. A complete discussion of air-lifting methods has been written by Kill (1973). After the water is lifted to the surface by whatever method, it is then collected and treated in the manner specified by the U.S. Geological Survey, Water Resources Division, Water-Quality Laboratory. Air-lift pumping may adversely affect the water sample; results should be interpreted with caution.

"Iron Horse"

To collect static water-level data and to monitor water-level changes during tests, two instruments were used: the "iron horse" and pressure transducers (discussed in the next paragraph). Instantaneous water levels were measured using a deep-well water-level measuring device, or "iron horse." When the "iron horse" probe is lowered to the water level in the well, an electrical circuit is completed which can be detected on a meter at the surface. The "iron horse" has proven useful during hydraulic testing in wells with water levels as deep as about 800 m (Weir and Nelson, 1976).

Transducer

During aquifer tests, it was desirable to have a continuous record of water-levels during pumping and recovery periods. This was done by connecting a cable from a continuous recorder to a pressure transducer that was lowered into the well. The transducer varies voltage in response to pressure changes. When calibrated properly and used in conjunction with the "iron horse" an accurate record of water-level can be obtained.

Hydrologic monitoring

Monitoring of drill-bit cuttings produced hydrologic information in addition to lithologic information. Drilling began on wells DOE-1 and 2, using dry air as the circulating fluid. While drilling proceeded in unsaturated cap rock, discharge of cuttings was dry and dust-like. This changed dramatically when "first water" was encountered; dust discharge ceased and moist granules of pulverized rock were observed. Quantity of produced fluid indicated the relative ability of the formation to produce water. In addition to observations of water quantity, water quality was checked periodically. Specific conductances and temperatures were measured on collected samples.

Results

Well DOE-1

Drill-bit cuttings were monitored to detect zones of water saturation. Moisture was first encountered at a depth of 151 m below land surface in the cap rock (fig. 3). All cap rock below this depth probably was saturated. After drilling to a depth of 161 m, the static water level was 113.4 m below land surface, resulting in an artesian rise of 38 m above the top of the saturated zone.

Casing was cemented into place to a depth of 228 m, or to 37 m below the cap rock-salt interface. After the well was completed, it was filled with brine; however, water level in the well declined with time, resulting from one of two possible conditions: (1) lithologic units penetrated below the bottom of the casing were receiving water during head equalization; or (2) water was flowing through the poorly-cemented annular space to cap rock during head equalization. The latter is considered the more likely explanation because: (1) there were other indications of a poor cement job; and (2) injection tests indicate that probably none of the salt sequence was able to receive liquids. The depth to water in the well on Nov. 4, 1978, or about 80 days after well completion, was 118.6 m; on Feb. 20, 1979, 122.7 m. The zone receiving the water has a lower head than the cap rock zone of 151-161 m.

When the well was at a depth of 161 m, water was swabbed from the well to obtain samples. Specific conductance of the samples ranged from 1,900 to 3,400 micromhos per centimeter at 25°C. These data suggest a dissolved-solids content in the upper part of saturated cap rock as low as about 1,200 mg/L. Water temperatures ranged from 22° to 24°C. Air-lift pumping of the same zone produced water samples having specific conductances in the range 3,200-4,700 micromhos and sample temperatures of 19° to 22°C.

The well was deepened an additional 2.1 m, and a sample was swabbed; its specific conductance was 7,250 micromhos.

Salt was encountered at 191 m below land surface (fig. 3), or at an altitude of 1,278 m above mean sea level. With further drilling to a total depth of 389 m, a total of 5 salt beds and 4 interbeds were penetrated. The salt beds ranged in thickness from 17 to 43 m; the interbeds from 4 to 12 m (table 5).

While the well was at a depth of 233 m, a water sample having a specific conductance of 150,000 micromhos was air-lifted. The high conductance probably resulted mostly from solution of salt at a depth of 191 to 225 m.

Slug-injection tests, using packers, were run on 3 zones of salt and interbeds (fig. 3). For the first test, the packers were set to isolate a zone from 277 to 292 m. The target was the thickest interbed encountered in drilling the well, from a depth of 280 to 290 m. Average hydraulic conductivity for the zone was computed as on the order of 1×10^{-4} m/d. This is a very low conductivity, equal to about 0.1 millidarcy. Test data are summarized in figures 5 and 6.

The second test was on part of a salt bed from depth 298 to 313 m. Average-computed hydraulic conductivity is on the order of 4 x 10^{-5} m/d, or 0.05 millidarcy. Test data are summarized in figures 7 and 8.

Parts of 3 salt beds and 2 interbeds were tested below a packer setting of 320 m to the bottom of the well at 389 m. Average computed hydraulic conductivity is on the order of 1 x 10^{-5} m/d, or about 0.01 millidarcy. Similar to the results of the tests described above, these values of hydraulic conductivity are very low. Test data are summarized in figures 9 and 10.

Well DOE-2

Following the procedure used for well DOE-1, drilling began on well DOE-2 below surface casing, using dry air as a circulating fluid. Moisture was first encountered at a depth of 112 m. This corresponds closely with static water levels measured later, probably indicating water-table conditions. Starting at a drilling depth of 115 m, air mist was used as the drilling fluid, making monitoring of water saturation difficult.

At a well depth of 144 m, a water sample was air-lifted, confirming the presence of water in the well and saturation in the penetrated lithologic units. At a well depth of 153 m, the static water level below land surface was measured at 112.2 m.

While the well remained at a depth of 153 m, the first pumping test was made. Transmissivity of the zone 112-153 m was calculated to be on the order of 2 x 10^{-1} m^2/d, and the average hydraulic conductivity, on the order of 5 x 10^{-3} m/d, or about 6 millidarcys. Test data are summarized in figures 11 and 12.

Following deepening the well to a depth of 159 m, static water level was measured and the second pumping test was made. The water level was 115.8 m below land surface. For the zone 112-159 m, the calculated values of transmissivity and average hydraulic conductivity are on the order of 2 x 10^{-1} m^2/d and 4 x 10^{-3} m/d (5 millidarcys), respectively. Test data are summarized in figures 13 and 14.

Following the test, water samples were pumped from the zone and prepared for laboratory analysis. Field parameters determined at the time of collection were temperature, 20°C; specific conductance, 7,750 micromhos; and pH, 7.0. Results of the laboratory analyses are listed in table 7. The water sample had high concentrations of calcium, magnesium, sodium, chloride, and sulfate. Total dissolved solids were 6,770 mg/L. The ^{14}C specific activity of the water yielded an uncorrected "age" of greater than 36,000 years. The $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios indicate that the sampled water was derived from atmospheric water vapor by precipitation and infiltration. The $^{13}C/^{12}C$ ratio indicates that the carbon content of the sampled water had a biogenic origin, such as from petroleum.

