UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RESULTS OF HYDRAULIC TESTS IN U.S. DEPARTMENT OF ENERGY'S WELLS DOE-4, 5, 6, 7, 8, AND 9, SALT VALLEY, GRAND COUNTY, UTAH

By Leonard E. Wollitz, William Thordarson, Merrick S. Whitfield, Jr., and James E. Weir, Jr.

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JAMES G. WATT, Secretary

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Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
Water Resources Division
Mail Stop 416, Box 25046
Denver Federal Center
Denver, Colorado 80225

For purchase, write to:

Open File Services Section
U.S. Geological Survey
Box 25425
Denver Federal Center
Denver, Colorado 80225
(303) 234-5888; FTS 234-5888

METRIC CONVERSION TABLE

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
millimeter (mm)	3.937×10^{-2}	inch
kilometer (km)	6.214×10^{-1}	mile
square kilometer (km^2)	3.86×10^{-1}	square mile
meter (m)	3.281	foot
degree Celsius (°C)	1.8°C + 32	degree Fahrenheit
meter per day (m/d)	3.281	foot per day
meter squared per day (m^2/d)	1.076×10^{1}	foot squared per day
milligram per liter (mg/L)	1/ 1.0	part per million
microgram per liter (μg/L)	1/ 1.0	part per billion
kilogram per square centimeter (kg/cm^2)	1.422×10^{1}	pound per square inch
liter per second (L/s)	1.585×10^{1}	gallon per minute
liter (L)	2.642×10^{-1}	gallon
kilogram (kg)	2.205	pound
kilopascal (kPa)	1.450×10^{-1}	pound per square inch
watt (W)	1.34×10^{-3}	horsepower

1/ Approximate.

SYMBOLS AND DIMENSIONS

Symbol	Description	Dimension
b	Thickness of tested interval	Meters
K	T/b; hydraulic conductivity	Meters per day
K'	Vertical hydraulic conductivity of confining layer	Meters per day
Q	Flow rate	Liters per second
r	Radial distance between wells	Meters
r_c	Radius of well casing	Meters
Δs	Drawdown for one log cycle	Meters
S_s	Specific storage of aquifer	Meters^{-1}
S'_s	Specific storage of confining bed	Meters^{-1}
s	Drawdown	Meters
s'	Residual drawdown	Meters
s''	Drawdown in observation well	Meters
T	Transmissivity	Meters squared per day
t	Time since discharge began	Minutes
t'	Time since discharge stopped	Minutes
t/t'	Time since discharge began/time since discharge stopped	Dimensionless
t_D	Time for well in pumped aquifer	Dimensionless
t'_D	Time for well in confining bed	Dimensionless
z	Vertical distance	Meters

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RESULTS OF HYDRAULIC TESTS IN U.S. DEPARTMENT OF ENERGY'S WELLS DOE-4, 5, 6, 7, 8, and 9, SALT VALLEY, GRAND COUNTY, UTAH

By

Leonard E. Wollitz, William Thordarson, Merrick S. Whitfield, Jr., and James E. Weir, Jr.

ABSTRACT

Six exploratory wells were drilled into the cap rock underlying Salt Valley, Utah, for geologic, geophysical, and hydrologic data to augment information obtained from three previous test wells. Drilling of three other test holes was abandoned due to caving and loss of drilling tools, before reaching the zone of saturation; the upper 100 meters of cap rock is unsaturated. Within the saturated part of the cap rock, hydraulic heads generally decrease with depth and to the northwest in this part of the valley.

Hydraulic conductivity of the cap rock, as determined from pumping tests, ranged from 9.3×10^{-5} to 2.06×10^{-1} meters per day; as a result, groundwater flow rates in the cap rock are low. Water ranges from a calcium bicarbonate sulfate type on the western edge of the valley to a calcium magnesium sodium bicarbonate, sulfate, chloride type near the center of the valley. Carbon-14 specific activity for cap-rock water yielded an uncorrected age of about 17,000 to 26,000 years before present near the western edge of the valley and about 41,000 years before present near the center of the valley.

INTRODUCTION

The U.S. Geological Survey, on behalf of the U.S. Department of Energy (DOE), has been conducting investigations related to the isolation of high-level radioactive wastes. These investigations have included geologic, geophysical, and hydrologic studies to locate suitable environments for waste storage and to develop new techniques for site exploration and evaluation. This report presents hydrologic information on the Salt Valley anticline in Grand County, Utah, in the northern part of the Paradox basin (fig. 1).

Purpose and Scope

The primary purpose of this investigation is to obtain geohydrologic and geophysical data for the cap rock of the Salt Valley anticline. These data provide a hydrologic framework for further work necessary to evaluate the acceptability of the underlying salt core of the anticline for storing toxic nuclear wastes. This report presents detailed hydrologic data, supporting geologic and geophysical information, and hydrologic interpretations for the rocks penetrated during drilling.

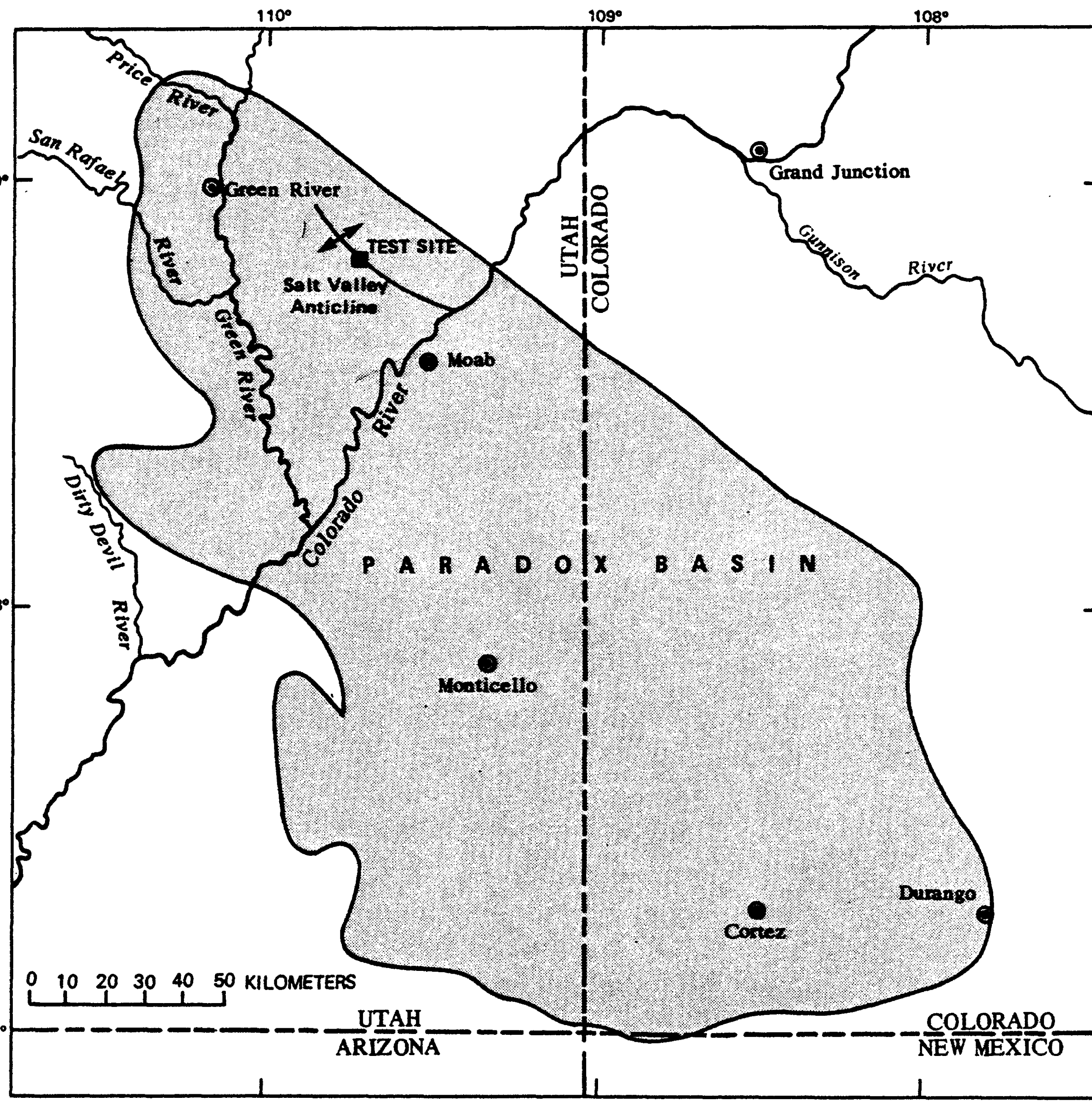


Figure 1.--Location of the test site in the Paradox basin of Utah and Colorado.

Location

Wells DOE-4 through 10 are located in Salt Valley on the Salt Valley anticline (fig. 1) in the NW 1/4 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 of which are large regional streams.

Detailed descriptions of the well locations from the northeast corner of NW 1/4 sec. 5, T. 23 S., R. 20 E., are: (1) DOE-4 is 502.3 m south and 270.1 m west; (2) DOE-5 is 500.8 m south and 265.3 m west; (3) DOE-6 is 368.6 m south and 388.5 m west and DOE-6A (abandoned) is 4.8 m northeast of DOE-6; (4) DOE-7 is 364.5 m south and 377.9 m west; (5) DOE-8 is 437.1 m south and 576.9 m west; (6) DOE-9 is 443.1 m south and 576.9 m west; (7) DOE-8A (abandoned) is 445.9 m south and 606.4 m west; (8) DOE-10 (abandoned) is 804.9 m south and 218.2 m west (fig. 2). The location of these wells in reference to each other and the altitude of each well are shown in figure 3.

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

GEOHYDROLOGIC SETTING

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 is defined as the area of southeastern Utah and southwestern Colorado that is underlain by a sequence of evaporites, mostly halite, of Pennsylvanian age. In the general area, evaporites are overlain by a thick sequence of continental sediments, mostly arkosic sandstone and conglomerate.

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). 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.

The term "cap rock" as used in this report is defined as the residue of collapsed beds of shale, gypsum, limestone, dolomite, and sandstone that overlies the salt beneath the floor of Salt Valley. The residual material formerly consisted of interbeds within the salt sequence; the cap rock formed after dissolution of the upper part of the salt core. Use of the term "cap rock" is consistent with usage in previous reports describing the deposits overlying the salt in Salt Valley (Hite and Lohman, 1973, pp. 35, 36, 38, 41, and 42; Hite, 1977, pp. 7, 13, and 15; Rush and others, 1980, pp. 7 and 9).

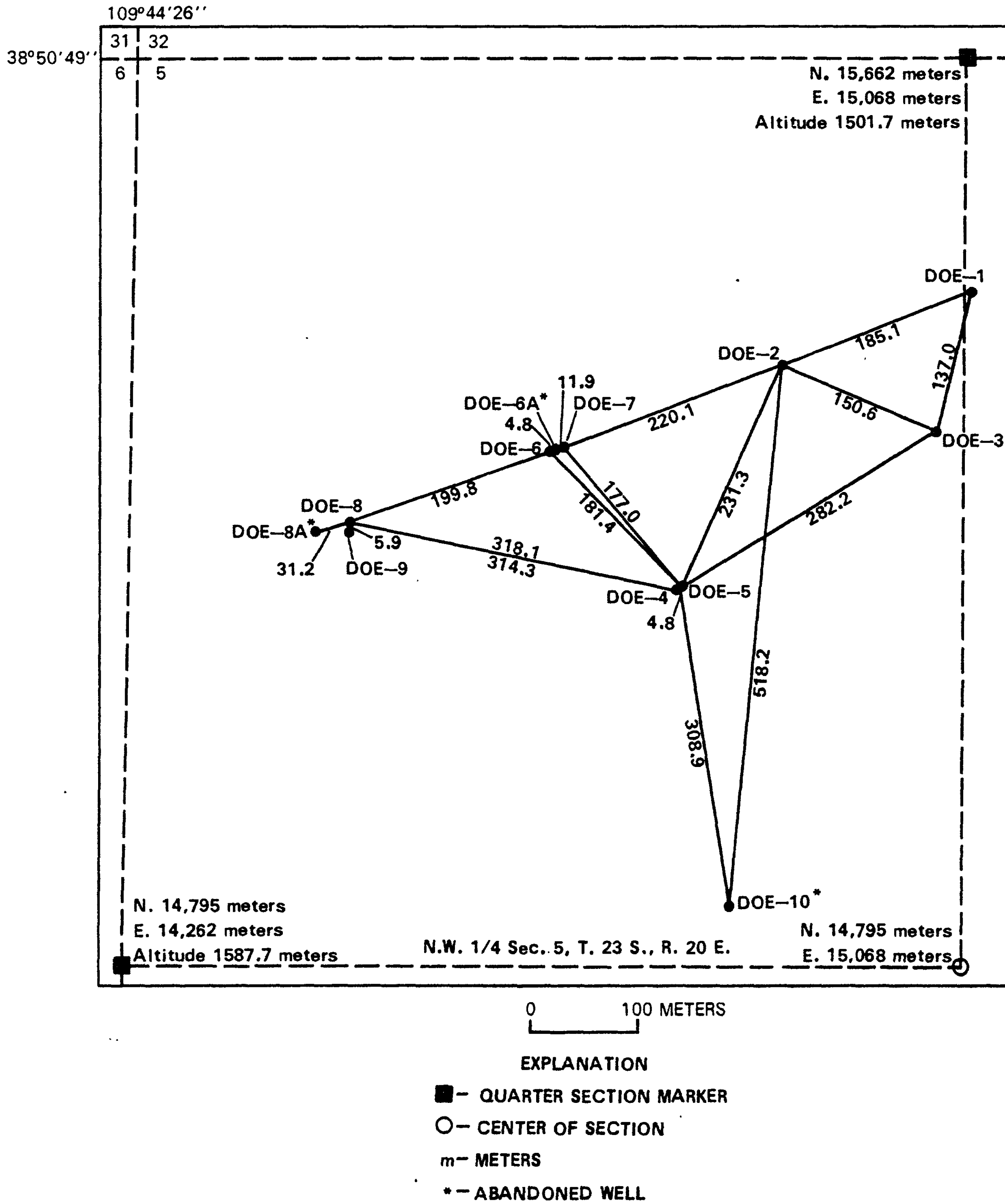
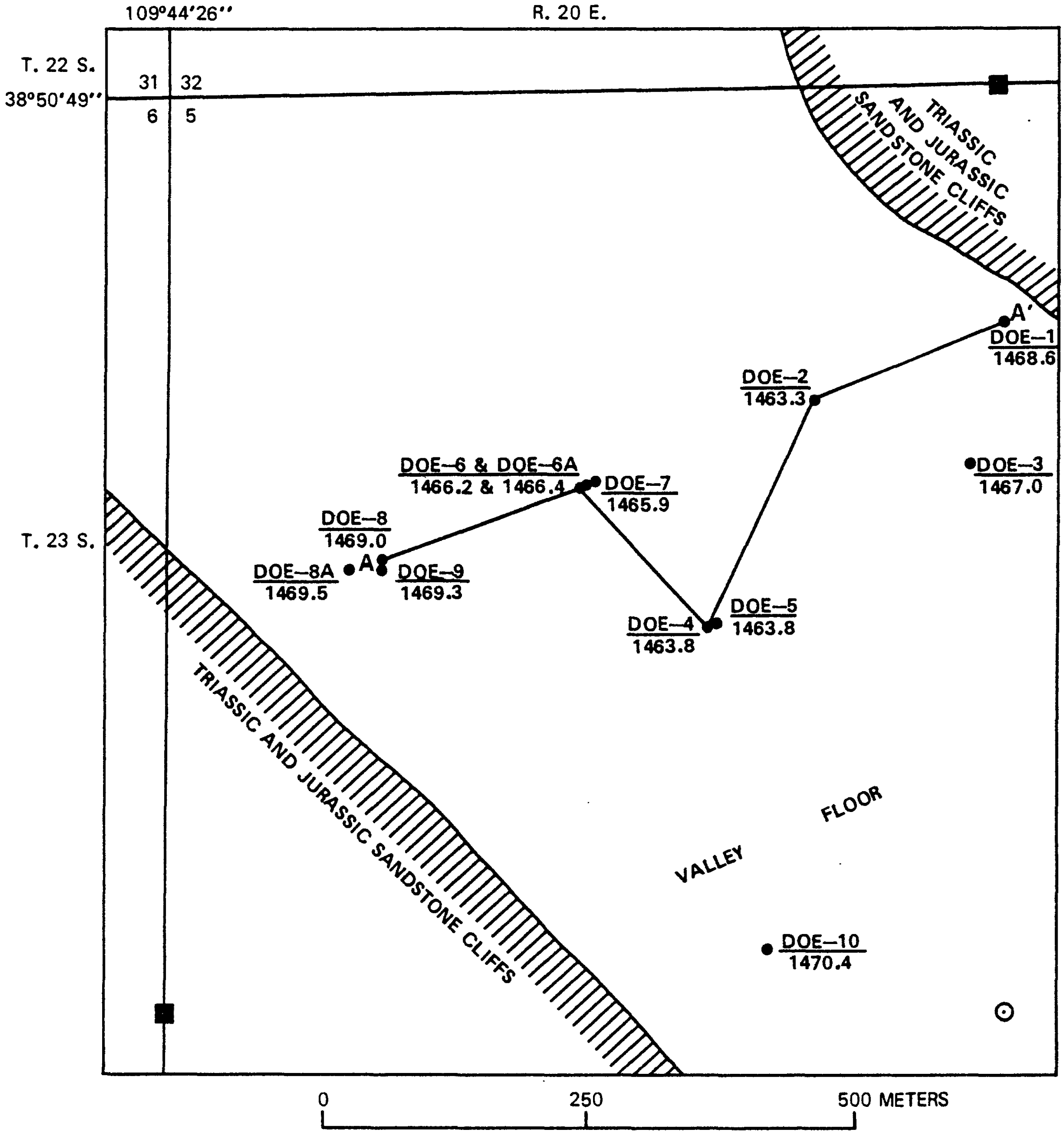


Figure 2.--Surveyed location of test wells and abandoned holes.



EXPLANATION

- ● TEST WELL—Upper number is well number. Lower number is altitude of land surface at well site, in meters above sea level.
- A●——●A' LINE OF SECTION SHOWN IN FIGURE 11
- ■ QUARTER-SECTION MARKER
- ⊙ CENTER OF SECTION

Figure 3.--Location and altitude of U.S. Department of Energy's wells.

In addition to the cap rock, blocks of Mesozoic rocks underlie the center of Salt Valley (Dane, 1935, p. 155; Williams, 1964). These blocks resulted from the collapse of the crest of the Salt Valley anticline in the Tertiary Period (Cater, 1970, p. 50).

Structure of both the cap rock and the salt is very complex due to deformation. An identifiable stratigraphic horizon cannot be mapped in the subsurface. Thickness of the cap rock beneath the floor of Salt Valley probably ranges from 150 to 300 m. The salt probably has a thickness of about 3,000 m in some areas along the anticlinal axis.

Rocks that comprise the cap rock in Salt Valley are quite heterogeneous in their lithologic makeup and vary widely in their water transmitting ability. Thus, hydrologic predictions are difficult to make even at a short distance from an existing well.

Sandstone and carbonate rocks in the cap rock generally are more transmissive than the siltstone, mudstone, and shale. The sandstone and siltstone generally have primary permeability, whereas the carbonate rocks, especially dolomite, have mostly secondary permeability. The matrix of salt and gypsum in these deposits is virtually impermeable. These rocks have a plastic character, and fractures therefore are commonly self-sealing at great depths; as a result, salt and gypsum transmit little if any ground water below the cap rock. Cores from well DOE-3 show that a large percentage of fractures are generally filled with gypsum (R. J. Hite, oral commun., 1981).

However, a potential exists for water movement along the contact of the cap rock and the underlying salt. Salt dissolution was observed during drilling of well DOE-8 at the cap rock-salt contact. Thus, there is localized evidence of ground-water flow along this contact. No tests were conducted during this investigation to assess this condition. The extremely low permeability of the salt and the shale interbeds within the salt suggest no significant movement of water in the salt (Rush and others, 1980, p. 22). Ground water moving downward through the cap rock probably discharges along the salt-cap rock interface but does not move into the salt.