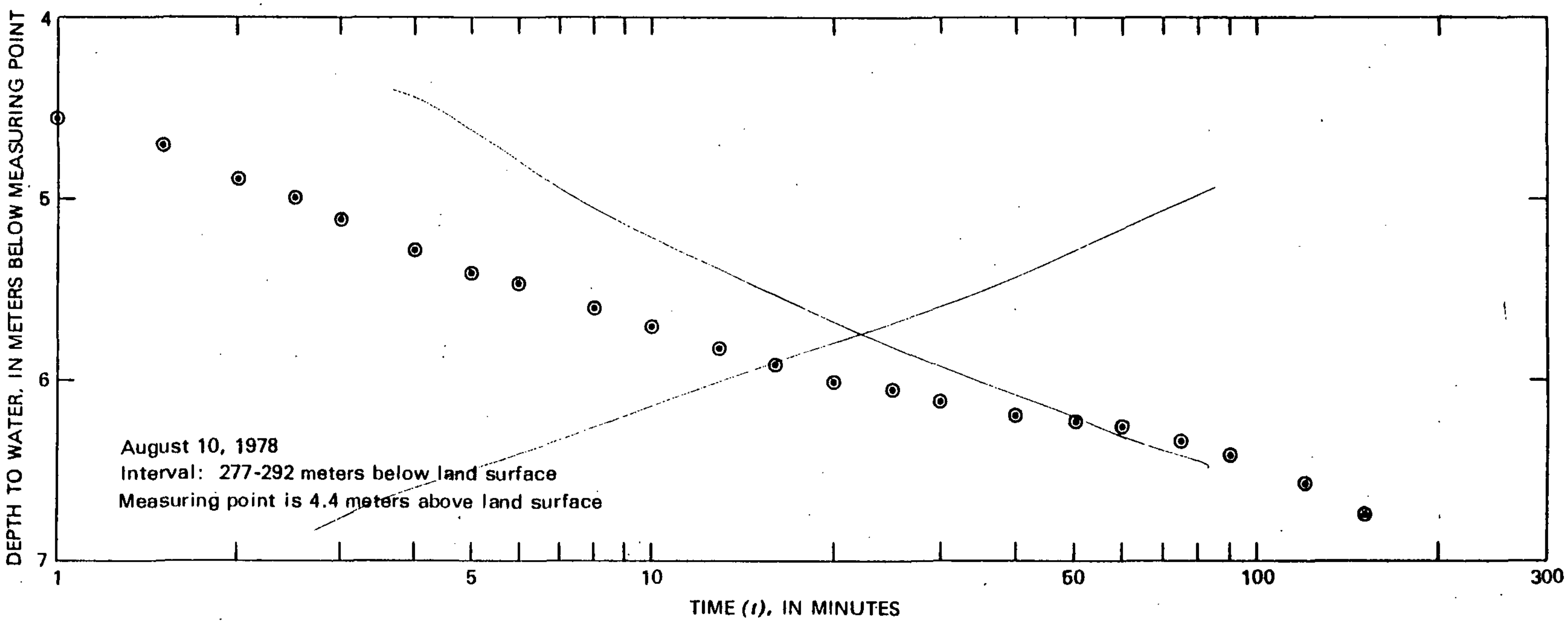

Figure 5.--Recovery of water level after slug injection, packer test 1, well DOE-1.

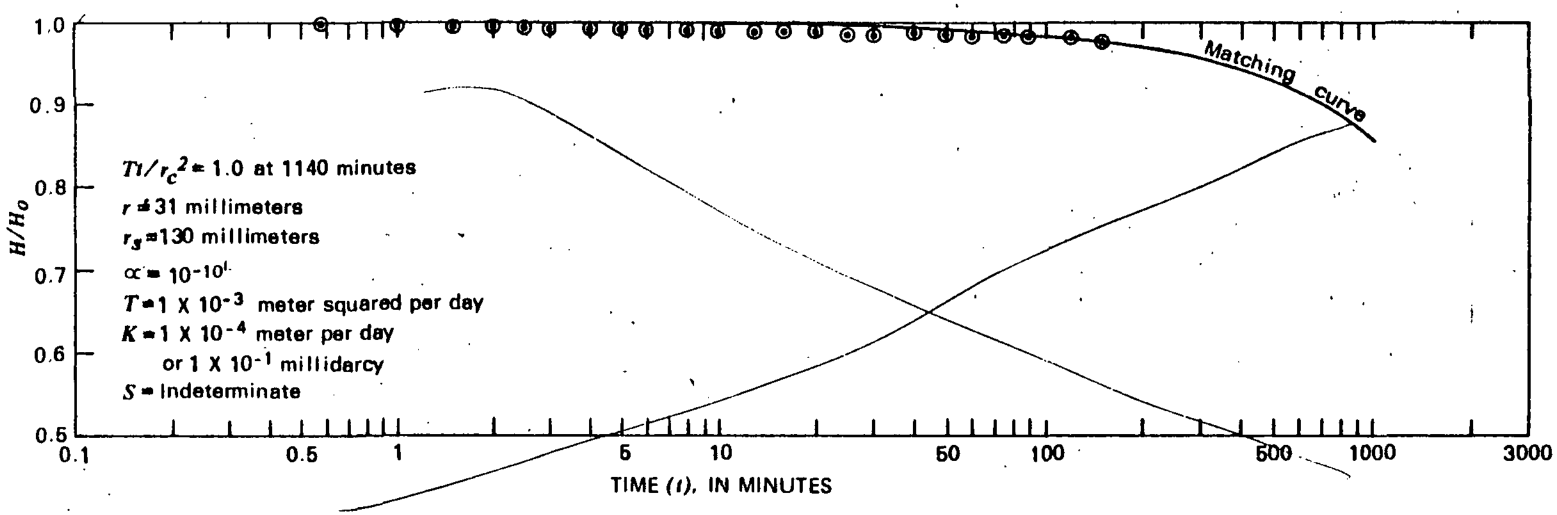

Figure 6.--Analysis of packer test 1, well DOE-1.