DRILLING PROCEDURES AND WELL CONSTRUCTION

The first three wells of the program, DOE-1 through 3, that were drilled for the U.S. Department of Energy in Salt Valley provided hydrologic data for the cap rock on the eastern side of the valley (Rush and others, 1980). Six additional wells, DOE-4 through 9, were drilled to investigate the cap rock in the center and west side of the test site. These wells were drilled in pairs, with both shallow and deep screen settings at each site, so that both lateral and vertical hydraulic continuity could be determined. This paired arrangement enabled either well to be used as an observation well during pumping. The deeper wells, DOE-4, 6, and 8, were drilled to the top of the salt and were designed to test the cap rock directly above the salt. The shallower wells, DOE-5, 7, and 9, were completed just above the screened interval in the deeper wells to test the shallower saturated part of the cap rock. The construction of these test wells is illustrated in figure 4. Construction characteristics of wells DOE-4 through 9 are listed in table 1.

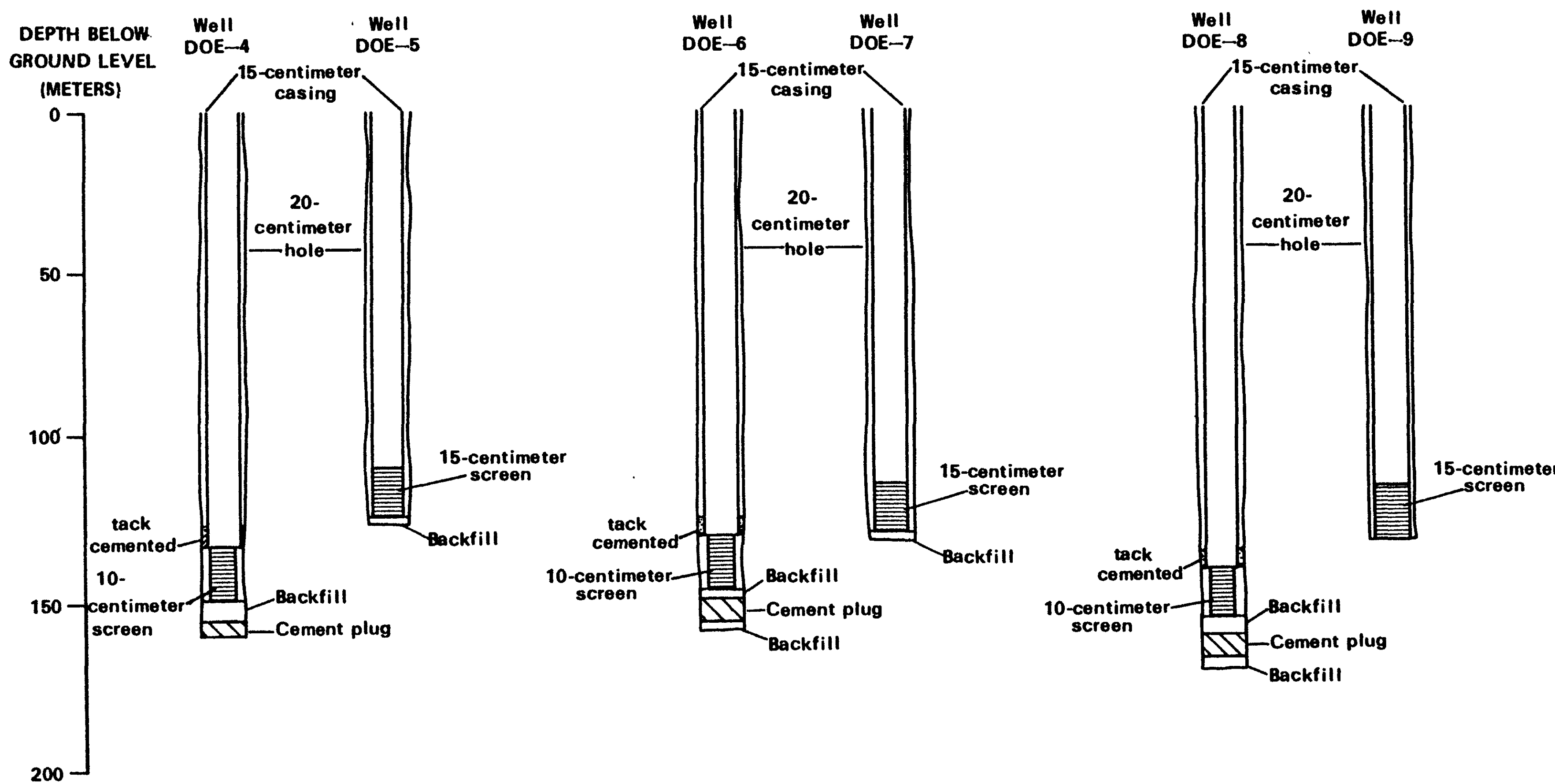


Figure 4.--Construction of test wells DOE-4 through 9.

Table 1.--*Contruction characteristics of the test wells*

[All depths measured from land surface; cm = centimeter; m = meter; mm = millimeters]

Construction characteristics	Well DOE-4	Well DOE-5	Well DOE-6	Well DOE-7	Well DOE-8	Well DOE-9
Started drilling below surface casing (1979)	Aug. 23	Aug. 30	Sept. 12	Sept. 21	Oct. 9	Oct. 24
Well completed (1979)	Sept. 7	Sept. 6	Sept. 24	Sept. 23	Oct. 23	Oct. 26
Surface casing:						
Diameter (cm)	25	25	25	25	25	25
Depth interval (m)	0-4.6	0-4.6	0-4.4	0-5.8	0-10.7	0-10.3
Main casing:						
Diameter (cm)	15	15	15	15	15	15
Depth interval (m)	0-134	0-110	0-133	0-118	0-145	0-121
Screen:						
Diameter (cm)	10	15	10	15	10	15
Opening (mm)	0.38	0.38	0.38	0.38	0.38	0.38
Interval (m)	134-150	110-125	133-148	118-133	145-160	121-137
Back fill interval (m)	150-156	125-128	148-151 160-161	133-134	160-165 172-175	-------
Cement plug interval (m)	156-161	-------	151-160	-------	165-172	-------
Completed depth (m)	150	125	148	133	160	137
Drilled depth (m)	161	128	161	134	175	137
Open-hole bit size (cm)	20	20	20	20	20	20

Drilling was done by Boyles Brothers Drilling Co., Salt Lake City, Utah. Support services, such as geophysical well logging and setting of submersible pumps, were provided by the U.S. Geological Survey. The geophysical logs available for these wells are listed in table 2, and logs appear in figures 5 through 10.

Table 2.--*Geophysical logs run in test wells DOE-4 through 9*

[Logs by U.S. Geological Survey]

Well	Caliper	Neutron	Gamma-gamma	Gamma	Single point resistivity
DOE-4	X	X	X	X	--
DOE-5	--	X	X	X	--
DOE-6	X	X	X	X	--
DOE-7	--	X	X	X	--
DOE-8	X	X	X	X	X
DOE-9	--	X	X	X	--

The major problem encountered during the drilling and hydraulic testing of the test wells was with hole caving above the saturated zone. To detect first moisture in the cap rock and to not seal off permeable zones, only dry air and air mist were used as drilling fluids in wells DOE-5 and 6; polymer mud was needed in drilling wells DOE-4, 7, 8, and 9. The water used with the drilling fluids was from a surface water source at Thompson, Utah. This water had a specific conductance of 1,300 micromhos per centimeter. The absence of a mud cake within the bore hole brought about considerable caving of the cap rock in two holes, DOE-6A and 10, both of which had to be abandoned prior to reaching the zone of saturation. Drilling fluids used in wells DOE-4 through 9 are summarized in table 3.

Drilling of well DOE-4 began at the bottom of the surface casing using dry air as a circulating fluid. A 20-cm hole was drilled to a depth of 130 m; the hole was then drilled to a depth of 144.8 m using air mist as a circulating fluid. The 20-cm hole was drilled to a total depth of 161.2 m using a polymer mud as the circulating fluid. After geophysical logging, casing, 15 cm in diameter, was installed to a depth of 133.8 m. A cement plug was set from 155.8 to 161.2 m leaving an open hole between 133.8 and 155 m. The hole was backfilled with cuttings and sand up to a depth of 122.5 m. The backfill was drilled out to a depth of 134.7 m using 6,550 kPa of air; then 454 L of cement slurry was pumped into the hole. The cement was forced from the bottom of the casing up into the annulus to provide a tack-cement area separating the upper section of the hole from the lower section that was to be tested. The cement plug and backfill were drilled out to 149.7 m; a stainless steel screen, 10 cm in diameter, was set from 134.1 to 149.7 m.

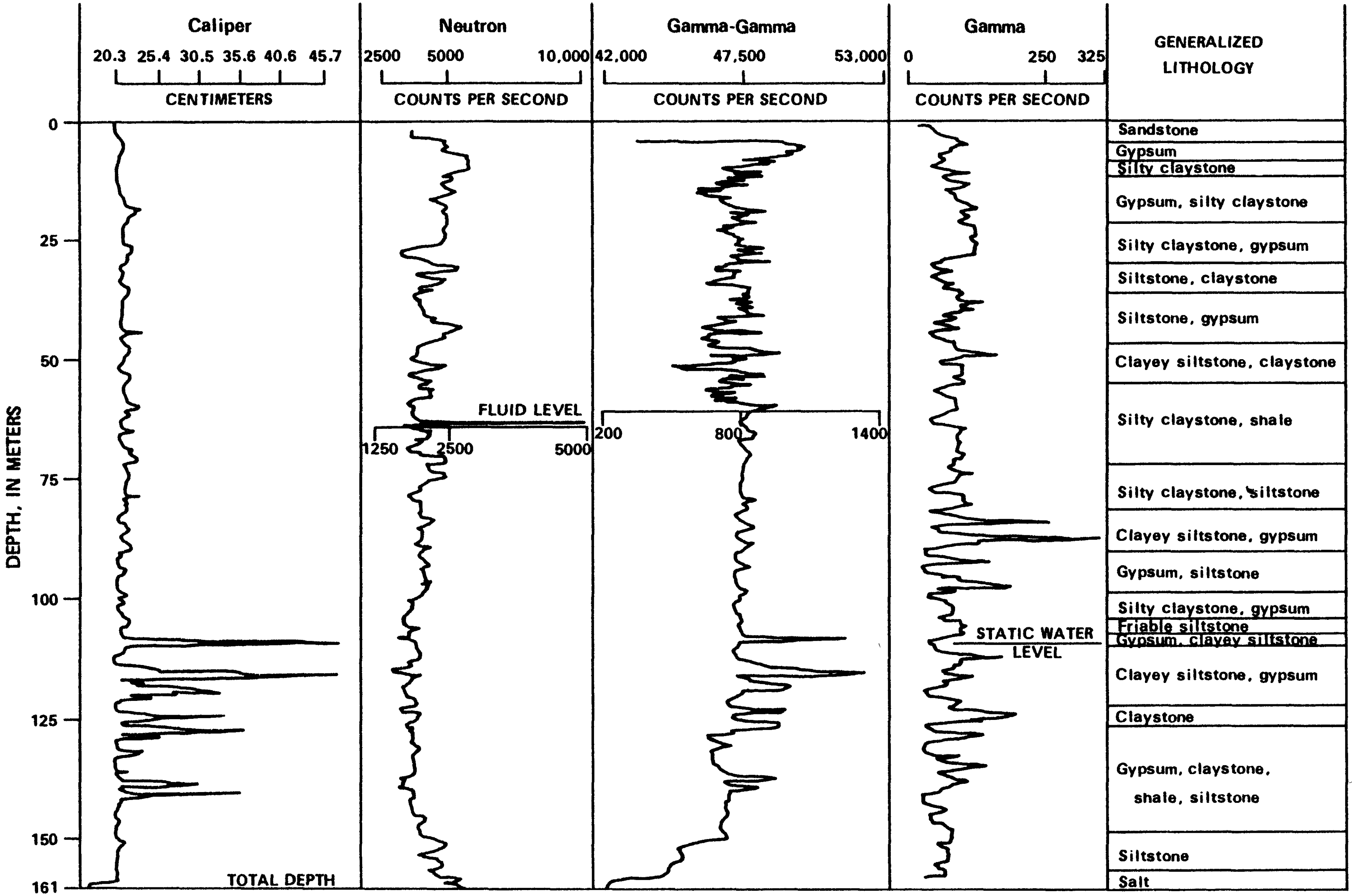


Figure 5.--Geophysical logs and general lithology for well DOE-4.

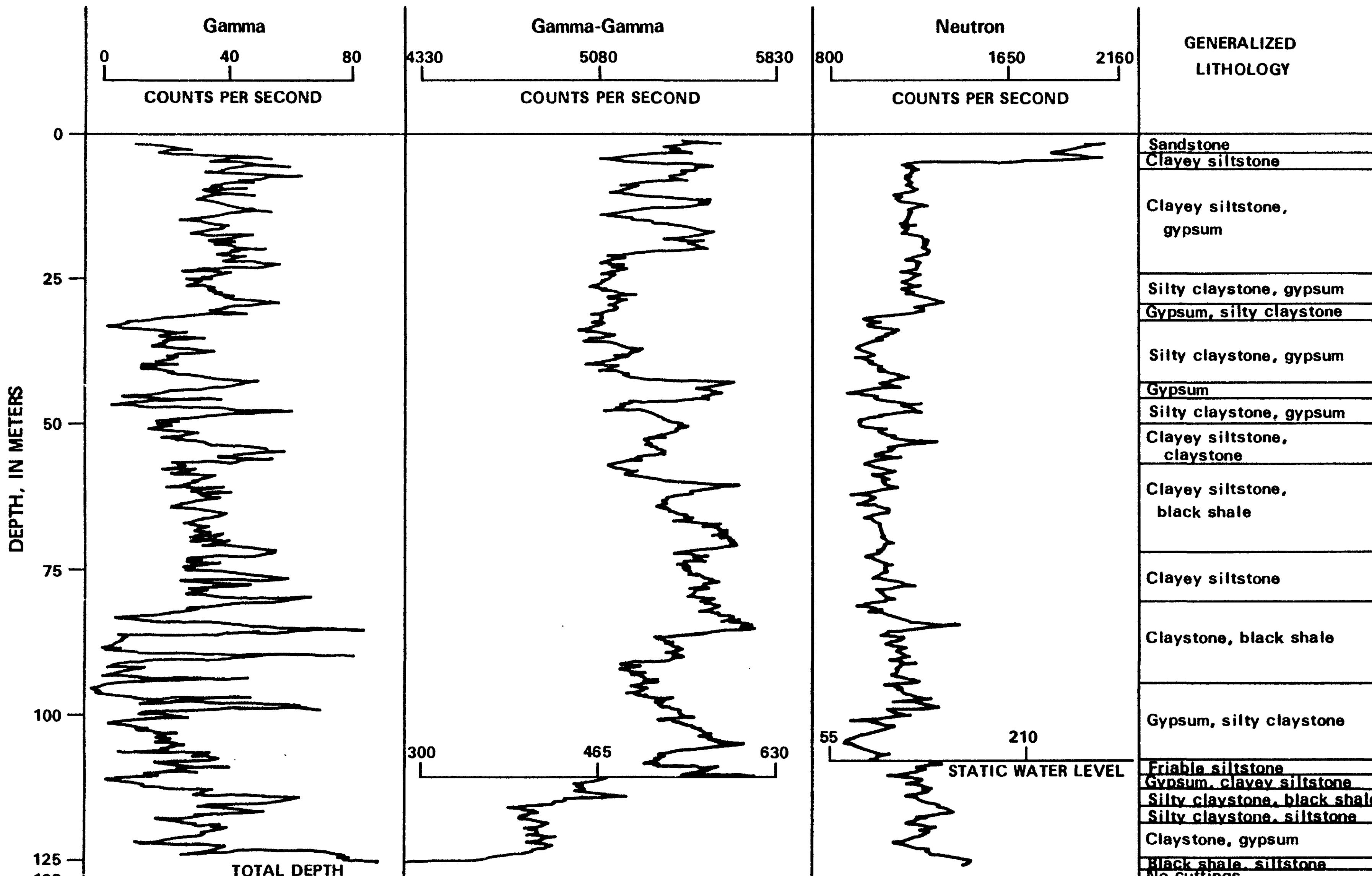


Figure 6.--Geophysical logs and general lithology for well DOE-5.

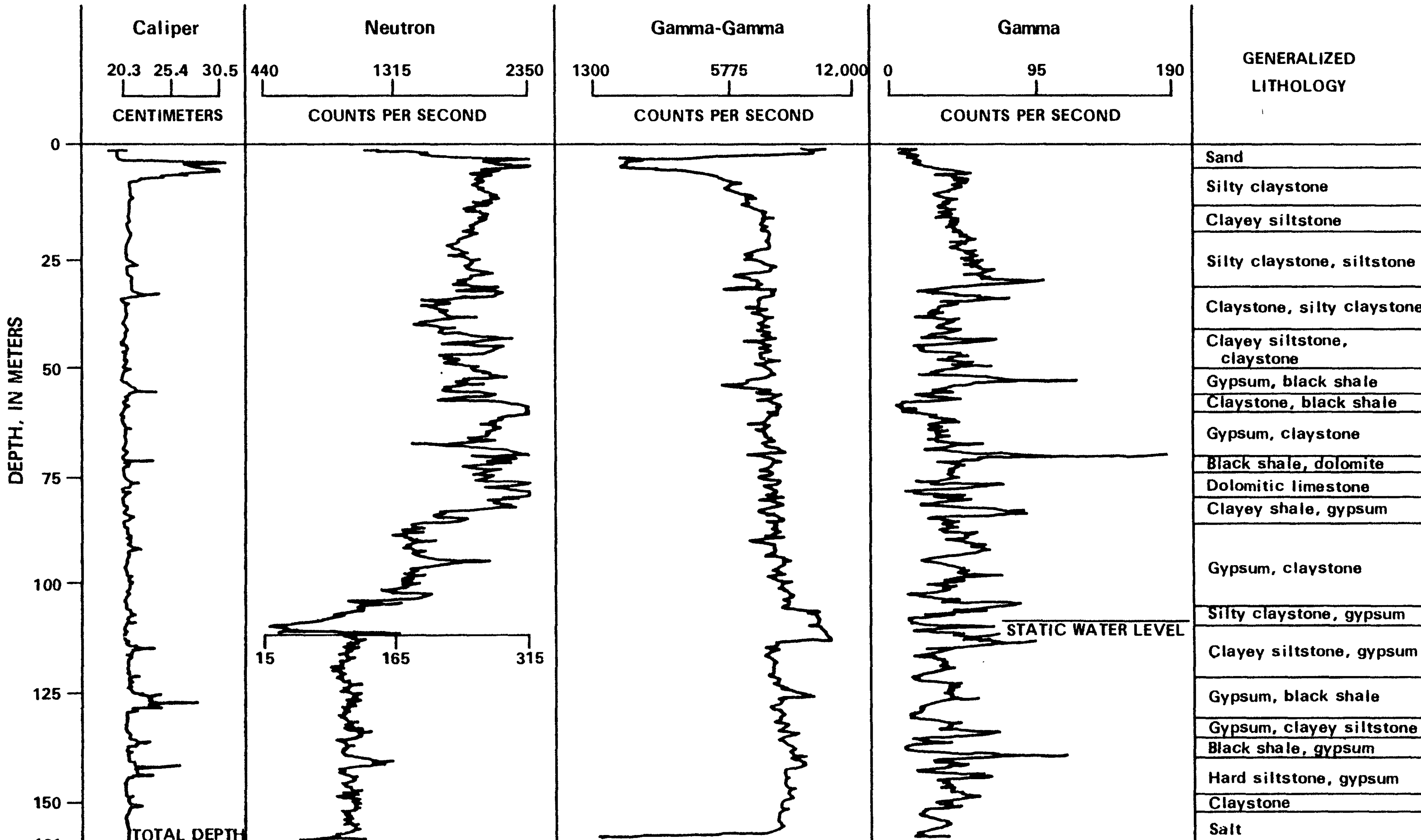


Figure 7.--Geophysical logs and general lithology for well DOE-6.