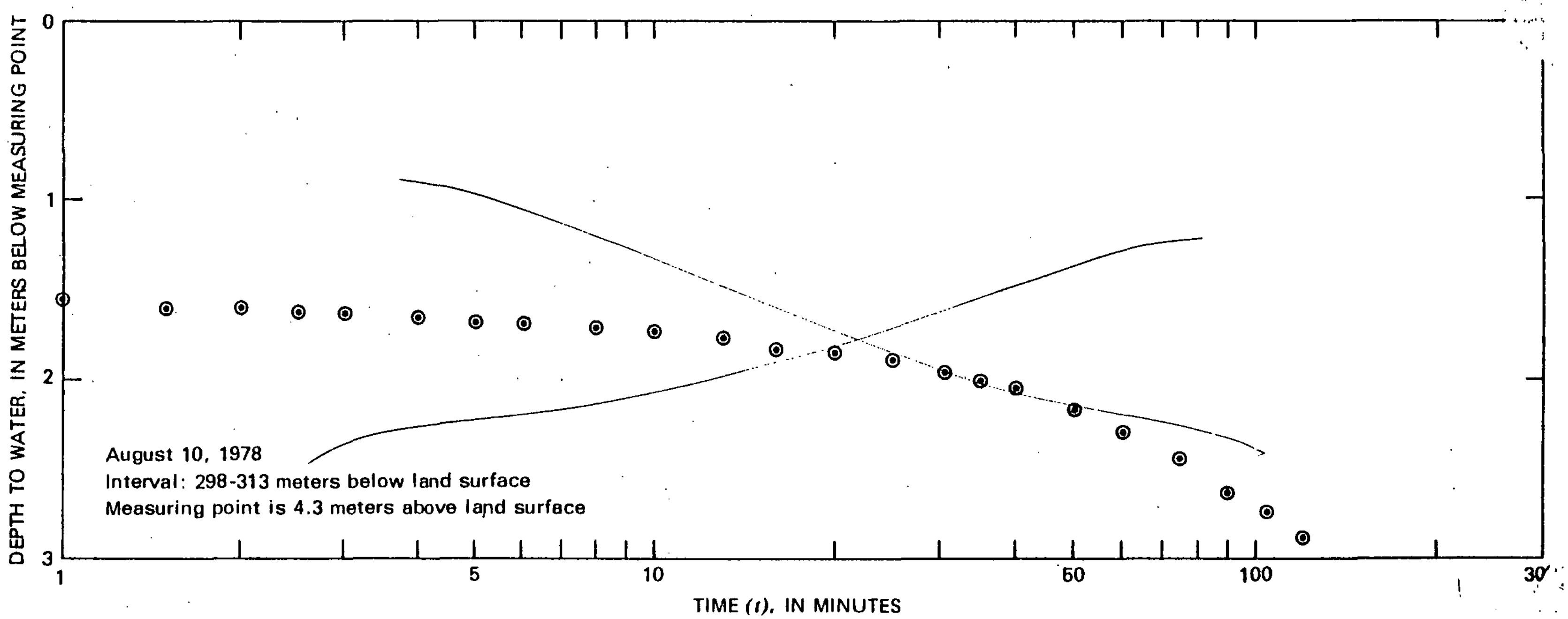

Figure 7.--Recovery of water level after slug injection, packer test 2, well DOE-1.

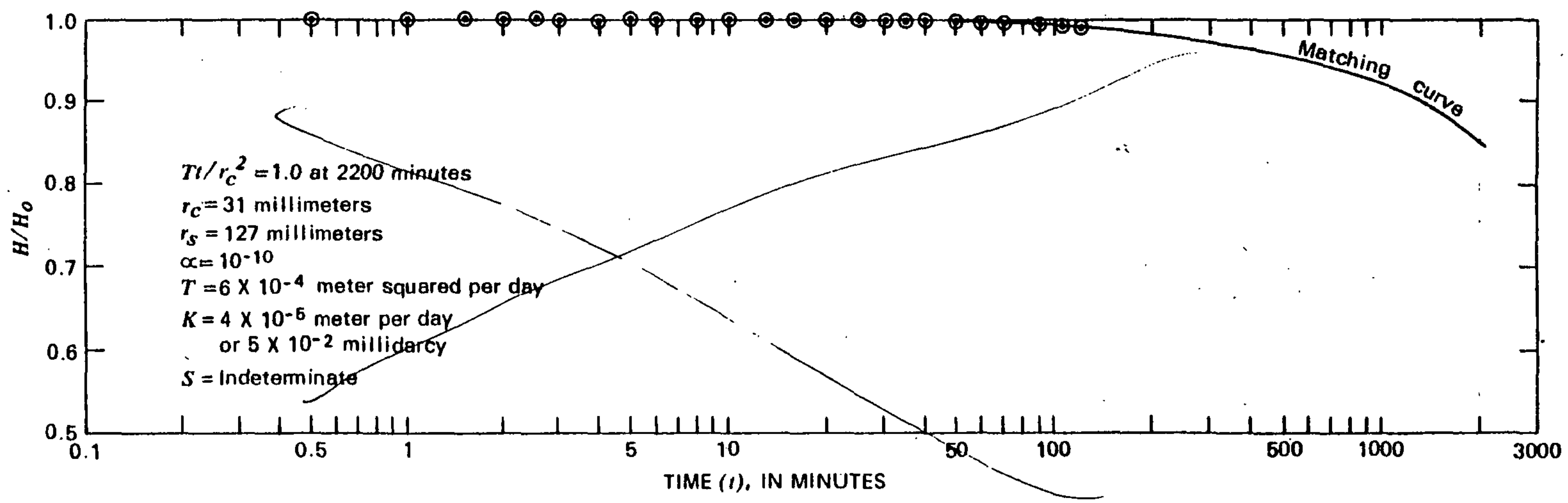

Figure 8.--Analysis of packer test 2, well DOE-1.