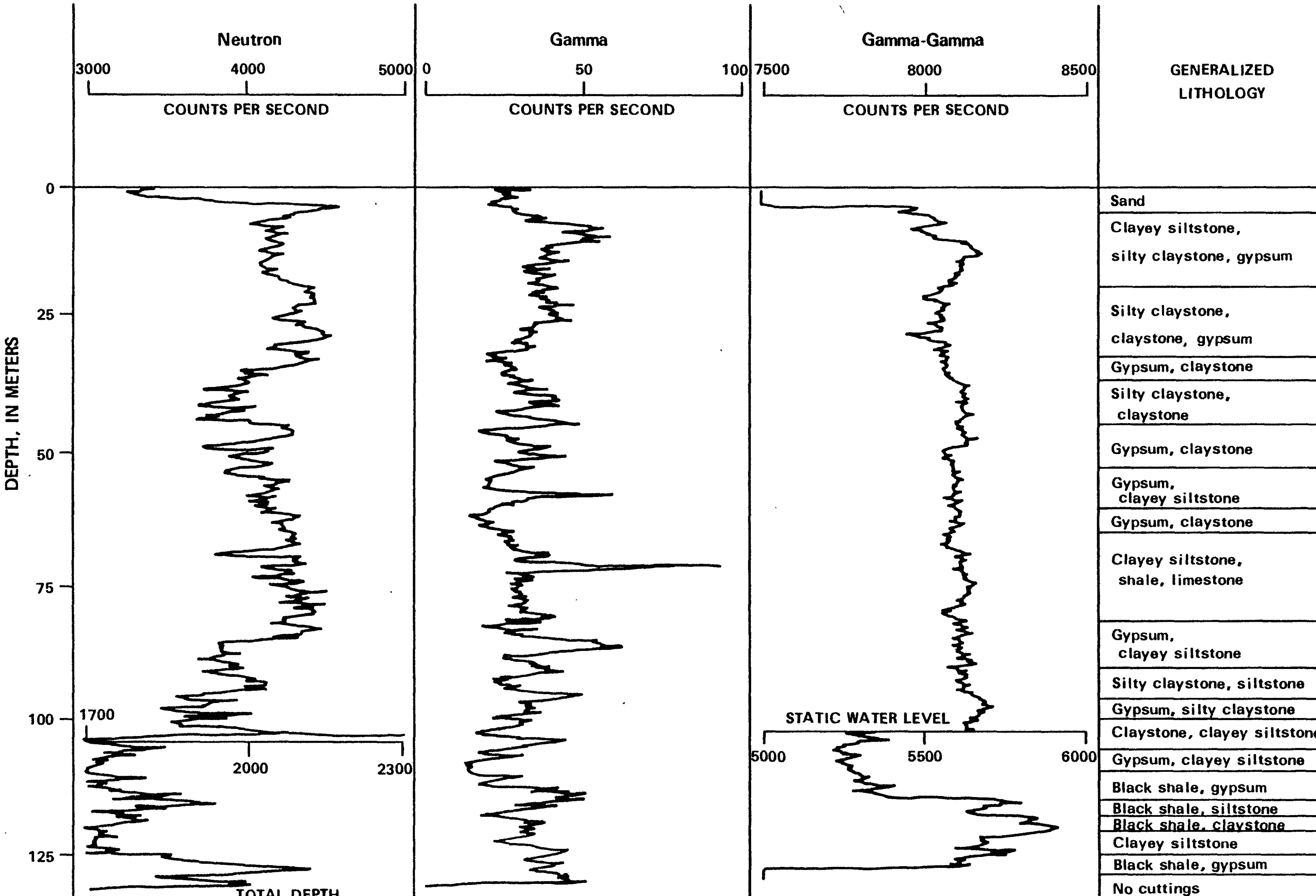


Figure 8.--Geophysical logs and general lithology for well DOE-7.

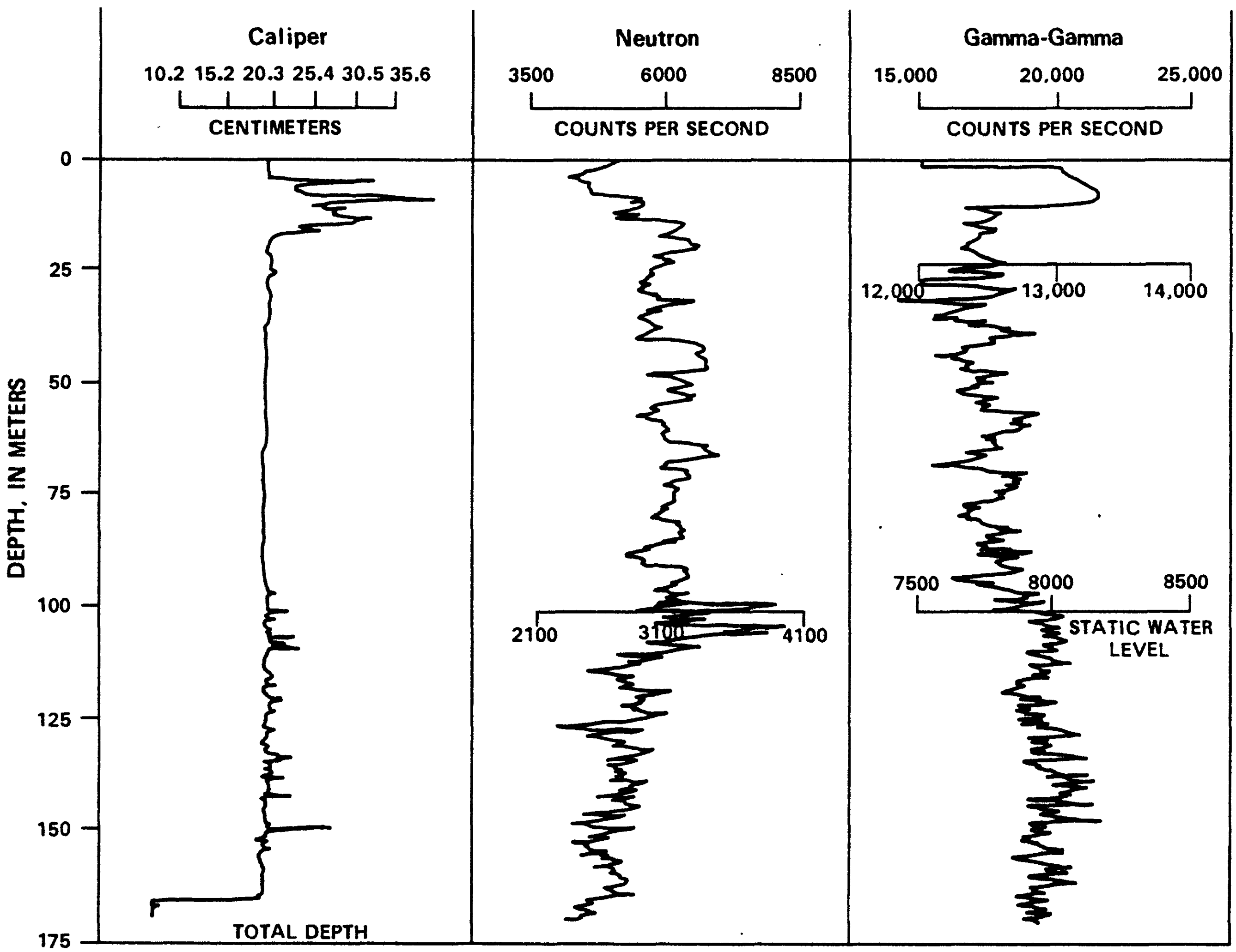


Figure 9.--Geophysical logs and general lithology for well DOE-8.

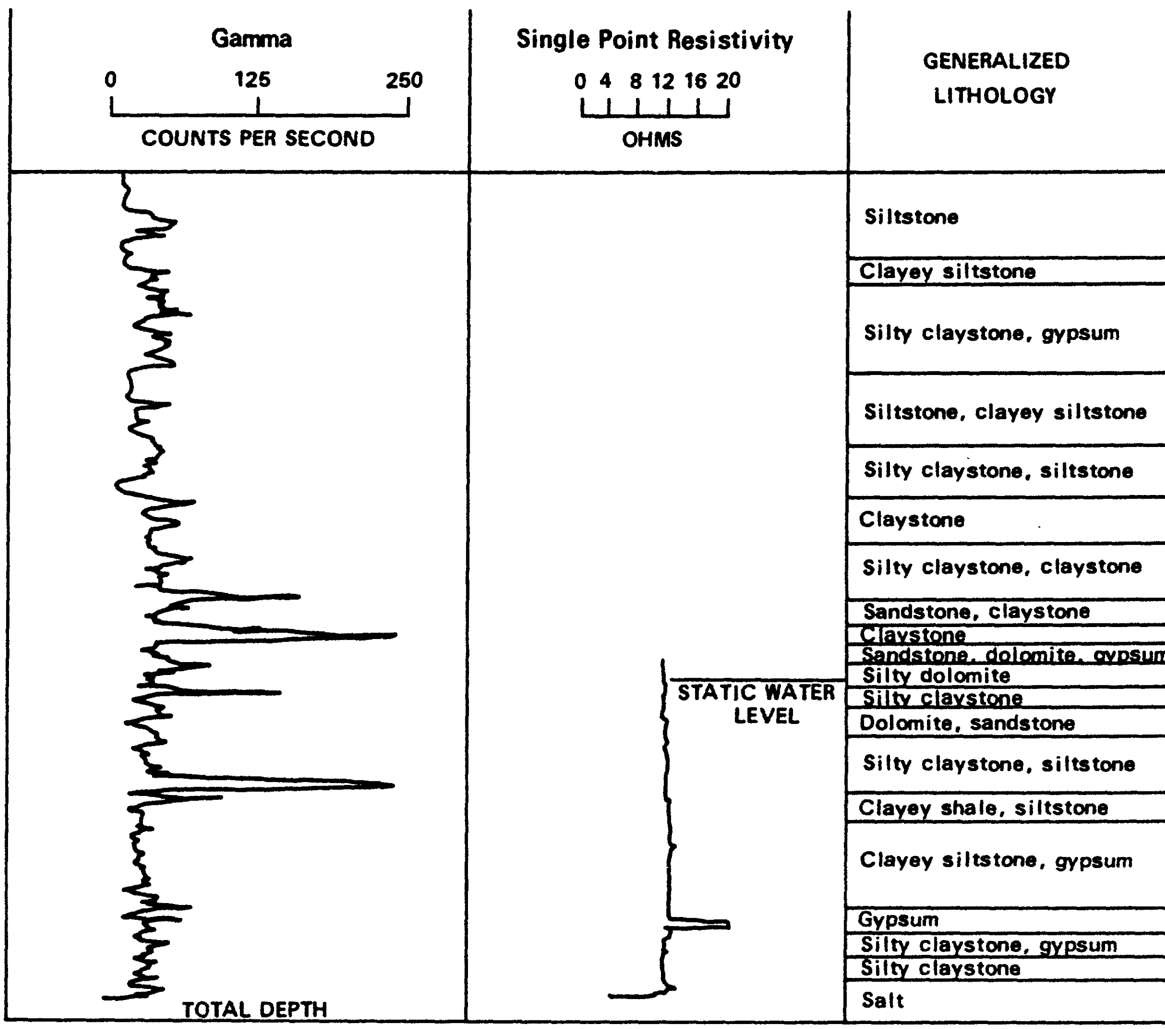


Figure 9.--Geophysical logs and general lithology for well DOE-8--Continued

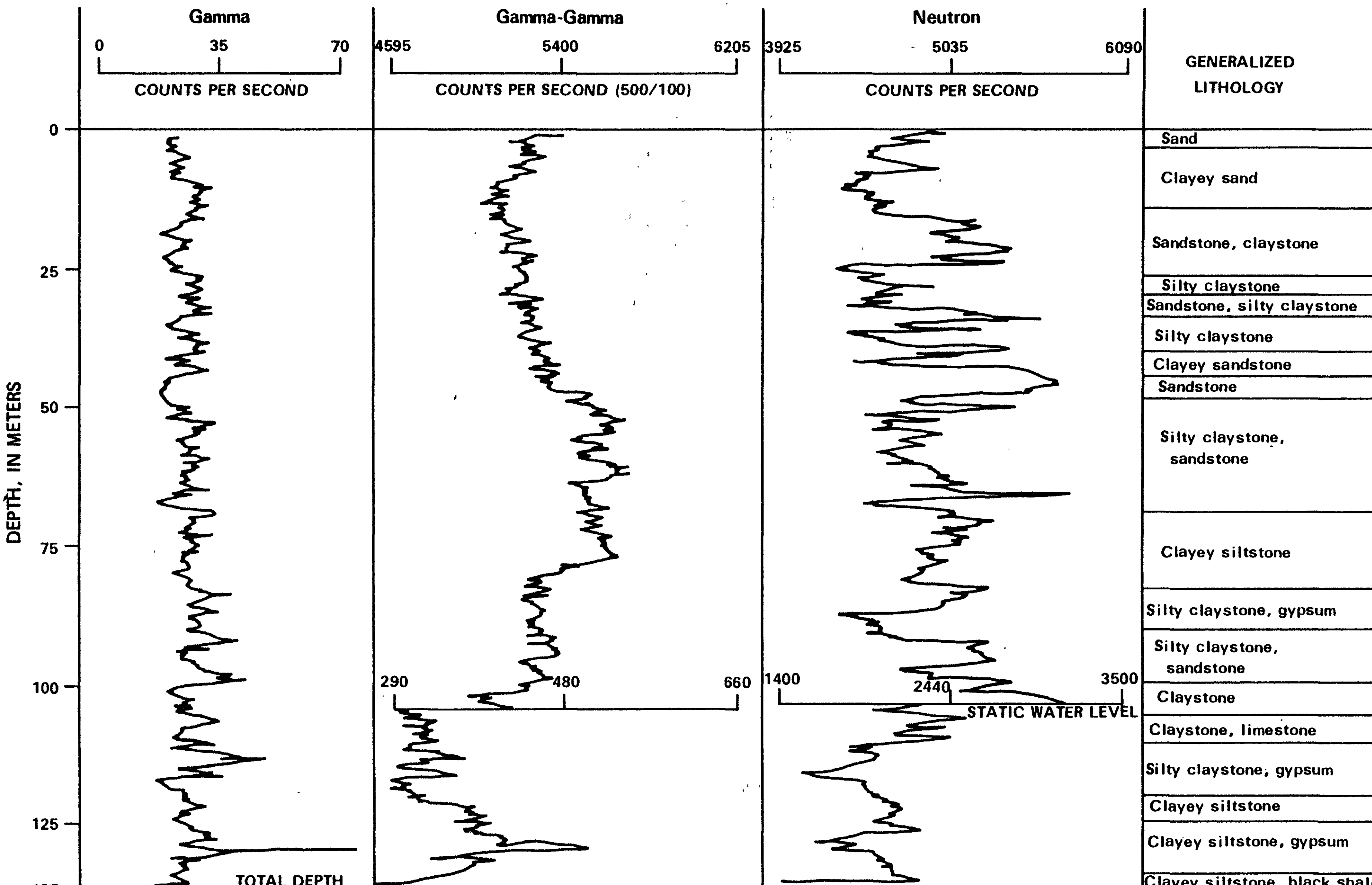


Figure 10.--Geophysical logs and general lithology for well DOE-9.

Table 3.--*Drilling fluids used in wells DOE-4 through 9*

[Not including fluids used for drilling surface-casing intervals; H_2S is hydrogen sulfide gas. Well depth is below land surface, in meters]

	DOE-4	DOE-5	DOE-6	DOE-7	DOE-8	DOE-9
Drilling fluid:						
Dry air	0-130	0-127	0-136	0-113	0-24	--------
Air mist	130-144.8	127-128.0	136-161.0	120-134.0	--------	--------
Polymer mud	144.8-161.2	---------	---------[1]	113-120	24-175	0-137
Drilling notes.	H_2S odor first detected at 89.9 meters.	Strong H_2S odor detected at 108.2 meters.	H_2S odor first detected at 82.9 meters. Some H_2S odor at 85 meters. Strong H_2S odor at 156.4 meters.	H_2S odor first detected at 106 meters.	At 46 meters, 36.3 kilograms soda ash added. At 104 meters, 11.4 kilograms lignosulphate added. At 109.4 meters, 4.5 kilograms of DISPAC[2] added. At 132 meters 45.4 kilograms of cottonseed added. At 132, 158, and 173 meters lost circulation. No H_2S noted during drilling.	No H_2S noted during drilling.

[1] Polymer was used to clean hole at a depth of 133.5 meters.

[2] Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

During drilling, drill-bit cuttings were monitored to detect zones of water saturation. Moisture was first detected at a depth of 108.2 m below land surface, but was not enough to produce a significant amount of water. The cuttings were dry from a depth of 109.1 to 117.7 m; there, the cuttings were again moist but the moisture still was not enough to produce a significant amount of water. From 127.4 to 134.7 m, returns were not obtained. At a depth of 144.8 m, cuttings resumed after 0.71 L of polymer mud was added to the mist tank to increase circulant viscosity. Hydrogen sulfide gas (H_2S) was first detected at a depth of 89.9 m; when the well was being pumped for hydraulic tests, H_2S odors became stronger as the test progressed.

Drilling of well DOE-5 began at the bottom of the surface casing using dry air as a circulating fluid. A 20-cm hole was drilled to a depth of 128 m using air mist as a circulating fluid. After geophysical logging, a well screen, 15 cm in diameter and 15.5 m in length, was welded to the 15-cm casing and lowered to a depth of 125.3 m. The screen was set on backfill; no cement secured the casing at any point.

During drilling, drill-bit cuttings were monitored to detect zones of saturation. Moisture was first detected at a depth of 108.2 m, and cuttings were moist for a thickness of 1 m. Before reaching the total depth of 128.0 m, two more thin zones with moisture were encountered at depths of 115.5 and 118.9 m; none of these zones produced a significant amount of water. During drilling, a strong H_2S odor was detected at a depth of 108.2 m; H_2S odors were also strong when the well was being pumped for hydraulic tests. Sparse greenish-yellow sulfur replacing gypsum occurred at depths of 70, 84, and 125 m. The H_2S is a product of microbacterial chemical reduction of sulfate to sulfide which is oxidized to sulfur (Jensen and Bateman, 1981).

Well DOE-6 was started in the same way as discussed in well DOE-4. Two previous unsuccessful attempts to drill DOE-6 are discussed later in this report. A 20-cm hole was drilled to a depth of 136 m using dry air; the 20-cm hole was then drilled to a total depth of 161.0 m using air mist. After geophysical logging, the hole was plugged with cement and back-filled from a depth of 148 to 161.0 m. The hole was cased to a depth of 133 m and tack-cemented at the bottom; a well screen, 10 cm in diameter, was installed from a depth of 133 to 148 m.

During drilling, the hole was difficult to clean out at a depth of 133.5 m, and the drill pipe pulled out of the hole at this point with difficulty. The driller unsuccessfully tried to clean the hole with air. Then a drilling fluid of polymer mud consisting of 1.4 L of powdered polymer, 1.4 L of liquid polymer, 11.4 L of a foaming agent, and 1,135.6 L of water was used to clean the hole.

During drilling, drill-bit cuttings were monitored to detect zones of saturation. Moisture was evident from a depth of 9.4 to 19.5 m; however, from a depth of 19.5 to 101.5 m, the cuttings were dry. Moisture again appeared at a depth of 101.5 m. None of these zones produced a significant amount of water. During drilling, some H_2S odor was detected at depths of 82.9 and 95 m; a strong H_2S odor occurred at 156.4 m, when the hole was blown dry with air. When the well was pumped for hydraulic tests, H_2S odors were strong. Replacement sulfur was found at depths of 112, 115, 120, and 136 m.

Well DOE-7 was drilled in the same way as for well DOE-5. A 20-cm hole was drilled to a depth of 113 m using dry air. At that depth, the drill pipe stuck in black clayey shale. A drilling fluid of polymer mud was needed to drill through the interval of black clayey shale to a depth of approximately 120 m. The 20-cm hole was then drilled to a total depth of 134.0 m, using air mist. After geophysical logging, a well screen, 15 cm in diameter and 15.5 m in length, was welded to the 15-cm casing and lowered to a depth of 133 m. The screen was set on one meter of backfill.

Cuttings were monitored to detect zones of saturation. Moisture was first detected at a depth of 8 m and again at depths of 19 and 59 m; however, cuttings were dry during other depth intervals. Cuttings were not returned at the total depth of 134 m. During drilling, a slight odor of H_2S was encountered at a depth of 106 m in an organic black claystone; when the well was being pumped for hydraulic tests, H_2S odors were strong. Sparse greenish-yellow sulfur replacing gypsum occurs at depths from 113 to 115 m.

Well DOE-8 was drilled to a total depth of 175 m. During drilling, the problems of hole caving, heaving clay, and lost circulation occurred. The hole caved at a depth of 24 m, and the drilling fluid had to be changed from dry air to polymer mud. Several tens of thousands of liters of water and several hundred liters of polymer mud were used to drill the remainder of the well down to the total depth. When drilling was complete, a sodium hypochlorite solution was added to the hole to break down the polymer mud. Other additives to the hole during drilling were 36.3 kg of soda ash (anhydrous sodium carbonate) at a depth of 46 m; 11.4 kg of lignosulfate at 104 m; 4.5 kg of a long chain polymer designed to reduce filter losses at 109.4 m, and 45.4 kg of cottonseed hulls to reduce lost circulation that occurred when the hole was 132 m deep. Lost circulation occurred during drilling at depths of 132, 158, and 173 m. At the depth of 173 m, approximately 3,200 L of drilling fluid dropped rapidly down the hole, probably into open fractures or a cavernous zone at an undetermined depth in the hole. In this well, the cement plug and backfill are from 160 to 175 m. The well was cased to a depth of 145 m and tack-cemented at the bottom; then a well screen, 10 cm in diameter, was installed from a depth of 145 to 160 m.