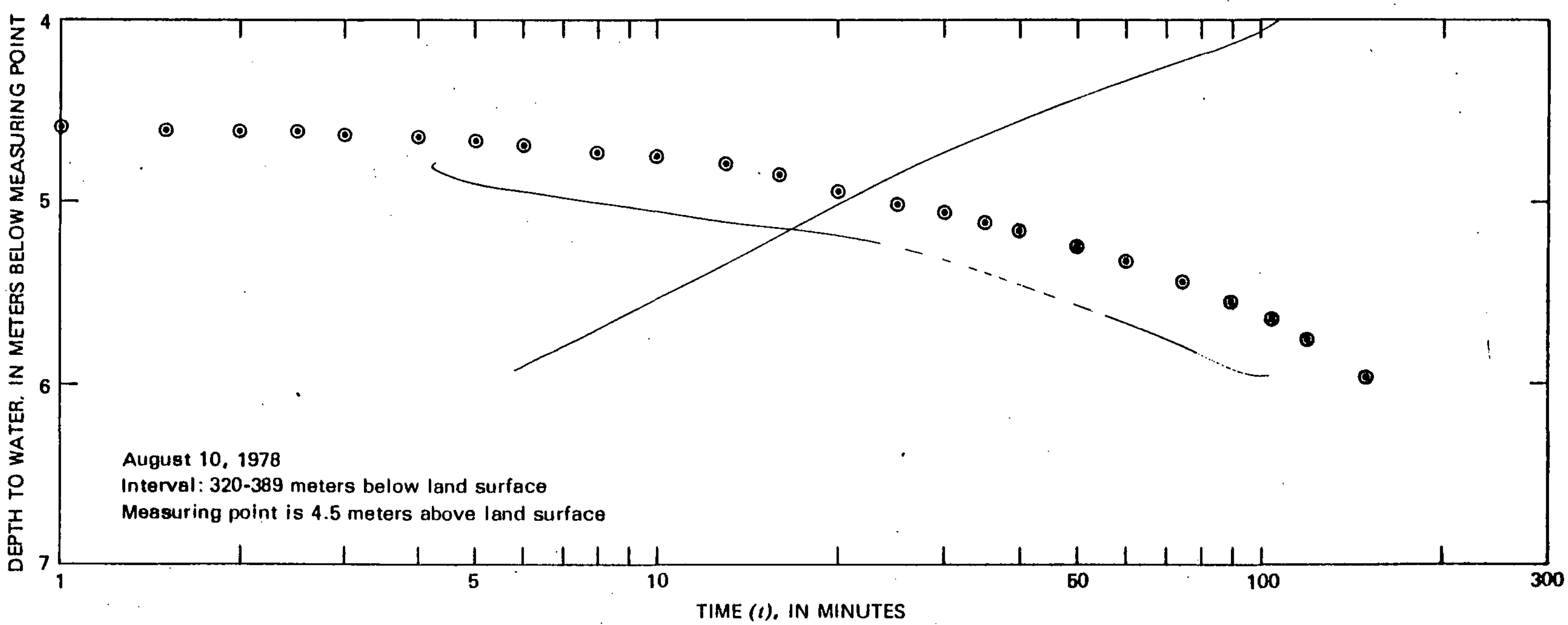

Figure 9.--Recovery of water level after slug injection, packer test 3, well DOE-1.

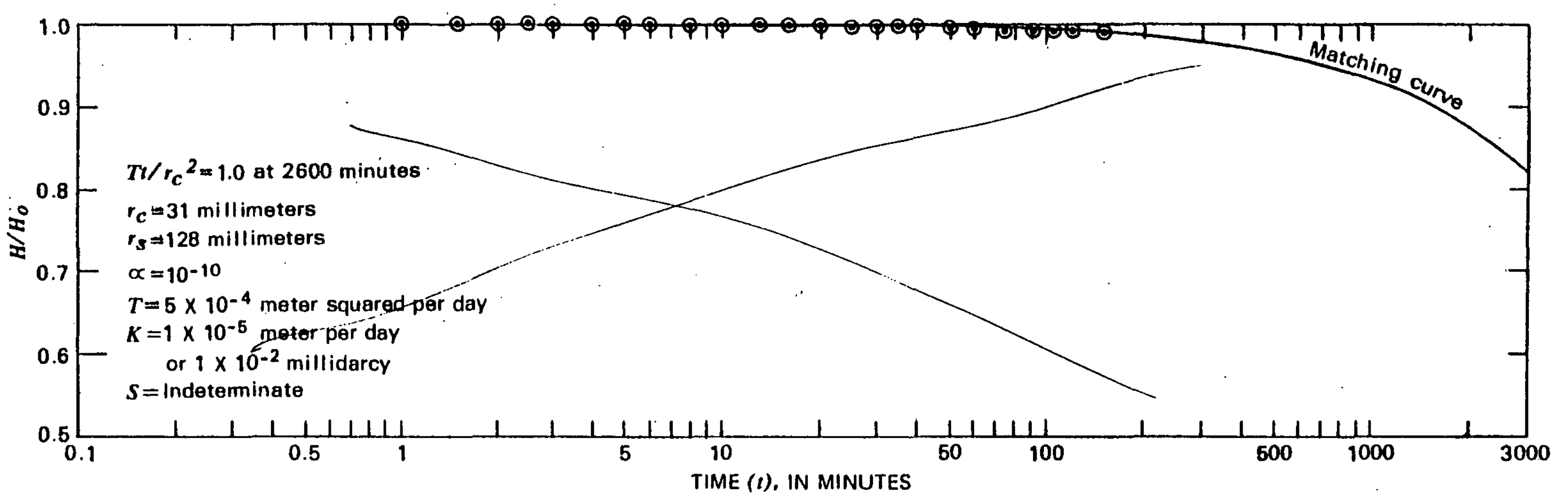

Figure 10.--Analysis of packer test 3, well DOE-1.

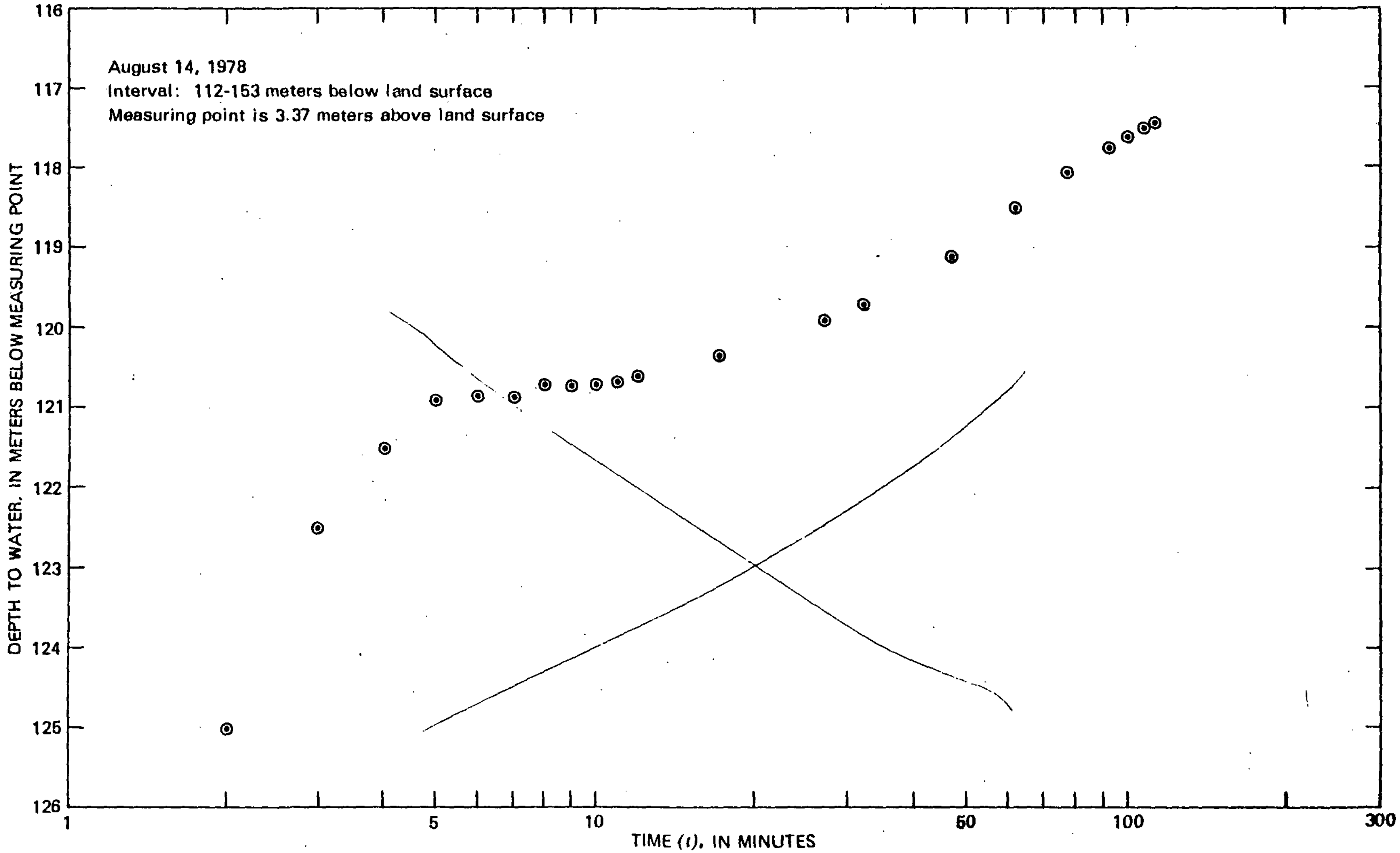

Figure 11.--Recovery of water level during pumping test 1, well DOE-2.

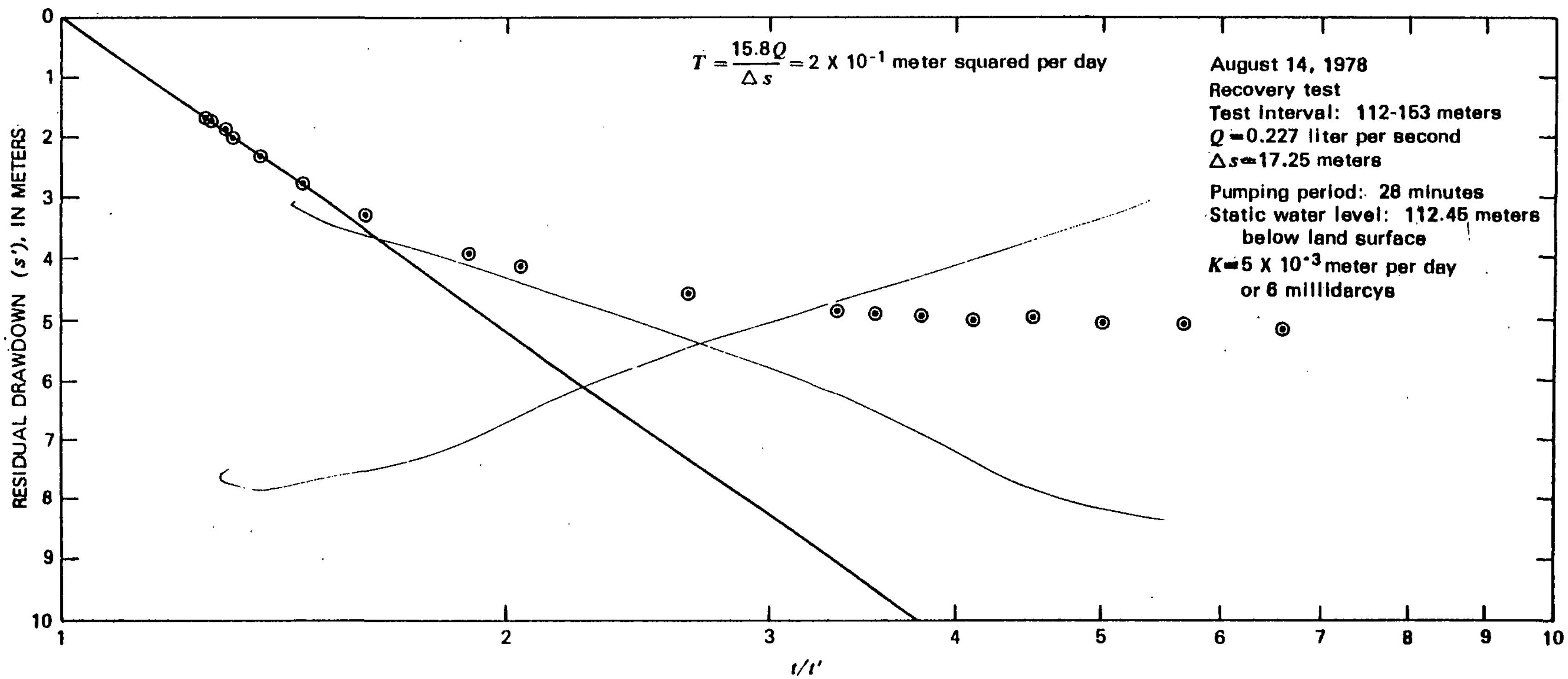

Figure 12.--Analysis of pumping test 1, well DOE-2.