In well DOE-8, neither moisture nor the zone of saturation was detected during drilling because drilling fluids were used from a depth of 24 m to the total depth. During drilling, H_2S odor was not detected; when the well was being pumped for hydraulic tests, H_2S odors were strong.

For well DOE-9, a 20-cm hole was drilled to a depth of 137 m, using polymer mud as circulating fluid. After geophysical logging, a well screen, 15 cm in diameter and 15.5 m in length, was welded to the 15-cm casing and lowered to a depth of 137 m and set on bottom.

Neither moisture nor the zone of saturation was detected during drilling because of the use of a polymer drilling fluid to the total depth. During drilling, odors of H_2S were not detected; when the well was being pumped for hydraulic tests, H_2S odors were strong. When drilling was complete, sodium hypochlorite solution was added to the hole to break down the polymer mud.

Dangerous concentrations of H_2S (10 ppm or more; National Institute for Occupational Safety and Health, 1977, p. 2) were detected during drilling and hydraulic testing of the saturated part of the cap rock. During drilling of wells DOE-4 through 7, H_2S was diluted by compressed air; polymer mud used in drilling wells DOE-8 and 9 tended to seal off the gas. Greater and more dangerous concentrations of H_2S occurred during hydraulic testing; a detector was used to monitor concentrations. The detector sensor was placed near the discharge pipe, which was connected to a meter and horn alarm located near the well head. The background concentration of H_2S at the discharge pipe generally was about 20 ppm, but on many occasions exceeded 100 ppm on the upper end of the scale on the detector meter. Hydrogen sulfide concentrations between 800 and 1,000 ppm were measured with high-range equipment during pumping of well DOE-2 (Rush and others, 1980, p. 5).

The locations of the three abandoned test holes are shown in figure 2. Abandoned hole DOE-6A was drilled to a depth of 23.5 m. The hole was abandoned when one of the slips, a tool used to connect or disconnect drill pipe, fell into the hole and could not be recovered economically. The lithology of the hole corresponded to that in well DOE-6. The hole was spudded 4.8 m northeast of the completed well, DOE-6.

Abandoned hole DOE-10 was drilled to a depth of 55.5 m. This hole was abandoned when the drill pipe became stuck on a trip out the hole. Drilling equipment left in the hole at a depth of 51.2 m consists of one 17.5-cm bit and a 0.4 m drill pipe coupling. All cuttings that were returned to the surface during drilling were dry.

Abandoned hole DOE-8A was drilled to a depth of 124.4 m before lost circulation and hole caving caused this hole to be abandoned. All of the pipe, drill collars, and bit were pulled out of the hole before moving to the well DOE-8 site, 31 m northeastward. In several intervals, no cuttings were returned, and lost circulation occurred, probably due to cavernous conditions or fractures in the unsaturated part of the cap rock.

LITHOLOGY

Lithologic units penetrated in test wells DOE-4 through 9 and in abandoned holes DOE-8A and 10 are summarized in tables 4 through 11. Depth intervals are based on both cuttings and geophysical logs. Geophysical logs for wells DOE-4 through 9 are presented in figures 5 through 10. Correlations across Salt Valley were not possible because of the complex geology. Lithologies above and below static water level consist of silty claystone, clayey siltstone, claystone, and gypsum; also minor to major amounts of dolomite and black clayey shale. The silt was predominantly selenite. At holes DOE-8A and 10, a very fine- to fine-grain sandstone containing some limestone occurs. These sandstones are probably the upper member of the Hermosa Formation, based on their lithologic similarity to nearby outcrops of the Hermosa Formation in the valley floor (R. J. Hite, U.S. Geological Survey, oral commun., 1981).

At well DOE-4, the cap rock-salt interface occurs at a depth of 161 m below land surface as evidenced by: (1) a decrease in air pressure from 861.9 to 517.1 kPa at a depth of 157.6 m; (2) an increase in specific conductance of the drilling fluid; (3) a lack of returned drill cuttings; and (4) salty tasting mud. At well DOE-6, the cap rock-salt interface occurred at a depth of 154 m below land surface, based on gamma, gamma-gamma, and neutron logs. At well DOE-8, the interface occurred at a depth of 165 m below land surface, based on geophysical logs and salty drilling fluids. Wells DOE-5, 7, and 9 were limited to the upper part of the cap rock; therefore, salt was not penetrated.

A generalized geohydrologic section of wells DOE-1, 2, 4, 6, and 8, showing the cap rock-salt interface and static water level, is presented in figure 11. This figure shows that the altitude of the cap rock-salt interface is highest at well DOE-6, and that the interface declines in altitude at the sides of Salt Valley.

HYDRAULIC TESTING

General Onsite Procedures

Cleaning, developing, pumping, testing, and collecting water samples were accomplished by temporarily setting a 3,730-watt submersible pump in either the deep or shallow well at a given site and monitoring water-level changes in both wells. To increase pumping time, the discharge rates for test pumping were less than 0.5 L/s. Testing of wells DOE-4 through 9 did not include studies of the lost circulation zones that occurred above the zone of saturation.

Table 4.--*Lithologic log, well DOE-4*

[Silt is selenite; clay is calcareous swelling clay; m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sandstone (caliche ?), light brown fine quartz sand, calcareous, hard.	0- 5	1,464-1,459	5
Gypsum, alabastrine, white to gray, some coarse selenite.	5- 8	1,459-1,456	3
Silty claystone and clayey siltstone, pale brown, silt is selenite, swelling calcareous clay, some alabaster and coarse selenite.	8- 12	1,456-1452	4
Gypsum, alabastrine, gray to white; and silty claystone and clayey siltstone, pale brown, silt is gypsum, very calcareous swelling clay.	12- 23	1,452-1,441	11
Silty claystone, pale brown to pale yellowish gray; and gypsum, alabastrine and coarse selenite.	23- 30	1,441-1,434	7
Calcareous siltstone, siltstone, and silty claystone, light gray to medium gray.	30- 37	1,434-1,427	7
Hard siltstone or dolomite, medium gray, slightly calcareous; coarse selenite; silty claystone; hard clayey siltstone; some black shale.	37- 47	1,427-1,417	10
Hard clayey siltstone, light brownish gray; silty claystone, medium gray, and some black shale, some coarse selenite.	47- 56	1,417-1,408	9
Silty claystone, medium gray; some coarse selenite; sparse black shale.	56- 64	1,408-1,400	8
Silty claystone, medium gray; black shale, some hard clayey siltstone.	64- 73	1,400-1,391	9
Silty claystone and clayey siltstone, medium gray.	73- 83	1,391-1,381	10

Table 4.--*Lithologic log, well DOE-4*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Clayey siltstone, medium gray; alabaster and coarse selenite; clayey shale, dark gray to black.	83- 92	1,381-1,372	9
Alabaster, light gray to medium gray, and hard silt-stone, light brownish gray, some coarse selenite.	92-100	1,372-1,364	8
Silty claystone, light gray, alabaster and selenite.	100-106	1,364-1,358	6
Friable siltstone, light gray, coarse silt; poorly cemented gypsum grains; sparse black organic fragments.	106-108	1,358-1,356	2
Selenite and alabaster, medium gray, some clayey siltstone, sparse black shale, organic dolomite and pyrite.	108-111	1,356-1,353	3
Clayey siltstone and silty claystone, light to medium gray, some coarse selenite, sparse black shale.	111-124	1,353-1,340	13
Claystone, dark gray, some shaly.	124-128	1,340-1,336	4
Alabaster, coarse selenite, some black shale, some hard silicified grayish orange siltstone, poor cuttings.	128-150	1,336-1,314	22
Hard siltstone, light gray calcareous and silica cement.	150-158	1,314-1,306	8
Salt.	158-161 (total depth)	1,306-1,303	3

Table 5.--*Lithologic log, well DOE-5*

[Silt is selenite; clay is calcareous swelling clay; m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sandstone (caliche ?), moderate reddish orange, very fine to medium-grained subround to round quartz grains, calcareous.	0- 4	1,464-1,460	4
Clayey siltstone, pale yellowish brown, silt is gypsum, calcareous swelling clay.	4- 6	1,460-1,458	2
Hard clayey siltstone and silty claystone, pale yellowish brown, alabaster, and coarse selenite.	6- 24	1,458-1,440	18
Silty claystone, pale yellowish brown, some coarse selenite.	24- 29	1,440-1,435	5
Coarse selenite and silty claystone, medium gray to light gray.	29- 32	1,435-1,432	3
Silty claystone and clayey siltstone, light gray, some alabaster and coarse selenite.	32- 43	1,432-1,421	11
Alabaster, light gray, medium dark gray, white, sparse selenite.	43- 45	1,421-1,419	2
Silty claystone, medium light gray, some alabaster and coarse selenite.	45- 50	1,419-1,414	5
Clayey siltstone and silty claystone, light gray to dark gray, some black clayey shale.	50- 57	1,414-1,407	7
Clayey siltstone and claystone, light gray, some dark gray, some black clayey shale, sparse greenish yellow sulfur.	57- 72	1,407-1,392	15
Hard clayey siltstone, light gray.	72- 80	1,392-1,384	8

Table 5.--*Lithologic log, well DOE-5*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Claystone, light gray to dark gray, coarse selenite, some alabaster, some dark gray clayey siltstone and black clayey shale with sparse pyrite, some silica veinlets, organic material.	80- 94	1,384-1,370	14
Alabaster, white to dark gray; silty claystone, black to dark gray; selenite, light gray, and claystone, light gray; organic sparse pyrite.	94-107	1,370-1,357	13
Friable siltstone, light gray, some cemented, some coarse selenite.	107-109	1,357-1,355	2
Alabaster and clayey siltstone, medium gray, some coarse selenite.	109-111	1,355-1,353	2
Silty claystone and clayey siltstone, medium light gray, and black clayey shale.	111-114	1,353-1,350	3
Silty claystone and clayey siltstone, medium light gray.	114-117	1,350-1,347	3
Claystone, medium light gray, clayey siltstone, light brownish gray; coarse selenite.	117-124	1,347-1,340	7
Clayey black shale; clayey siltstone, pale yellowish brown to black; some coarse selenite and alabaster; sparse greenish yellow sulfur, sparse pyrite, organic.	124-126	1,340-1,338	2
No sample.	126-128 (total depth)	1,338-1,336	2

Table 6.--*Lithologic log, well DOE-6*

[Silt is gypsum; clay is calcareous swelling clay; m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sand.	0- 5	1,466-1,461	5
Silty claystone, pale yellowish brown, silt is gypsum, some coarse selenite, sparse dipyramidal quartz crystals, trace of clear fluorite, calcareous swelling clay.	5- 14	1,461-1,452	9
Clayey siltstone, pale yellowish brown, sparse quartz dipyramids, slightly calcareous.	14- 20	1,452-1,446	6
Silty claystone, clayey siltstone, light gray, and coarse selenite.	20- 32	1,446-1,434	12
Silty claystone and claystone, medium gray, some alabaster and coarse selenite, some clayey black shale.	32- 42	1,434-1,424	10
Clayey siltstone, silty claystone, medium gray, black clayey shale, sparse dark gray dolomitic limestone.	42- 51	1,424-1,415	9
Gypsum, alabaster and coarse selenite, white, some gray, some fissile clayey shale.	51- 57	1,415-1,409	6
Claystone, medium gray, some selenite, some black fissile shale.	57- 60	1,409-1,406	3
Alabaster, very light gray, some coarse selenite, some claystone.	60- 72	1,406-1,394	12
Shale, dark gray to black, fissile, clayey, and hard dark gray silty dolomite, organic.	72- 74	1,394-1,392	2
Dolomitic limestone, dark gray, some medium gray claystone.	74- 81	1,392-1,385	7

Table 6.--*Lithologic log, well DOE-6*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Clayey shale, dark gray to black; alabaster, very light gray; coarse selenite, some dolomite, medium gray, with tiny vugs; trace pyrite.	81- 87	1,385-1,379	6
Selenite, white to very light gray, and claystone, medium gray, some clayey siltstone.	87-107	1,379-1,359	20
Silty claystone, medium gray and coarse selenite; some alabaster, medium gray, with tiny vugs; trace of black organic material, trace greenish yellow sulfur.	107-111	1,359-1,355	4
Clayey siltstone, medium gray; some alabaster, very light gray; trace greenish yellow sulfur.	111-123	1,355-1,343	12
Alabaster white to medium gray, and claystone, medium light gray, trace black clayey shale.	123-133	1,343-1,333	10
Alabaster and coarse selenite, and clayey siltstone, medium light gray; some black shale; trace greenish yellow sulfur.	133-137	1,333-1,329	4
Black clayey shale, coarse selenite, and alabaster.	137-141	1,329-1,325	4
Hard siltstone, medium light gray, silica cement, slightly calcareous, some dipyramidal quartz crystals.	141-142	1,325-1,324	1
Alabaster, medium light gray, hard siliceous siltstone, and black shale.	142-151	1,324-1,315	9
Claystone, light medium gray.	151-154	1,315-1,312	3
Salt.	154-161 (total depth)	1,312-1,305	7

Table 7.--*Lithologic log, well DOE-7*

[Silt is selenite; clay is calcareous swelling clay; m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sand (caliche ?), pale yellowish brown, very fine to fine subrounded quartz, very calcareous.	0- 5	1,466-1,461	5
Clayey siltstone and silty claystone, pale yellowish-brown, laminated, silt is selenite, calcareous swelling clay, trace of quartz dipyramids.	5- 19	1,461-1,447	14
Silty claystone, pale yellowish brown, some alabaster.	19- 33	1,447-1,433	14
Coarse selenite and alabaster, clear to light gray, and silty claystone, medium gray.	33- 37	1,433-1,429	4
Silty claystone, medium gray, and claystone and silty claystone, medium dark gray.	37- 45	1,429-1,421	8
Selenite, fine to coarse, light gray to medium gray; some claystone, medium gray; some black clayey shale.	45- 53	1,421-1,413	8
Selenite, fine to coarse, light gray, and clayey siltstone and silty claystone, medium gray.	53- 59	1,413-1,407	6
Alabaster, light gray, some coarse selenite, some claystone, medium gray.	59- 65	1,407-1,401	6
Clayey siltstone, light gray, some coarse selenite, some black clayey shale, some hard clayey limestone or dolomite, dark gray.	65- 82	1,401-1,384	17
Selenite, clear, coarse, and clayey siltstone, light gray, some black clayey shale.	82- 90	1,384-1,376	8

Table 7.--*Lithologic log, well DOE-7*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Silty claystone and clayey siltstone, medium gray, and black clayey shale, sparse clear quartz dipyramids.	90- 96	1,376-1,370	6
Gypsum, alabaster and coarse selenite, and silty claystone, sparse quartz dipyramids.	96- 99	1,370-1,367	3
Claystone and clayey siltstone, medium gray, and black organic claystone, some coarse selenite, some black clayey shale.	99-106	1,367-1,360	7
Alabaster, medium light gray, and coarse selenite, some clayey siltstone, sparse black dolomitic limestone, sparse pyrite in gypsum, sparse gypsum veinlets.	106-110	1,360-1,356	4
Black clayey shale, slightly to noncalcareous clay, some alabaster, pale yellowish brown, sparse black shale, sparse pyrite, sparse gypsum veins, sparse coarse selenite, sparse greenish yellow sulfur replacing coarse selenite and alabaster.	110-115	1,356-1,351	5
Black clayey shale and siltstone, pale yellowish brown, sparse greenish yellow sulfur, sparse dipyramidal quartz in silica veinlet, sparse pyrite in quartz-selenite-pyrite veinlet.	115-118	1,351-1,348	3
Black clayey shale and claystone, medium gray, some clayey dolomitic limestone.	118-120	1,348-1,346	2
Clayey siltstone, light gray.	120-125	1,346-1,341	5
Black clayey shale, some limestone with pyrite, some coarse selenite and alabaster.	125-129	1,341-1,337	4
No cuttings returned.	129-134 (total depth)	1,337-1,332	5

Table 8.--*Lithologic log, well DOE-8*

[From 0-98 m, silt and sand are quartz, from 98-170 m, silt is gypsum, m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Siltstone, pale reddish brown, friable, subangular to subround coarse quartz silt, calcareous swelling clay matrix.	0- 11	1,469-1,458	11
Siltstone, grayish yellow, hard, silica cement, non-calcareous, coarse quartz silt.	11- 18	1,458-1,451	7
Clayey siltstone, light red to very pale orange, some siltstone, calcareous swelling clay matrix.	18- 23	1,451-1,446	5
Silty claystone, pale reddish brown, some white gypsum crystals.	23- 41	1,446-1,428	18
Hard siltstone, clayey silt-stone, and silty claystone, pale reddish brown to very pale orange, trace of green chlorite.	41- 55	1,428-1,414	14
Silty claystone, pale reddish, some white siltstone.	55- 66	1,414-1,403	11
Claystone, medium gray, medium light gray, and yellowish gray.	66- 76	1,403-1,393	10
Silty claystone, yellowish gray, and claystone, medium light gray.	76- 87	1,393-1,382	11
Sandstone, yellowish gray silt to fine quartz sand, some medium grains, and silty claystone, light gray.	87- 92	1,382-1,377	5
Claystone, medium dary gray.	92- 96	1,377-1,373	4
Sandstone, yellowish gray to medium light gray, hard, slightly calcareous.	96- 98	1,373-1,371	2
Dolomite, black, laminated, dense, fine grained, sparse selenite.	98-100	1,371-1,369	2

Table 8.--*Lithologic log, well DOE-8*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Silty dolomite, medium dark gray, dense, fine grained, silt is gypsum.	100-105	1,369-1,364	5
Silty claystone, medium gray, some black to dark gray dolomite.	105-109	1,364-1,360	4
Dolomite and shaly dolomite, black; some hard fine-grained sandstone.	109-115	1,360-1,354	6
Silty claystone, medium gray, and clayey siltstone, very light gray.	115-127	1,354-1,342	12
Clayey shale, dark gray, very calcareous, and clayey siltstone, very light gray.	127-129	1,342-1,340	2
Clayey siltstone, light gray, and silty claystone, medium gray, silt is gypsum, some coarse selenite.	129-132	1,340-1,337	3
Clayey siltstone and silty claystone, very light gray, silt is gypsum, some coarse selenite.	132-151	1,337-1,318	19
Selenite, coarse.	151-155	1,318-1,314	4
Silty claystone, clayey siltstone and selenite, medium gray.	155-161	1,314-1,308	6
Silty claystone, medium gray.	161-165	1,308-1,304	4
Salt (from geophysical log).	165-175 (total depth)	1,304-1,294	10

Table 9.--*Lithologic log, well DOE-9*

[Silt is quartz from 0-90 m; silt is selenite from 90-137 m; clay is calcareous swelling clay, m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sand (caliche ?), light brown, very fine to fine grained, subround to round quartz, calcareous.	0- 4	1,469-1,465	4
Clayey sand, pale reddish brown, very fine to fine grained, subround to round quartz, calcareous swelling clay.	4- 15	1,465-1,454	11
Sandstone, very light gray, very fine to medium subangular to round quartz, and clay, pale reddish brown, calcareous swelling clay.	15- 20	1,454-1,449	5
Sandstone, very pale orange to yellowish gray, very fine to fine grained quartz, and some claystone, yellowish gray to pale reddish brown.	20- 27	1,449-1,442	7
Silty claystone, pale reddish brown.	27- 30	1,442-1,439	3
Sandstone as in 20- 27 m and silty claystone as in 27- 30 m.	30- 34	1,439-1,435	4
Silty claystone, moderate reddish brown.	34- 41	1,435-1,428	7
Clayey sandstone, very pale orange, very fine to fine subangular to subround quartz, trace of moderate green chlorite.	41- 45	1,428-1,424	4
Sandstone, very pale orange, very fine to medium subangular to subround quartz, trace of green chlorite.	45- 49	1,424-1,420	4
Silty claystone, pale red to pale reddish brown, some sandstone.	49- 68	1,420-1,401	19