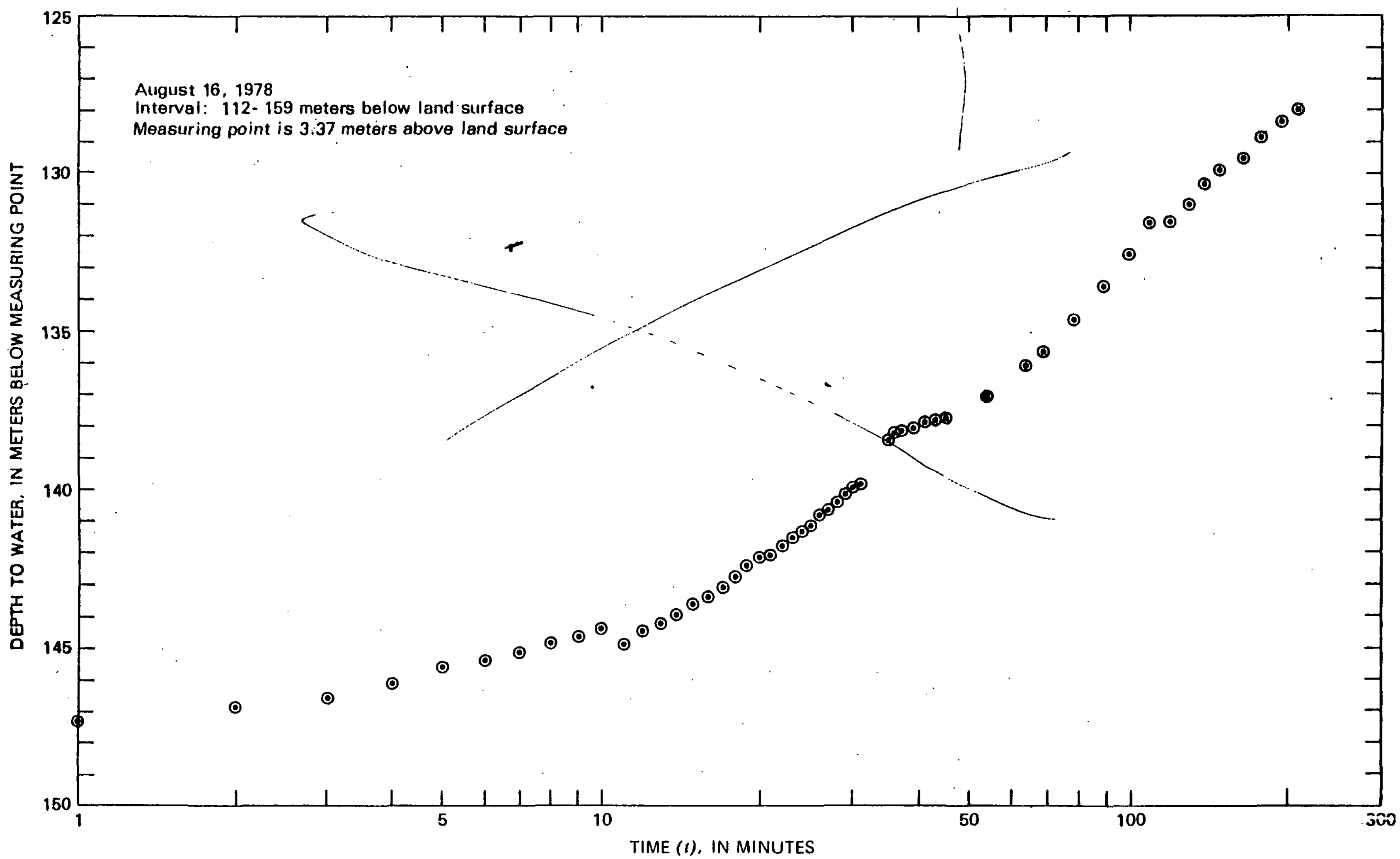

Figure 13.--Recovery of water level during pumping test 2, well DOE-2.

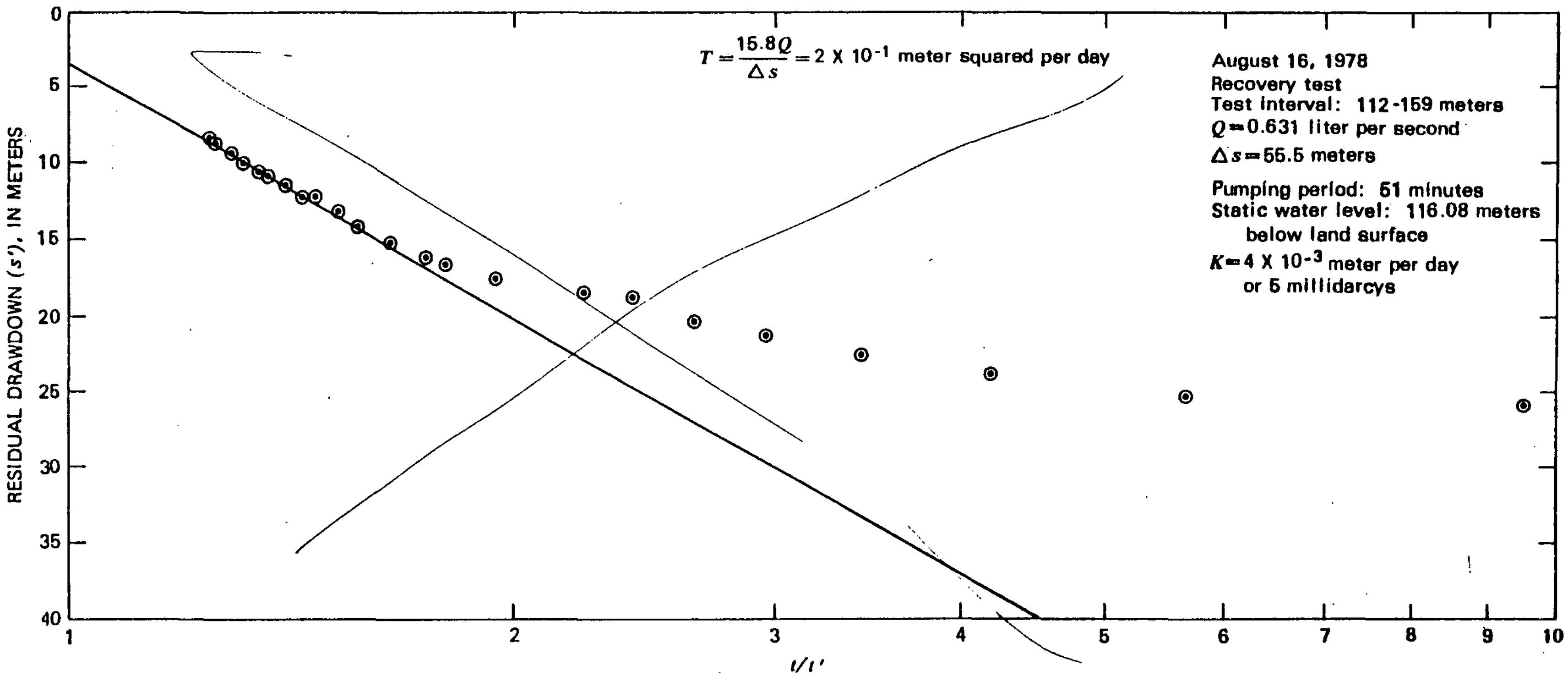

Figure 14.--Analysis of pumping test 2, well DOE-2.

Table 7.--*Chemical analysis of water samples from depth interval 112-159 m, well DOE-2*

[Units of concentration: mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter]

Alkalinity, total (as $CaCO_3$)	mg/L	440
Aluminum, dissolved	µg/L	0
Bicarbonate	mg/L	540
Carbon-14, uncorrected age-H_2O	years	>36,000
Calcium, dissolved	mg/L	620
Carbon, dissolved organic	mg/L	12
Carbon-13/carbon-12 ratio[1]	----	-19.4
Carbonate	mg/L	0
Chloride, dissolved	mg/L	1,400
Deuterium-hydrogen ratio ($^{2}H/^{1}H$)	----	-121
Tritium in water, liquid scintillation	pCi/L	<300
Hardness, noncarbonate	mg/L	2,700
Hardness, total	mg/L	3,100
Iron, dissolved	µg/L	80
Lithium, dissolved	µg/L	600
Magnesium, dissolved	mg/L	380
Manganese, dissolved	µg/L	3,400
Oxygen-18/oxygen-16 ratio ($^{18}O/^{16}O$)	----	-16.0
pH, field	----	7.0
pH, laboratory	----	6.7
Potassium, dissolved	mg/L	27
Residue, dissolved calculated sum	mg/L	6,530
Residue, dissolved 180°C	mg/L	6,770
Silica, dissolved	mg/L	23
Sodium, dissolved	mg/L	900
Specific conductance, field	µmho	7,750
Specific conductance, laboratory	µmho	8,260
Strontium, dissolved	µg/L	13,000
Sulfate, dissolved	mg/L	2,900
Uranium, dissolved, direct fluorometric	µg/L	3.0
Water temperature	°C	20.0

[1]Deviation in parts per thousand from PDB Standard.

The top of the salt was at a depth of 163 m. A barite plug was set to isolate the salt from the saturated cap rock, and a static water level of 113.7 m was measured in the cap rock.

After the well had reached a total depth of 370 m, a slug-injection test was made on the salt sequence below a depth of 203 m. During an injection period of 50 minutes, no injection was observed, indicating very-low transmissivity and hydraulic conductivity.

Approximately eight months after well DOE-2 was completed, a temperature log of 122 data points was made in the well. Figure 15 shows the results of that log. The bottom hole temperature was 23.4°C or about 10 degrees warmer than the average annual air temperature for the site.

The temperature profile has six segments, each with different slopes caused by variations in thermal conductivity of the penetrated lithology. The following table summarizes the temperature gradients and thermal conductivities of the segments.

Segment (fig. 15)	Depth range (m)	Temperature gradient (I, in °C/km)	Thermal conductivity (K, in mcal/cm s°C)
A	3-21	131.	1.6
B	21-85	31.9	6.5
C	85-124	35.5	5.8
D	124-168	41.1	5.0
E	168-265	13.2	15.[1/]
F	265-369	14.4	

Computation of heat flow to land surface

$$\text{HFU} = 10^{-2}KI$$

$$= 10^{-2} \left(\frac{13.2+14.4}{2}\right) 15 = 2.1\ \mu\text{cal/cm}^2\text{s}$$

[1/] From Weast (1978, p. E-4).

The penetrated salt has the lowest gradient, about 14°C/km. Cap rock, whether saturated or unsaturated, averaged about 35°C/km. The upper 21 m of the penetrated lithology has a high gradient, 131°C/km, indicating a distinctly different lithology not recognized by other observations. The computed thermal conductivity of this upper 21 m is 1.6 mcal/cm s°C. This is indicative of clay (Rush, 1979, manuscript table 2). The interval between depths of 21 and 168 m has values generally expected for shale and some other sedimentary rocks. The heat flow to land surface is calculated to be 2.1 μcal/cm^2 s using a thermal conductivity for the salt of 15 mcal/cm s°C. This value is near the upper end of the heat flow unit (HFU) range expected for the Colorado Plateaus of Utah (Rush, 1979, manuscript p. 18).

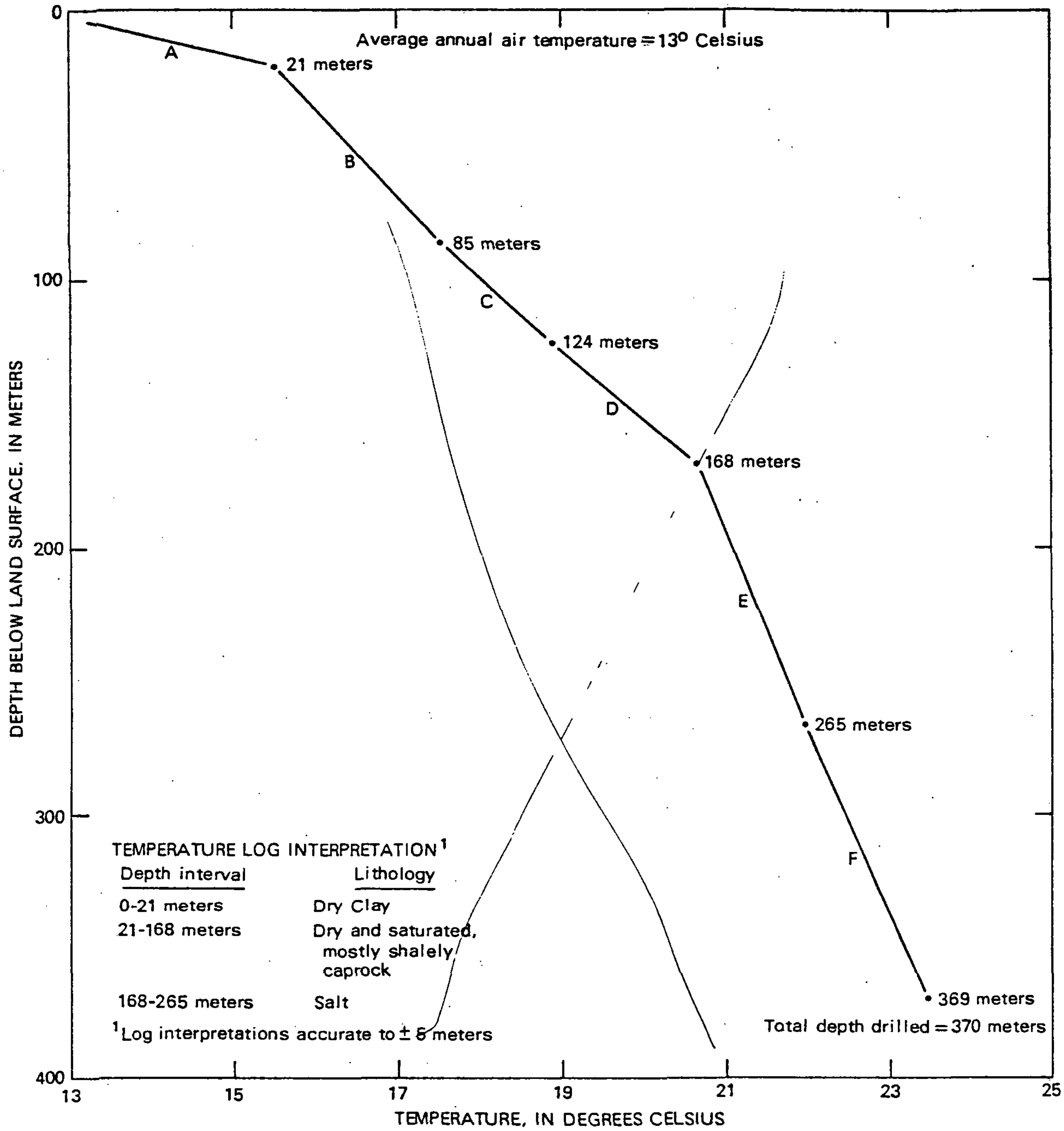

Figure 15.—Temperature profile on Apr. 25, 1979, of rocks penetrated in well DOE-2.