Table 9.--*Lithologic log, well DOE-9*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Clayey sandstone, yellowish gray, very fine to fine subangular to subround quartz.	68- 69	1,401-1,400	1
Silty claystone, pale yellowish brown.	69- 83	1,400-1,386	14
Clayey siltstone, yellowish gray.	83- 90	1,386-1,379	7
Silty claystone, medium dark gray, silt is selenite, some coarse selenite, calcareous swelling clay.	90- 97	1,379-1,372	7
Silty claystone, medium gray, calcareous, and sandstone, medium gray, very fine to fine quartz.	97- 99	1,372-1,370	2
Claystone, medium gray.	99-106	1,370-1,363	7
Claystone, medium gray, and some dolomitic limestone, medium gray, dense, fine grained.	106-111	1,363-1,358	5
Silty claystone, light olive gray, silt is selenite, sparse coarse selenite.	111-120	1,358-1,349	9
Clayey siltstone, light olive gray.	120-125	1,349-1,344	5
Clayey siltstone, light olive gray, and some coarse selenite.	125-134	1,344-1,335	9
Clayey siltstone, medium gray, sparse black clayey shale.	134-137	1,335-1,332	3
	(total depth)		

Table 10.--*Lithologic log, abandoned hole DOE-8A*

[Silt and sand are quartz; clay is calcareous swelling clay, bottom of formation was not encountered; m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Silt.	0- 12	1,470-1,458	12
Siltstone, pale reddish brown, some fine grained sandstone.	12- 17	1,458-1,453	5
Siltstone, pale red to pale reddish brown, some grayish orange pink silty dolomite.	17- 33	1,453-1,437	16
Claystone, pale reddish brown, some silty limestone, light yellowish gray.	33- 37	1,437-1,433	4
Silty limestone, pale red.	37- 42	1,433-1,428	5
Silty shale, moderate reddish brown, and pale red to white silty dolomitic limestone.	42- 46	1,428-1,424	4
Dolomite, moderate reddish brown, some circular to elongate algal fossils, and grayish red clayey siltstone.	46- 55	1,424-1,415	9
Sandstone, yellowish gray, very fine grained, slightly calcareous.	55- 60	1,415-1,410	5
Clayey siltstone, pale reddish brown, slightly calcareous.	60- 61	1,410-1,409	1
Sandstone, light yellowish gray, very fine to fine grained, calcareous white matrix.	61- 63	1,409-1,407	2
Silty claystone, pale reddish brown.	63- 65	1,407-1,405	2
Sandstone, moderate reddish orange to yellowish gray, fine to medium grained, calcareous clay matrix.	65- 76	1,405-1,394	11
Sandstone, moderate orange pink, friable, poorly cemented.	76- 78	1,394-1,392	2
Silty claystone, moderate reddish brown, some silty limestone.	78- 81	1,392-1,389	3

Table 10.--*Lithologic log, abandoned hole DOE-8A*--Continued

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sandstone, yellowish gray, fine to medium grained, calcareous clay matrix.	81- 84	1,389-1,386	3
Silty claystone and clayey siltstone, light grayish orange.	84- 85	1,386-1,385	1
Sandstone, very pale orange, fine to medium grained, manganese oxide stains.	85- 87	1,385-1,383	2
Sandy claystone, grayish orange.	87- 88	1,383-1,382	1
Sandstone, light grayish orange, friable, fine grained.	88- 92	1,382-1,378	4
Sandstone, light yellowish to light grayish orange, calcareous clay matrix.	92-102	1,378-1,368	10
No cuttings returned.	102-121	1,368-1,349	19
Siltstone, medium light gray, hard, silica matrix, slightly calcareous, some medium gray limestone.	121-124	1,349-1,346	3
	(total depth)		

Table 11.--*Lithologic log, abandoned hole DOE-10*

[m = meter]

Lithology	Depth interval below land surface (m)	Altitude interval above sea level (m)	Thickness (m)
Sand, (caliche ?), grayish orange pink, very fine to fine quartz, calcareous.	0- 4	1,470-1,466	4
Sandstone, grayish orange, hard, very fine subangular quartz, calcareous.	4- 10	1,466-1,460	6
Sandstone, hard, and clayey sandstone, grayish orange, very fine subangular quartz.	10- 19	1,460-1,451	9
Sandstone, medium gray to light olive gray, some grayish orange, very fine subangular quartz, calcareous, some manganese oxide stains.	19- 23	1,451-1,447	4
Sandstone, (same as above) and some black to dark gray slightly calcareous siltstone, some swelling clay.	23- 33	1,447-1,437	10
Sandstone, (same as above) and some medium gray limestone.	33- 37	1,437-1,433	4
Sandstone, same as interval 19- 23 m, and black to dark gray slightly calcareous siltstone.	37- 46	1,433-1,424	9
Sandstone, (same as above) stone is grayish orange.	46- 51 (total depth)	1,424-1,419	5

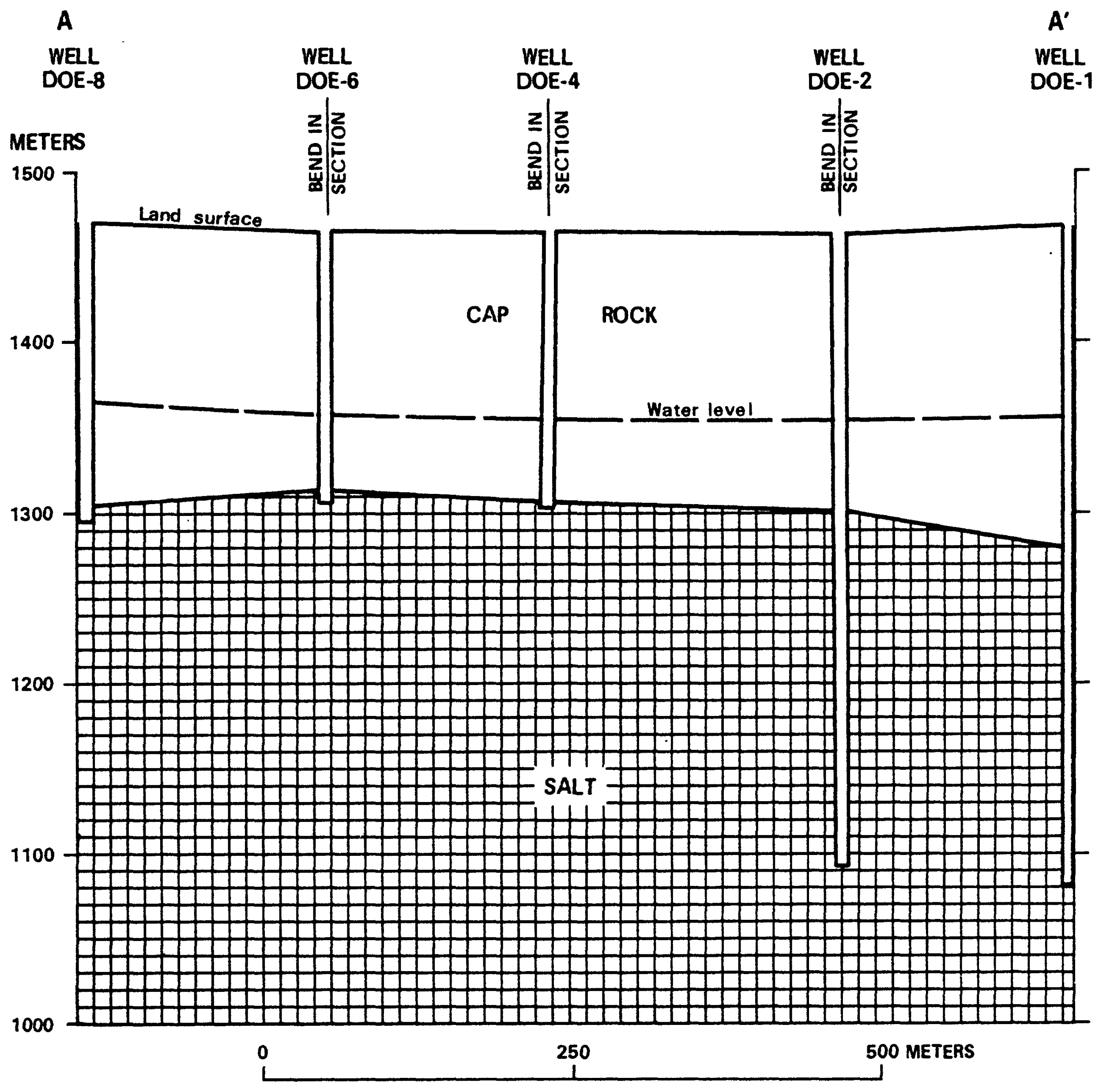


Figure 11.--Generalized geohydrologic section of wells DOE-1, 2, 4, 6, and 8 showing land surface, water level, cap rock-salt interface, and well depth (see fig. 3 for line of section).

A considerable amount of time was necessary to clean the drilling fluid from the test holes because they had not been bailed or pumped out after drilling operations; 2 to 4 months elapsed between drilling the first hole and the completion of hydraulic testing. Some fluid invasion probably occurred for short distances into the formation; however, because of minimal permeability of the cap rock and light weight of the drilling fluid, the amount was probably very small. The biggest problem in cleaning the wells was created by their small yields. The wells could only be pumped for short periods of time before water levels reached the pump intake. When this happened, the pump had to be shut off to allow the water level to recover, which required several hours for most of the wells.

During the pumping tests, water levels in both the deep and shallow wells were monitored by transducers or by direct measurement with tapes or electrical devices (Weir and Nelson, 1976). Typically, a high-range transducer (0-345 kPa) was set just above the pump intake in the pumped well. A low-range transducer (0-103 kPa) was set just below the water surface in the observation well. Depth of this setting depended on how much drawdown was observed in the well during cleaning and developing. The transducer output was recorded on continuous-trace strip-chart recorders for the pumped well and observation well.

Analytical Methods

Aquifer transmissivity and hydraulic conductivity were determined from analysis of pumping-test data by following standard methods (Ferris and others, 1962; Heath and Trainer, 1968; Lohman, 1972; Walton, 1970; and Weeks, 1978). In wells DOE-4 through 9, the installation of well screens facilitated pumping tests, and the drilling of pairs of wells close together allowed observation wells to be used in standard pumping-test procedures.

The Theis formula for recovery (Ferris and others, 1962, p. 100-103) was applicable to every well, as it was for wells DOE-1 through 3 (Rush and others, 1980, p. 12). The Jacob straight-line method (Jacob, 1950 and Lohman, 1972) was applicable to every well except well DOE-7 for which drawdown data was not obtained because the water level declined to the pump intake within minutes. The Jacob straight-line method and the Theis recovery method were developed for artesian conditions. These methods were used to determine the hydraulic properties of the cap rock, because the very low hydraulic conductivity in the cap rock allows artesian conditions to dominate in a short test, even though declines in head with depth indicate water-table conditions.

A time criterion was used in each analysis after which wellbore storage effects diminish so that the drawdown or recovery test data satisfy the Theis equation. This time criterion is given by the equation:

$$t > \frac{25r_c^2}{T}$$

where t = time in days, r_c = radius of well casing in meters, and T = transmissivity, in m^2/d (Weeks, 1978, p. 23). The transmissivity used in this calculation was that determined by the Theis recovery method.

For those pumping tests involving observation wells, the ratio method was used to evaluate the vertical hydraulic conductivity in the confining beds (Neuman and Witherspoon, 1972, p. 1,288). To use the ratio method, an approximation of specific storage, 3.3×10^{-6} per meter, was made, the same value as used in approximations by Lohman (1972, p. 53).

Results

Wells DOE-4 through 9 were cleaned and developed by pumping, following the setting of well screens. Pumping tests were conducted in each of these wells. Analyses of transmissivity and average hydraulic conductivity for these wells are presented in figures 12 through 30, and the results are in table 12. Results indicate that the cap rock at the tested sites has a very low transmissivity and hydraulic conductivity. The transmissivities range from 0.0014 to 3.09 m^2/d, and the hydraulic conductivities range from 0.000093 to 0.206 m/d as calculated from Theis recovery method. The results obtained using the Jacob straight-line method for drawdown were reasonably close to the results obtained by Theis method.

Most of the slopes used to determine Δs were those after or near the calculated time criterion. However, in the Jacob straight-line analyses of drawdown in wells DOE-5, 8, and 9, the slopes occurred well in advance of the calculated time criteria, and therefore emphasis was placed on the results of the analyses using the Theis recovery method for these three wells.

Observation wells were used to determine both the degree of vertical hydraulic connection and the vertical hydraulic conductivity between the upper and lower parts of the cap rock. No drawdown was observed at well DOE-7 while pumping well DOE-6, or at well DOE-6 while pumping well DOE-7. The lack of observed drawdown at well DOE-6 and DOE-7 could have been the result of: (1) The presence of very tight zones that greatly restrict vertical movement of water; and (2) short pumping periods because of slow inflow of water to the wells. Some drawdown was observed at well DOE-4 while pumping well DOE-5, and at well DOE-5 while pumping well DOE-4. Also, some drawdown was observed at well DOE-8 while pumping well DOE-9, and at DOE-9 while pumping well DOE-8.

The vertical hydraulic conductivity between wells DOE-4 and 5 was calculated to be 1.0×10^{-3} m/d (fig. 18) using the ratio method to determine vertical hydraulic conductivity in confining beds (Neuman and Witherspoon, 1972). The vertical hydraulic conductivity between wells DOE-8 and 9 was calculated to be 2.7×10^{-4} m/d using the same ratio method (fig. 27).

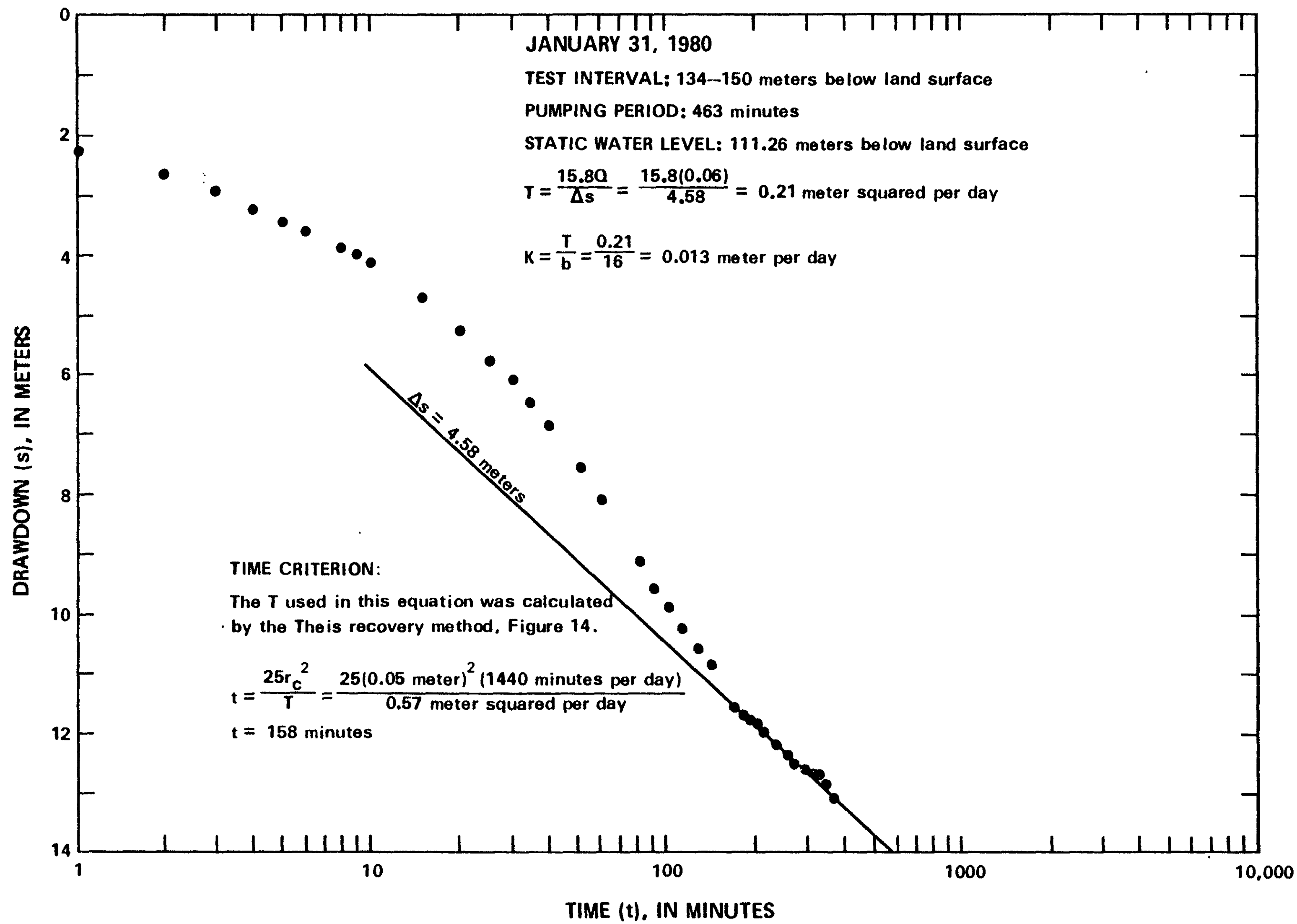


Figure 12.--Analysis of drawdown of water level, pumping test, well DOE-4.

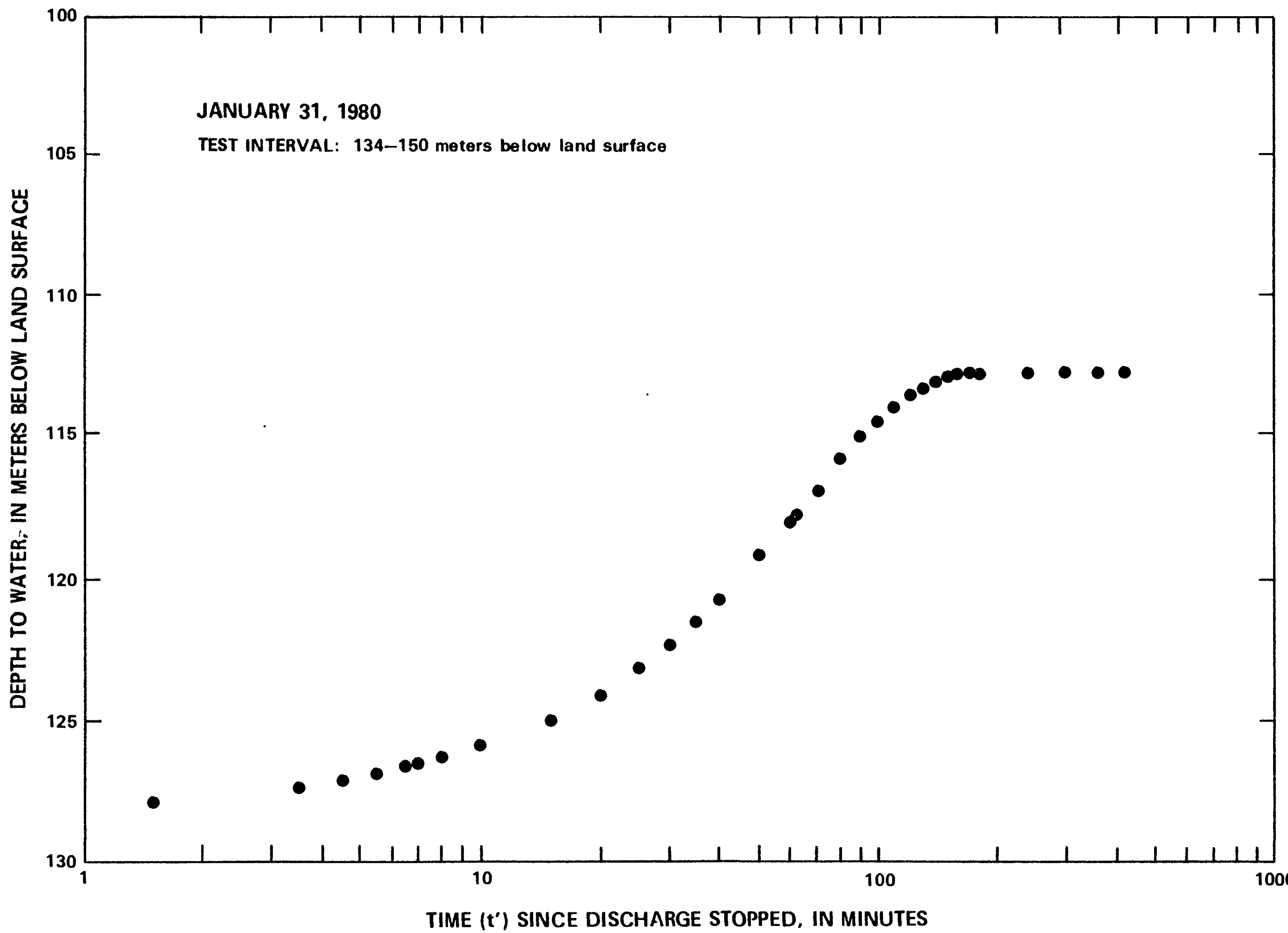


Figure 13.--Recovery of water level, pumping test, well DOE-4.