Well DOE-3

The principal objective for drilling well DOE-3 was to obtain a continuous core of cap rock, interbeds, and salt. As a result, drilling fluids, saltwater and saltwater gel (table 3), prevented identifying zones of water saturation and measuring static water levels in the well.

The cap rock-salt interface was reached at a depth below land surface of 165 m, or an altitude of 1,302 m above sea level (table 6). Water swabbed from the saturated cap rock had a specific conductance of about 50,000 micromhos initially; later, during the swabbing, it increased to about 100,000 micromhos. Rapid decline of water level in the well during swabbing and the subsequent slow-recovery rate indicated that the cap rock was not capable of yielding water at a sufficient rate to obtain representative water from the formation. As a result, no samples were collected for laboratory analysis.

Four drill-stem tests were made during the period of coring, and six after the well had reached its total depth of 1,238 m. None of the tests had pressures high enough to flow gas, oil, or formation water to the surface. Table 8 is a summary of the zones tested, mostly interbeds. Test intervals are also shown on plate 1. Initial and final test pressures are listed in the table; however, these are generally less than formation pressures, because equilibrium was not generally reached during the test periods. The slow progression toward equilibrium is the result of very low hydraulic conductivities in the tested zones.

Most of the drill-stem tests recovered only drilling mud. Three tests had shows of formation water, gas, and oil (table 8). In addition, some cores of shale, when inspected at land surface, had small quantities of gas or oil.

A slug-injection test was made on the salt and interbed sequence below a packer setting of 222 m, to the total depth of the well at 1,238 m. No systematic decline in water level was detected that could be attributed to injection of water into the tested lithologies. As a result, the tested lithologies probably have very low hydraulic conductivities.

SUMMARY OF SITE HYDROLOGY

The cap rock at well DOE-1 is 191 m thick. It is 163 m and 165 m thick in the other two wells. The data indicate that considerable altitude variation is present along the cap rock-salt interface.

The unsaturated zone of the cap rock is more than 100 m thick. The shallowest indication of water saturation was at a depth of 112 m in well DOE-2. Saturation was not identified in well DOE-1 until a depth of 151 m was penetrated; however, static water level in the well rose to a depth of 113 m. Water-table conditions probably prevail at well DOE-2.

Table 8.--*Results of drill-stem tests of interbeds in well DOE-3*

[All interbeds tested except three minor beds with an aggregate thickness of 5 m]

Depth interval (m below land surface)	Date (1968)	Temperature of interval (°C)	Shut-in pressure[1/] Initial (kg/cm^2)	Shut-in pressure[1/] Final (kg/cm^2)	Hydraulic head[1/] (m above sea level)	[2/]Remarks
425- 463	9-19	28	9.8	4.9	1,120	
488- 539	11-3	28	10.5	11.1	1,060	
554- 606	11-3	30.5	8.6	5.9	970	
627- 678	11-2	35	18.1	18.1	1,000	Two interbeds in tested interval.
736- 788	11-2	35	11.9	13.6	840	Do.
962-1,012	10-13	33.5	10.5	5.9	580	
996-1,047	11-1	46.5	10.2	10.1	550	Fluid recovered was very slightly water-cut mud.
1,054-1,105	11-1	46.5	9.1	10.6	490	Do.
1,132-1,174	10-21	----	28.7	22.8	600	Five interbeds in tested interval.
1,173-1,224	10-31	49	16.9	21.4	480	Fluid recovered was gas-cut mud with a trace of oil.

[1/]Shut-in pressures and calculated hydraulic head may not be representative of formation conditions, because equilibrium may not have been reached during test.

[2/]Unless otherwise indicated, fluid recovered in test was drilling mud.

Two components of potential ground-water flow were identified in the cap rock, based on apparent hydraulic gradients: (1) heads decrease with depth within the saturated cap rock causing a potential ground-water flow downward; and (2) head apparently decreases from well DOE-1 southwestward towards well DOE-2, resulting in an apparent component of flow in that direction.

The cap rock is semilithified, resulting in difficulties in some aspects of drilling, coring, and hydraulic testing. In addition, the hydrogen sulfide that was dissolved in cap rock water was a problem during testing.

Ground water in the cap rock has ion concentrations that apparently vary within the saturated zone. Lowest specific conductances of samples were from the upper part of the zone, and were as low as 1,900 micromhos. Generally deeper samples had much higher conductances, as high as 7,750 micromhos in well DOE-2.

Two pumping tests of the saturated cap rock yielded hydraulic conductivity values of 5×10^{-3} m/d and 4×10^{-3} m/d. These very low values would probably limit ground-water flow to very low rates. As a result, a long length of time would be required to circulate water through the cap rock ground-water system. A carbon-14 age dating of a water sample from the cap rock of greater-than 36,000 years supports this conclusion; the water is meteoric in origin.

The salt and interbed sequence at the site had minor shows of oil and gas, but in general, the lithologies have very low porosity and very low hydraulic conductivities. The latter generally are 1×10^{-4} m/d or less for 5 tests.

SUGGESTED FURTHER STUDIES

The three wells drilled as part of this program produced some useful hydrologic information, but little was learned for the site concerning the following: (1) Boundaries of the ground-water flow-system in the cap rock of Salt Valley; (2) directions and rates of ground-water flow and the resulting rate of salt solution at the base of the cap rock; (3) areas of recharge to and discharge from the cap rock; and (4) variations in hydraulic properties of the cap rock. If the ground-water system is to be more thoroughly understood, then additional wells would have to be drilled into the cap rock and perhaps into adjoining lithologic units for hydraulic monitoring and testing. The number of wells needed would depend on the degree of system definition desired. A small expansion of knowledge could be obtained from only a few wells. Extensive hydrologic-system definition may require 50 or more wells. Because of instability of cap rock during testing, hydraulic tests generally should be made inside well casing and screens.

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