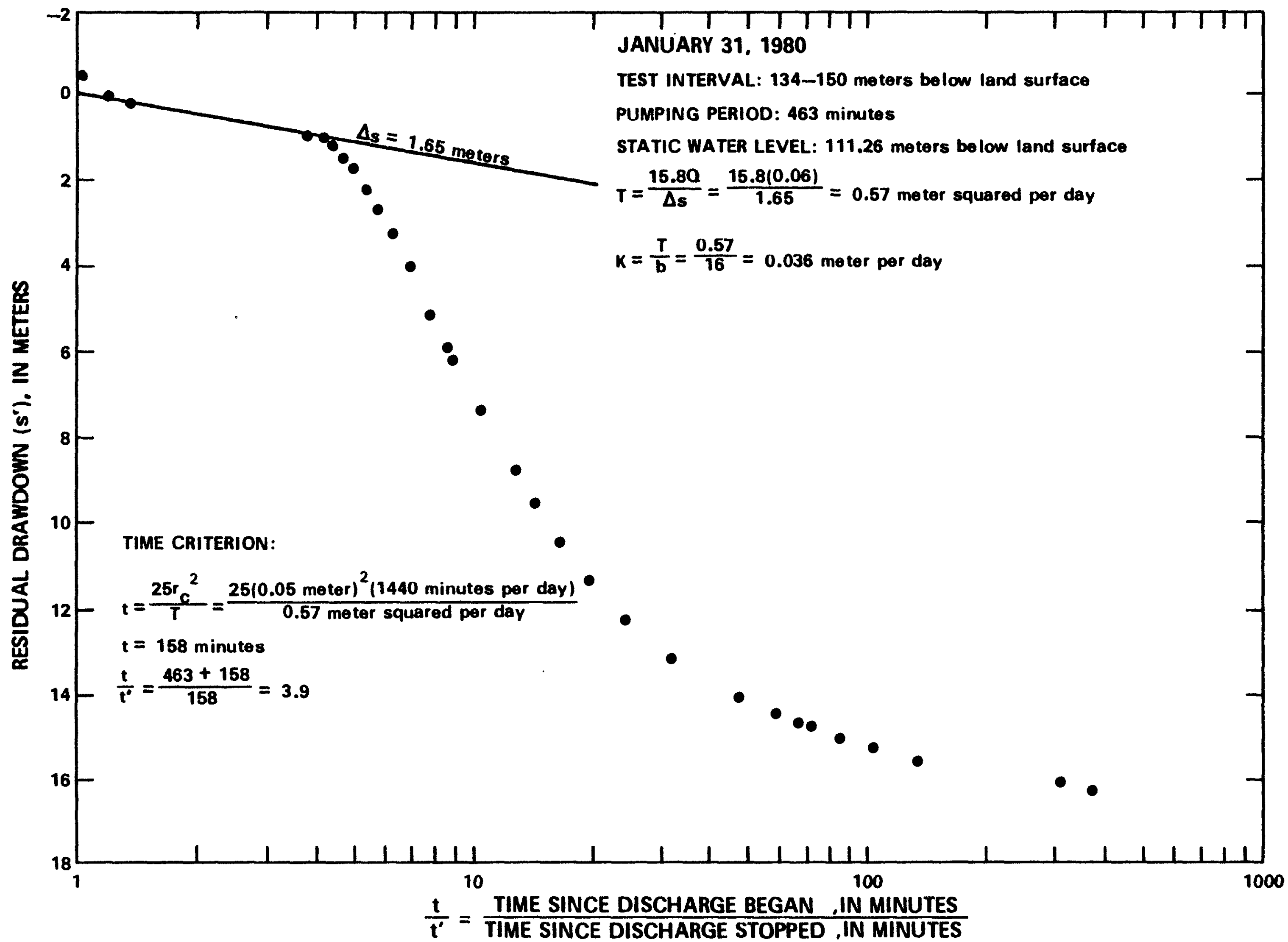


Figure 14.--Analysis of recovery of water level, pumping test, well DOE-4.

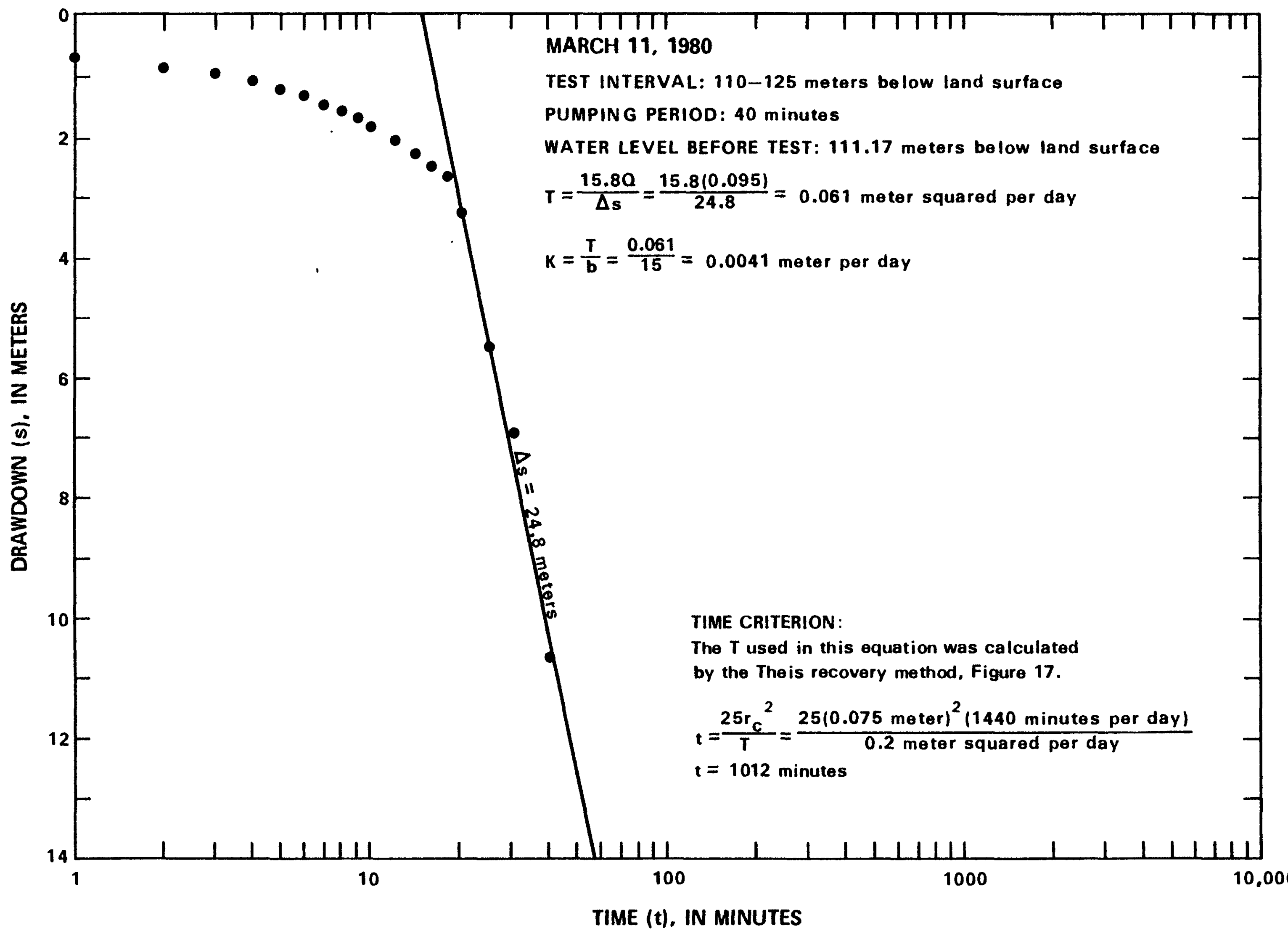


Figure 15.--Analysis of drawdown of water level, pumping test, well DOE-5.

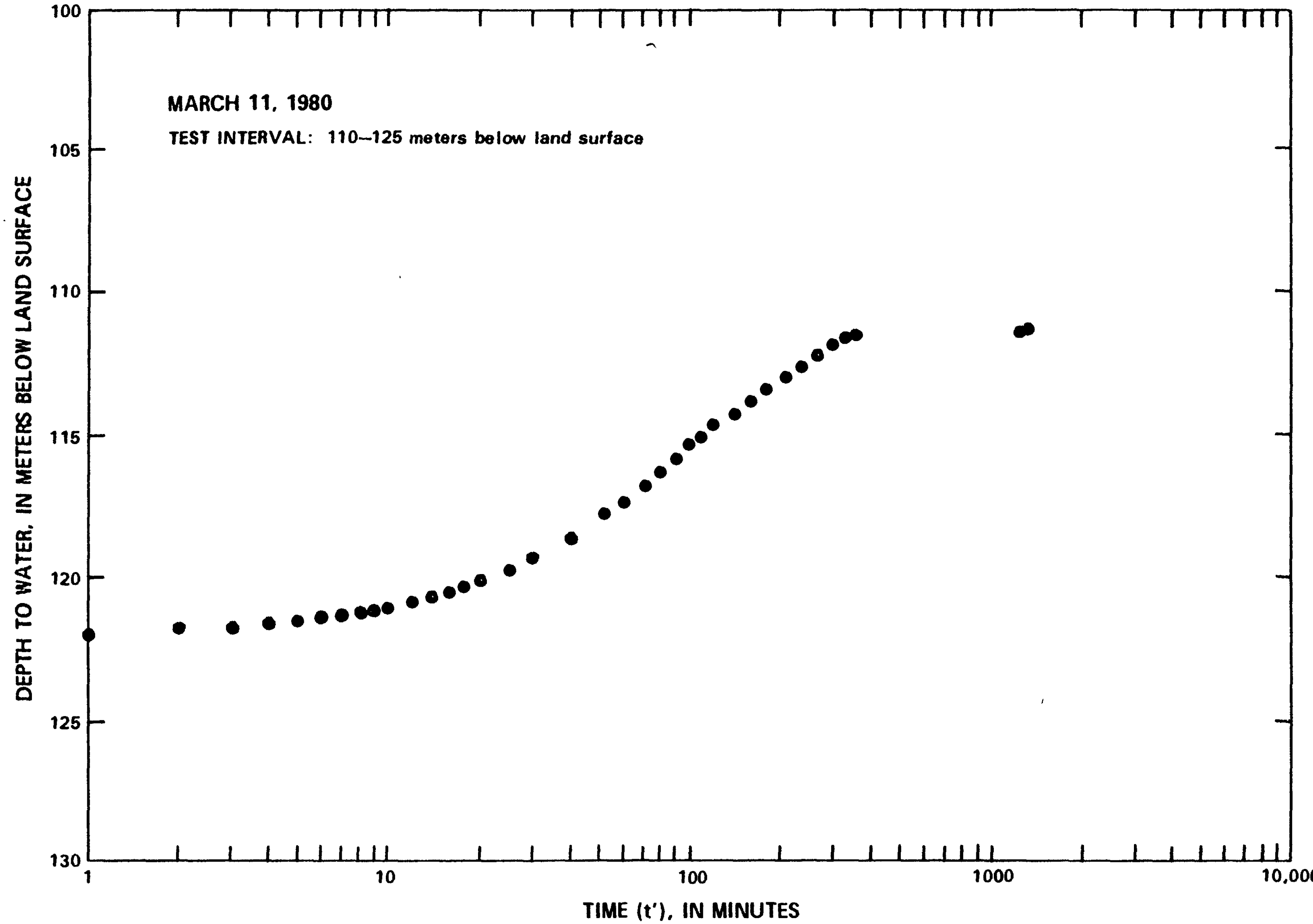


Figure 16.--Recovery of water level, pumping test, well DOE-5.

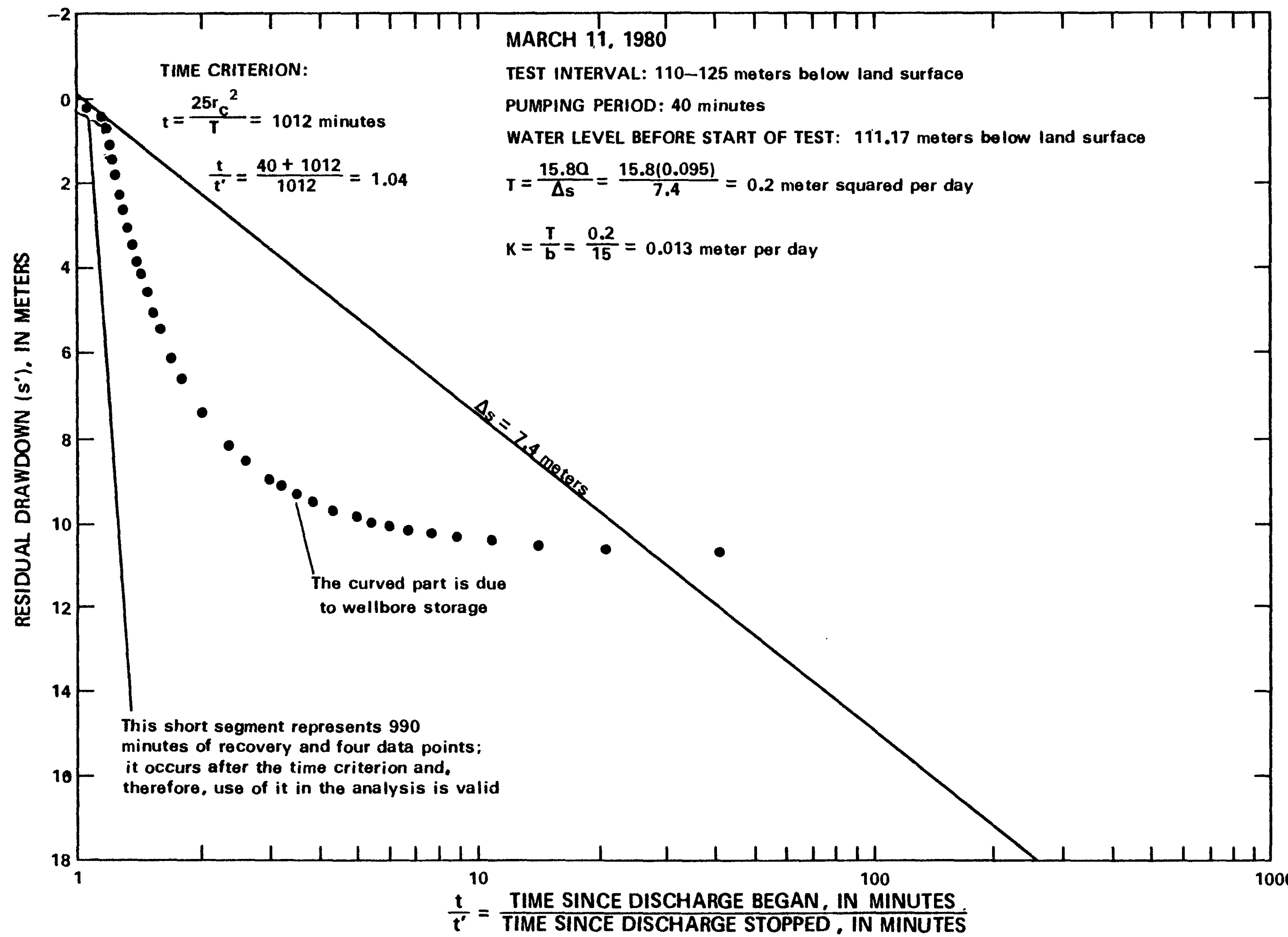


Figure 17.--Analysis of recovery of water level, pumping test, well DOE-5.

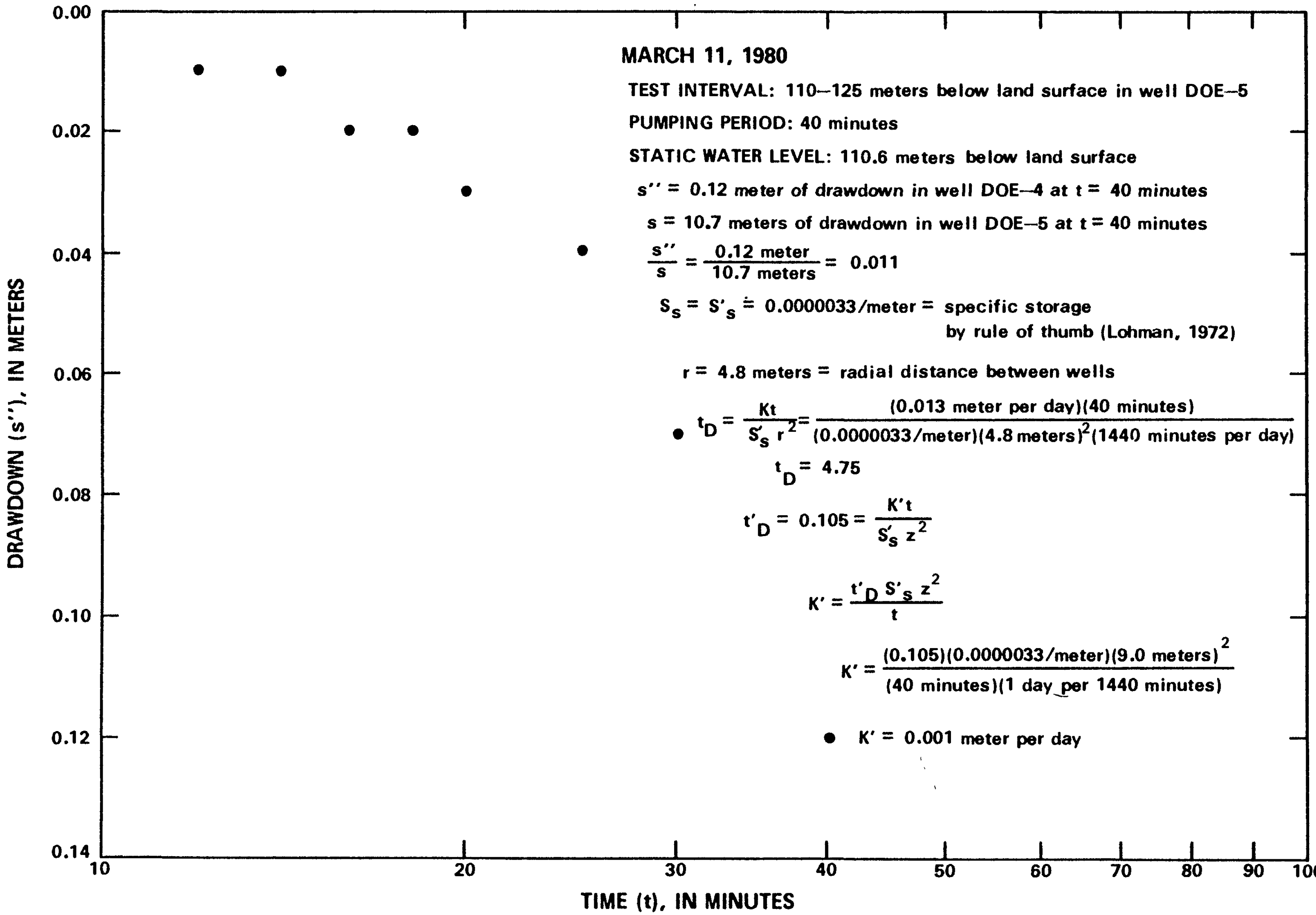


Figure 18.--Analysis of drawdown of water level in observation well DOE-4 during pumping test of well DOE-5, using the Neuman-Witherspoon ratio method.

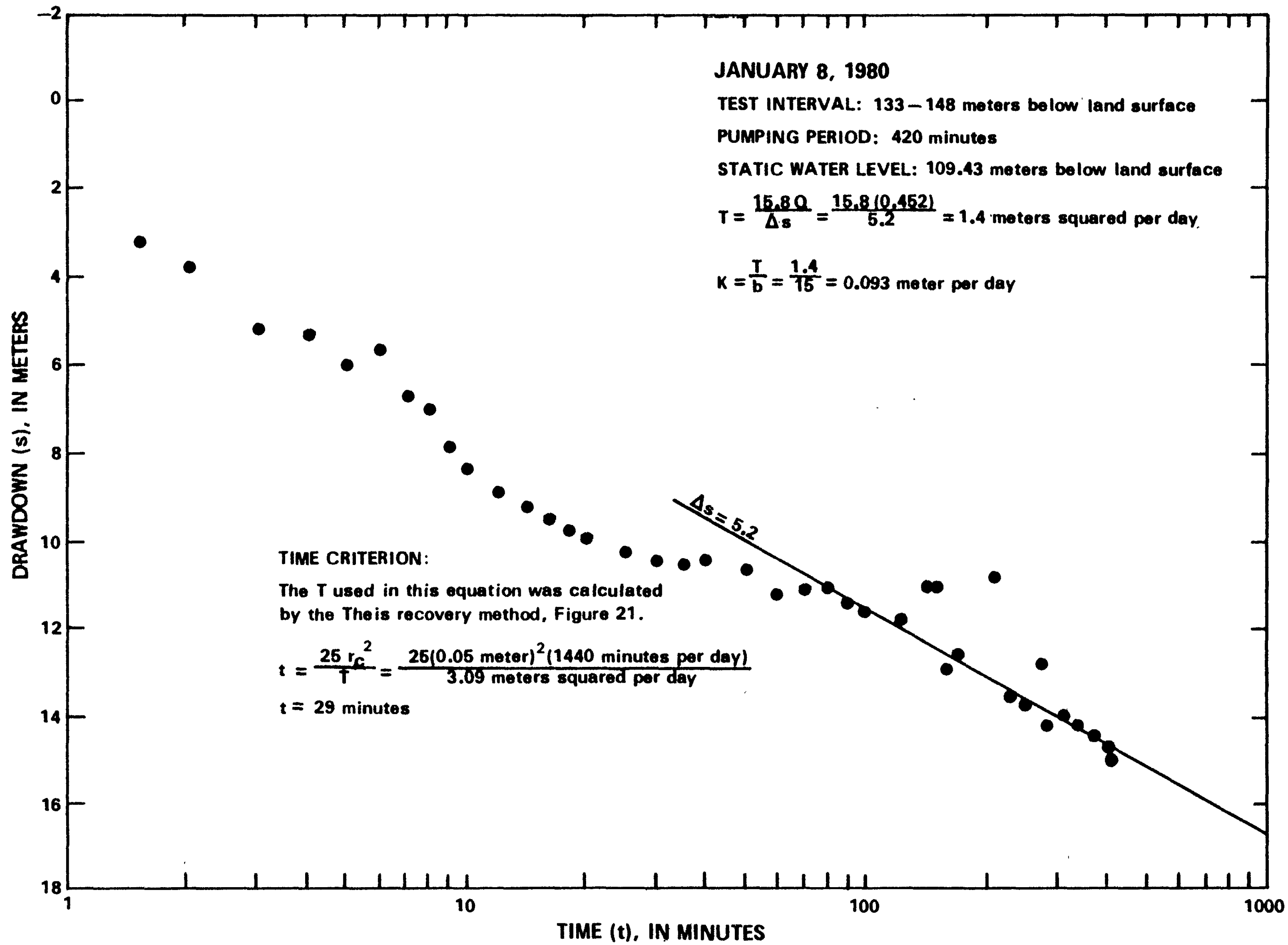


Figure 19.--Analysis of drawdown of water level, pumping test, well DOE-6.

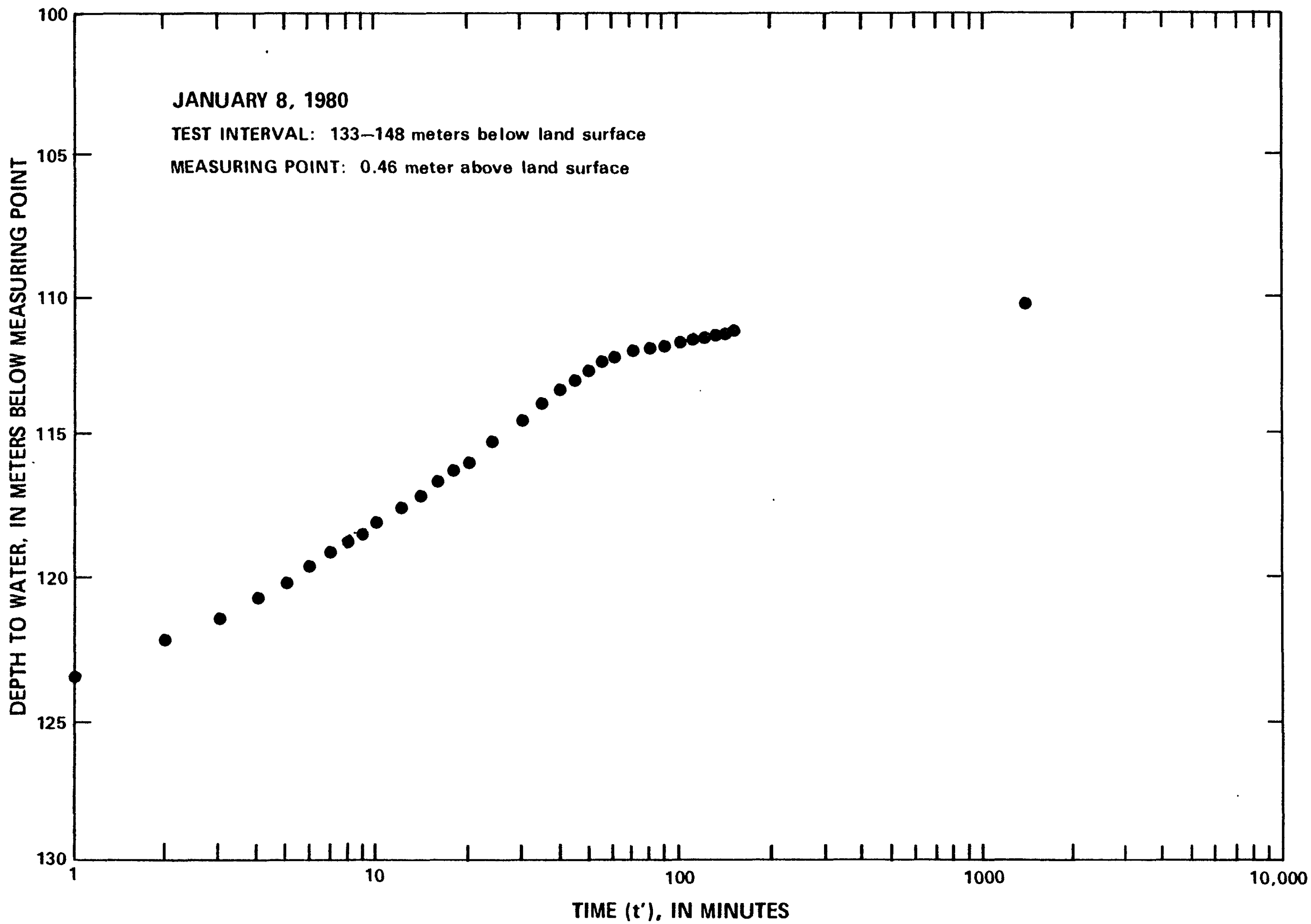


Figure 20.--Recovery of water level, pumping test, well DOE-6.

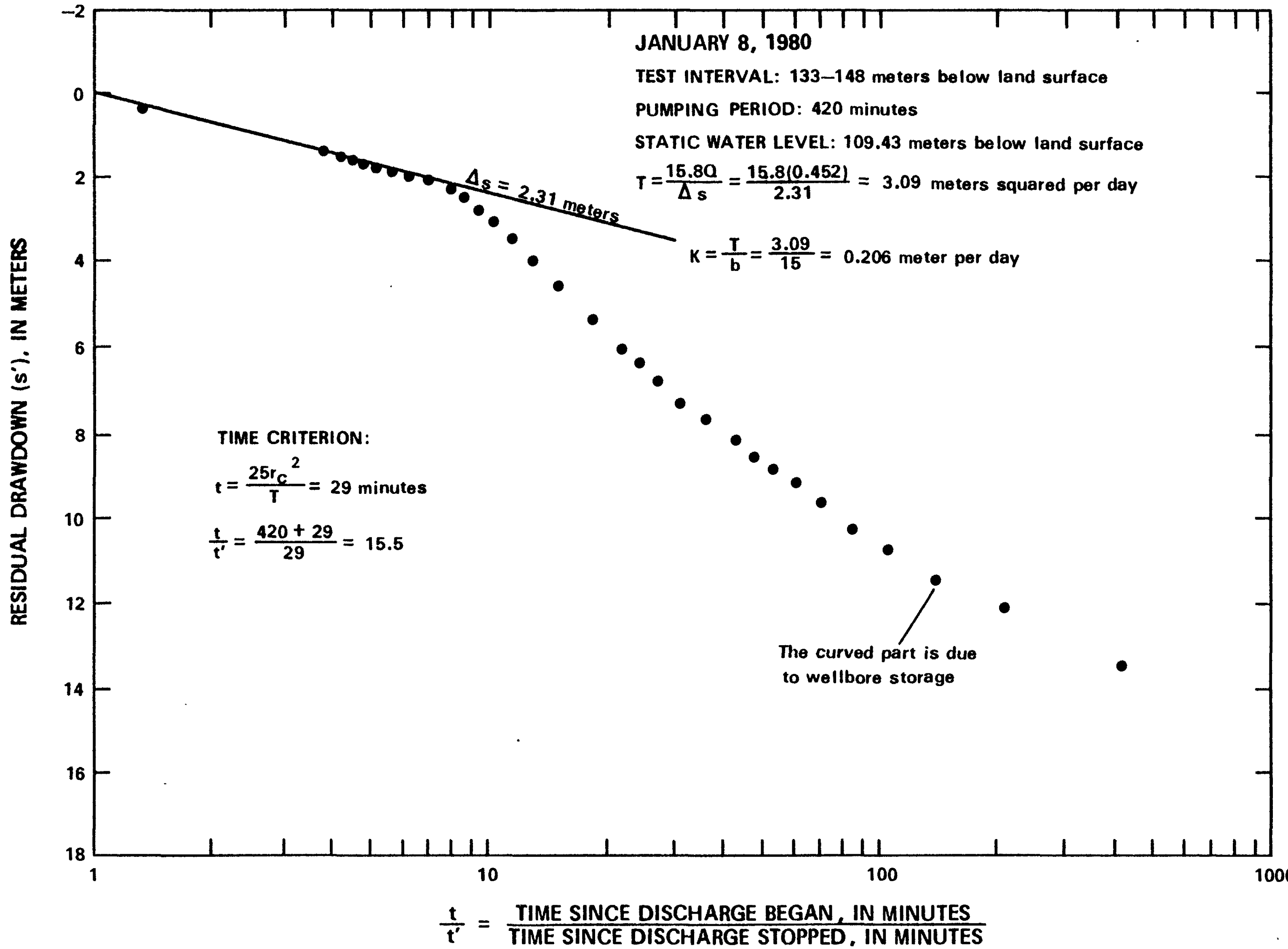


Figure 21.--Analysis of recovery of water level, pumping test, well DOE-6.

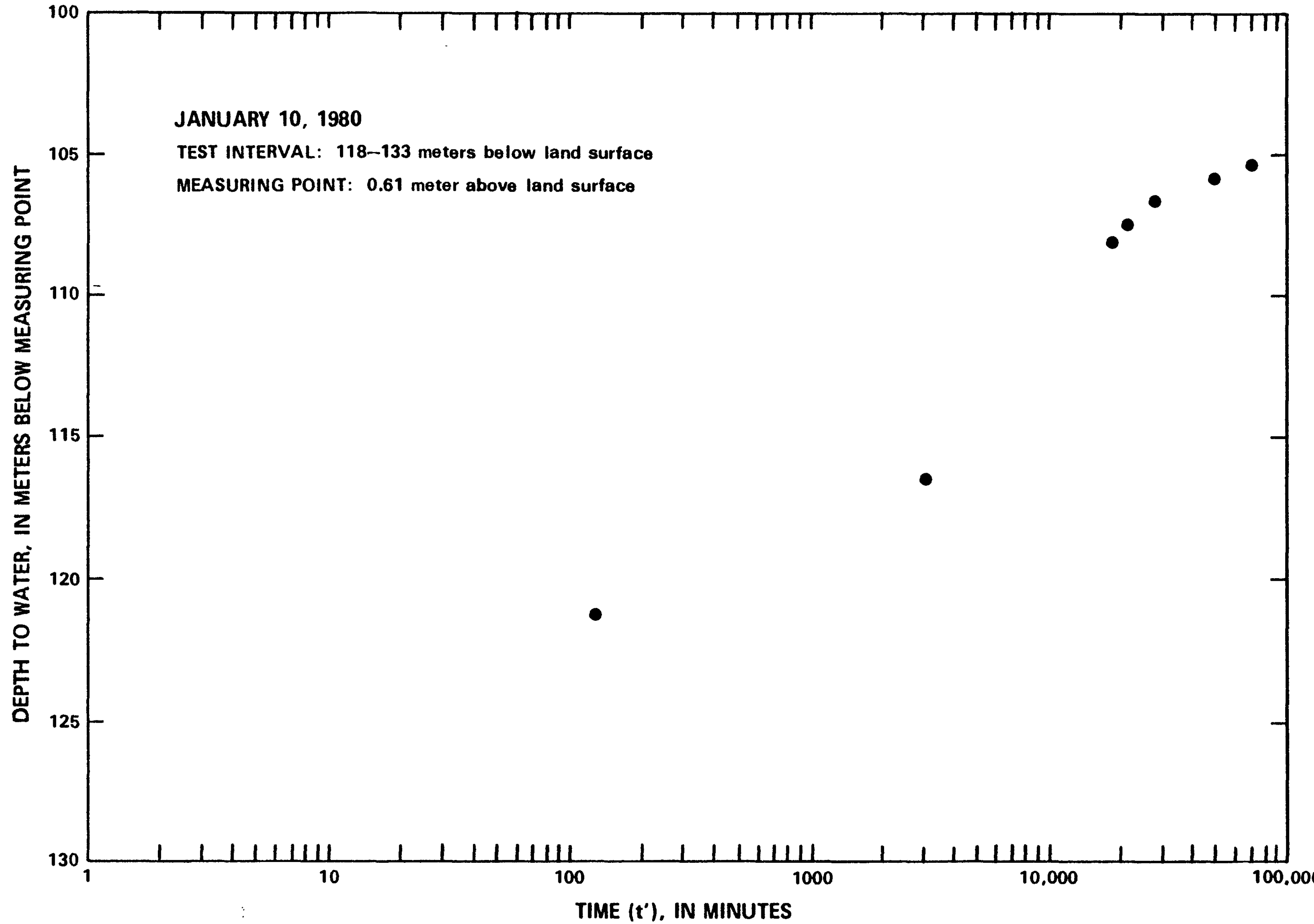


Figure 22.--Recovery of water level, pumping test, well DOE-7.

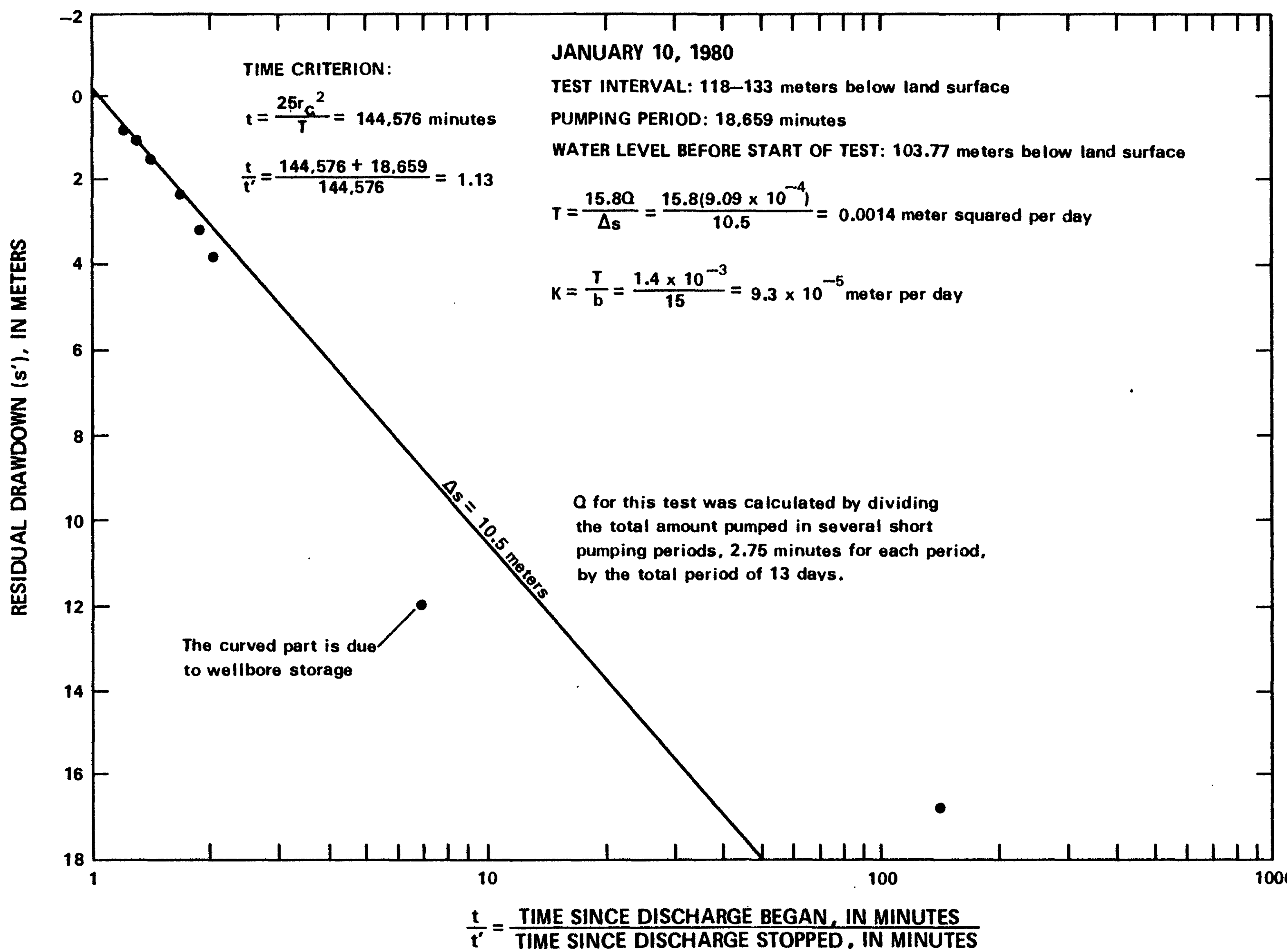


Figure 23.--Analysis of recovery of water level, pumping test, well DOE-7.

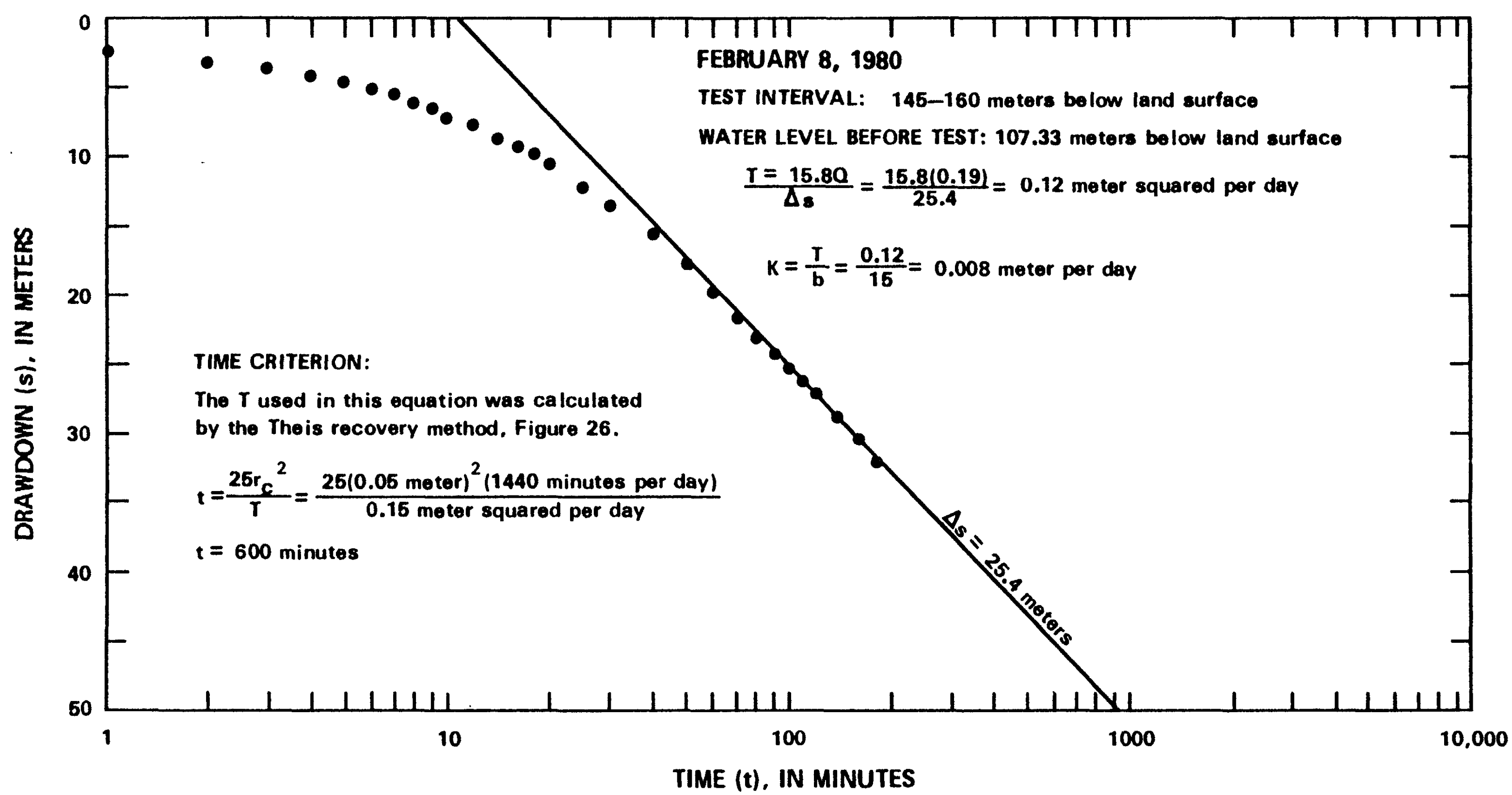


Figure 24.--Analysis of drawdown of water level, pumping test, well DOE-8.

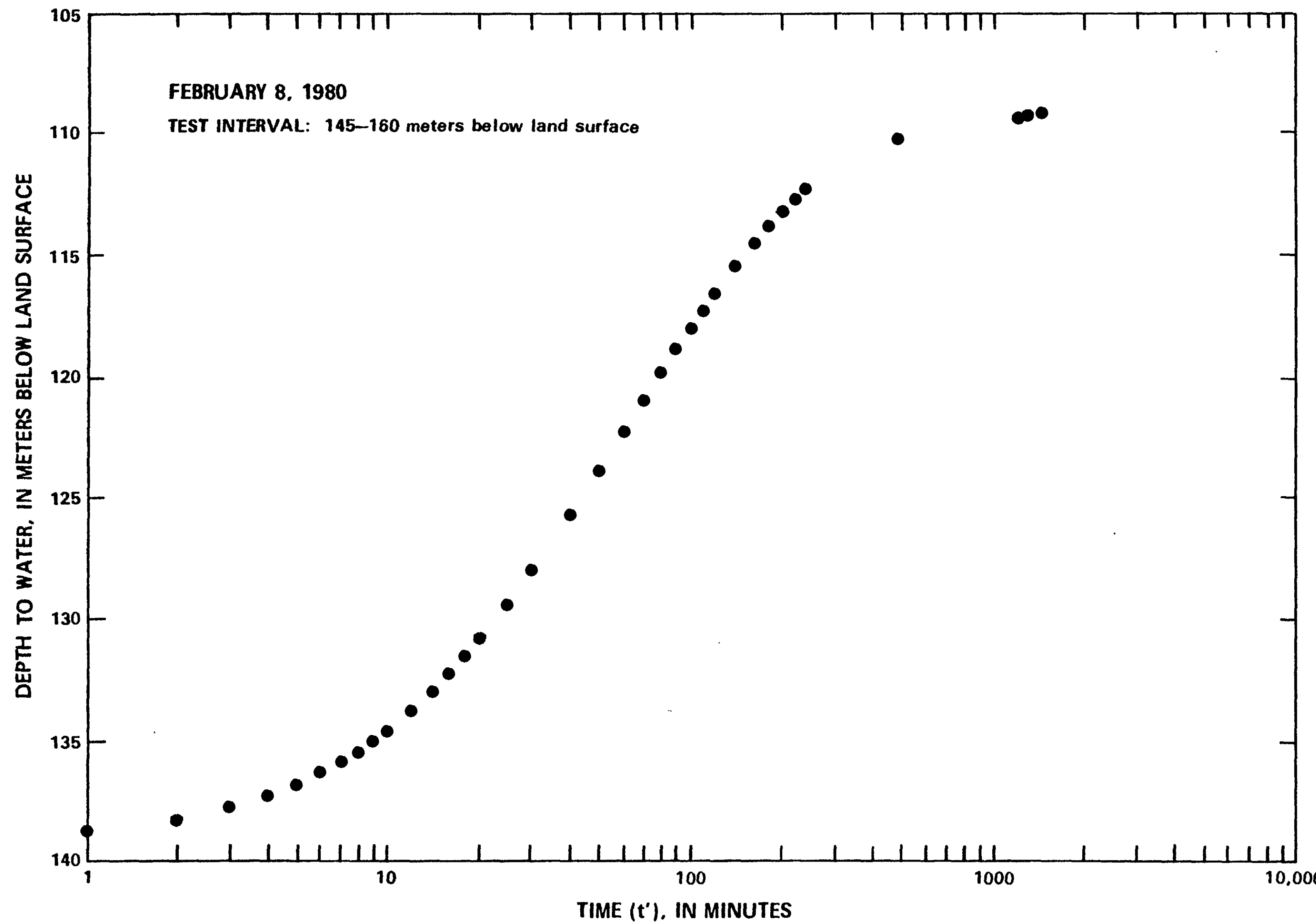


Figure 25.--Recovery of water level, pumping test, well DOE-8.

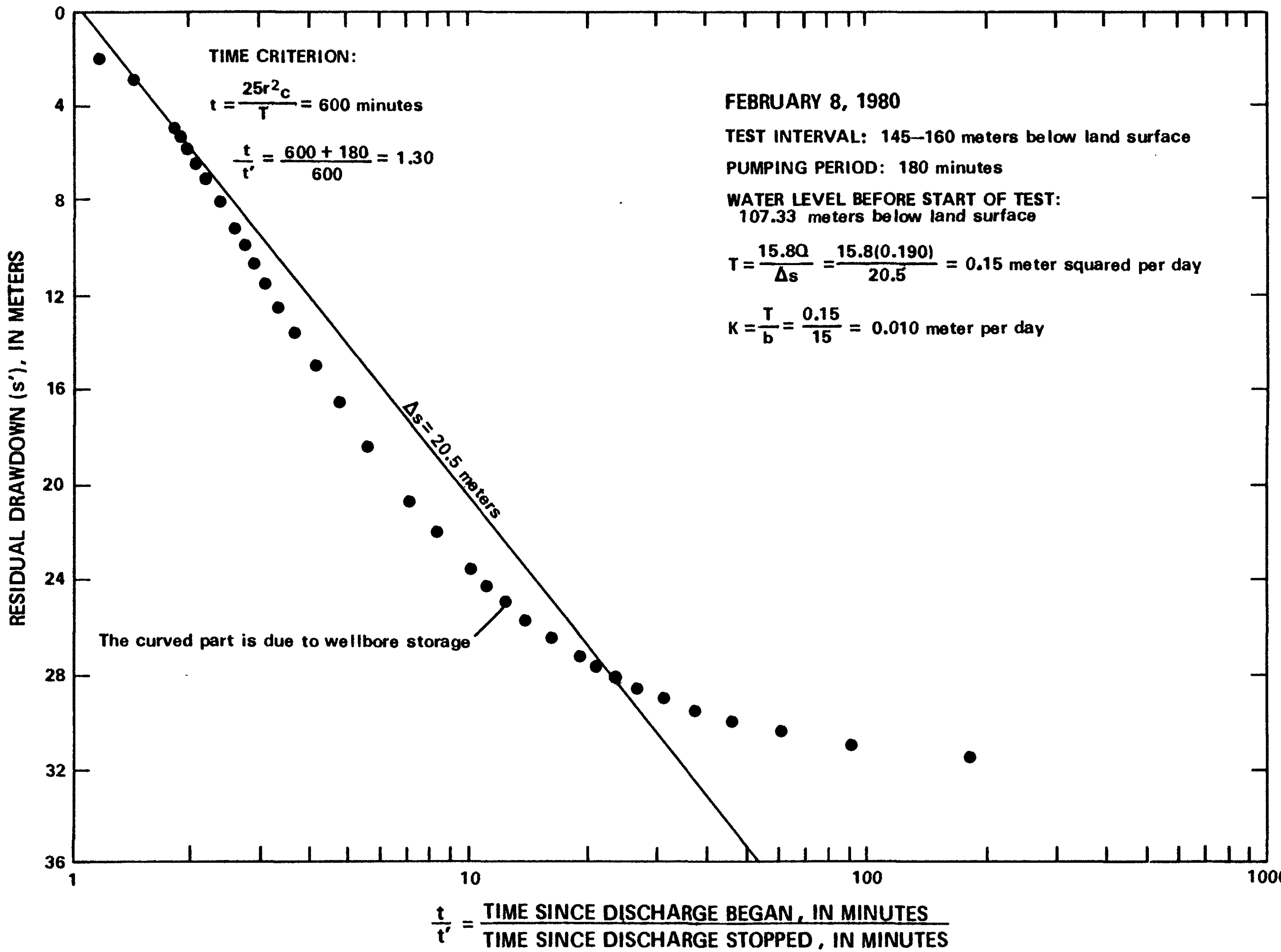


Figure 26.--Analysis of recovery of water level, pumping test, well DOE-8.

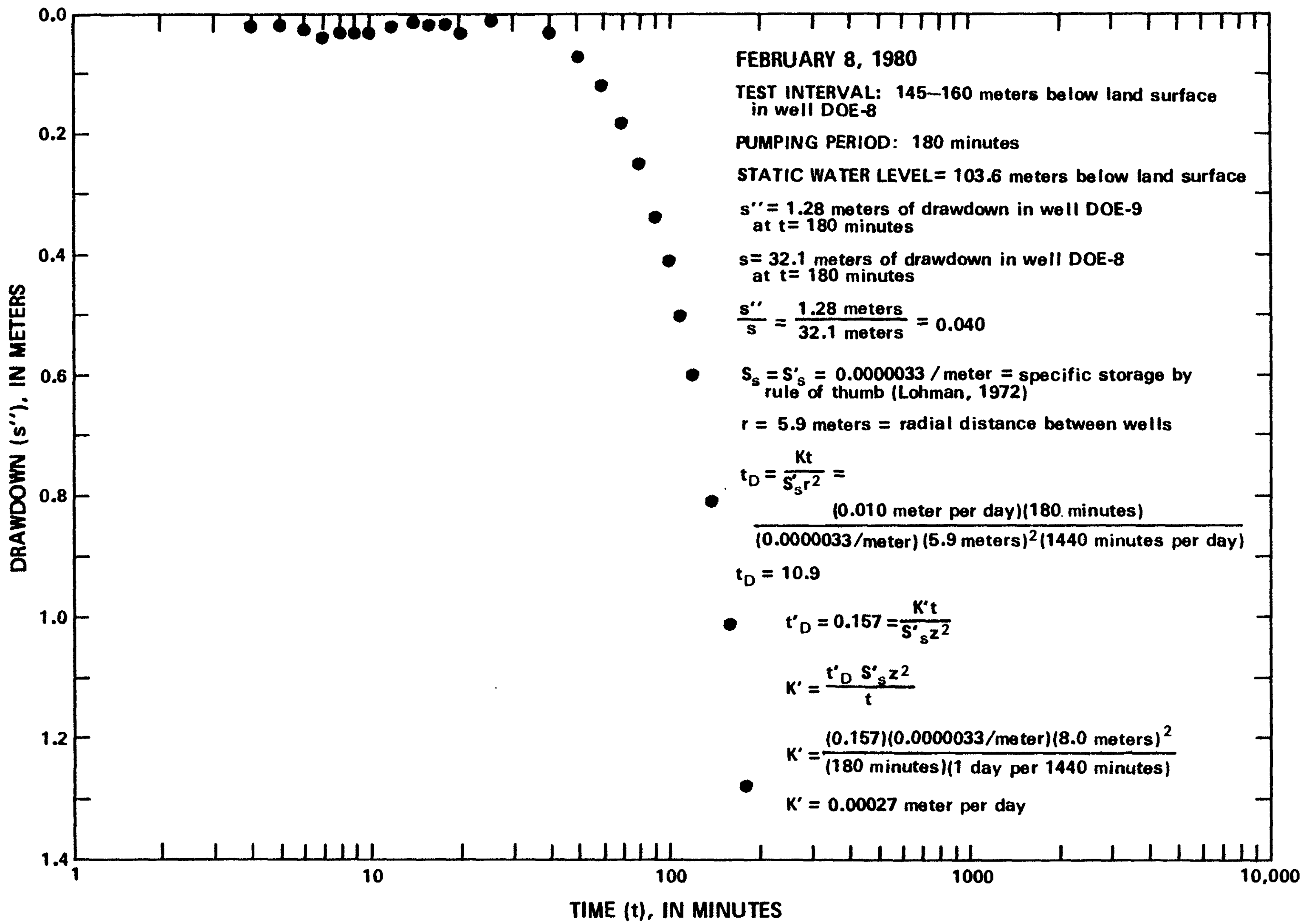


Figure 27.--Analysis of drawdown of water level in observation well DOE-9 during pumping test of well DOE-8, using the Neuman-Witherspoon ratio method.

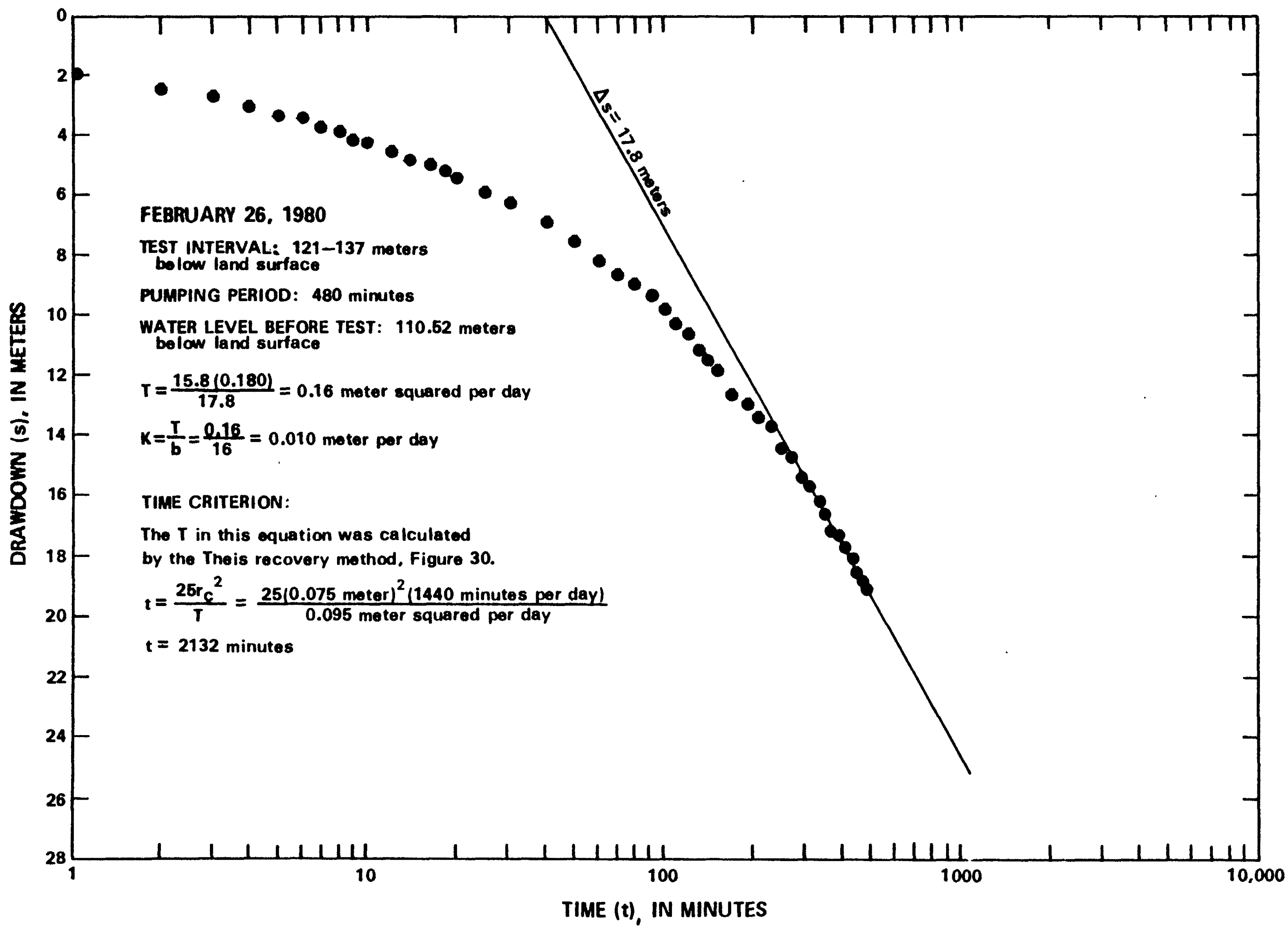


Figure 28.--Analysis of drawdown of water level, pumping test, well DOE-9.

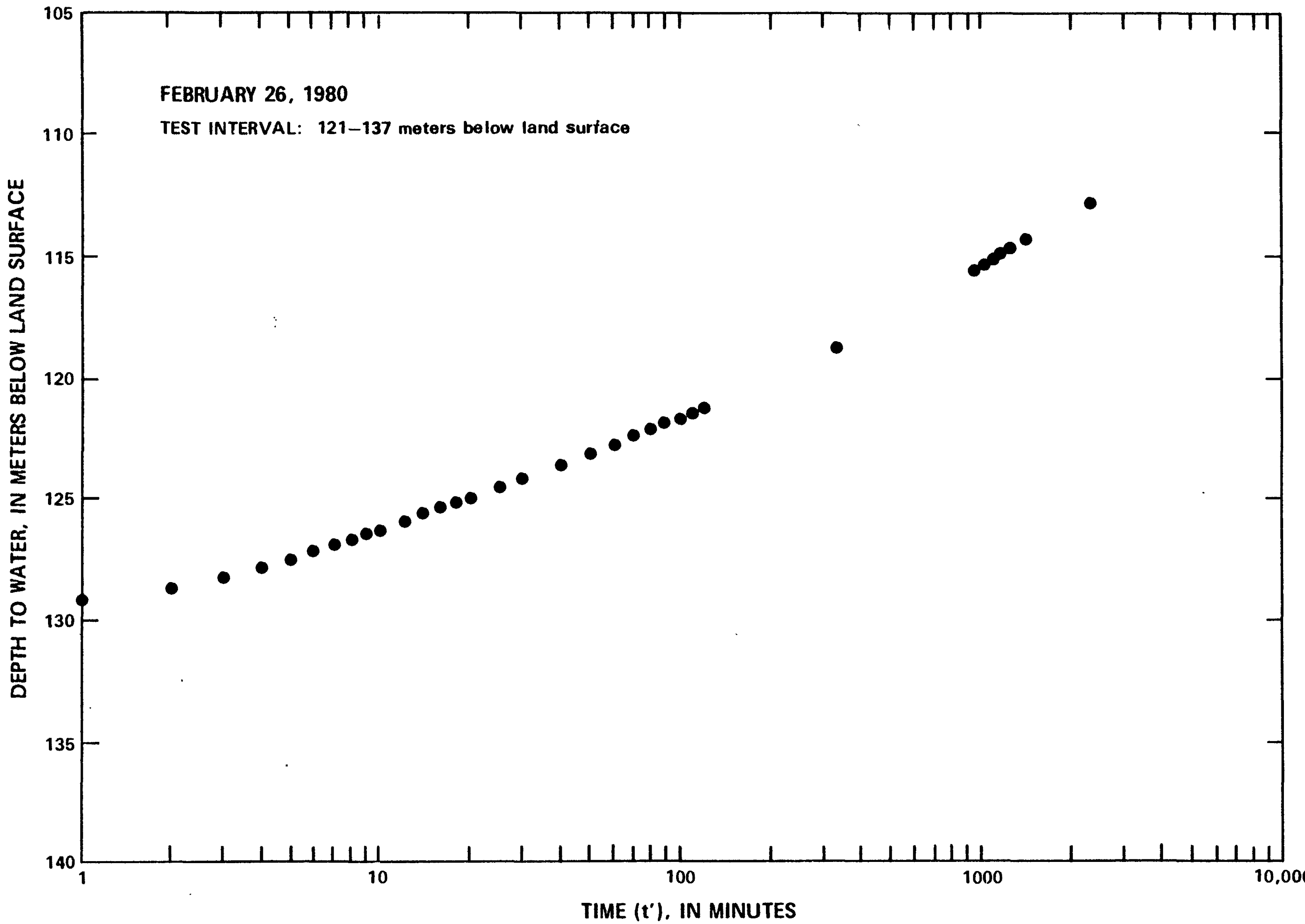


Figure 29.--Recovery of water level, pumping test, well DOE-9.

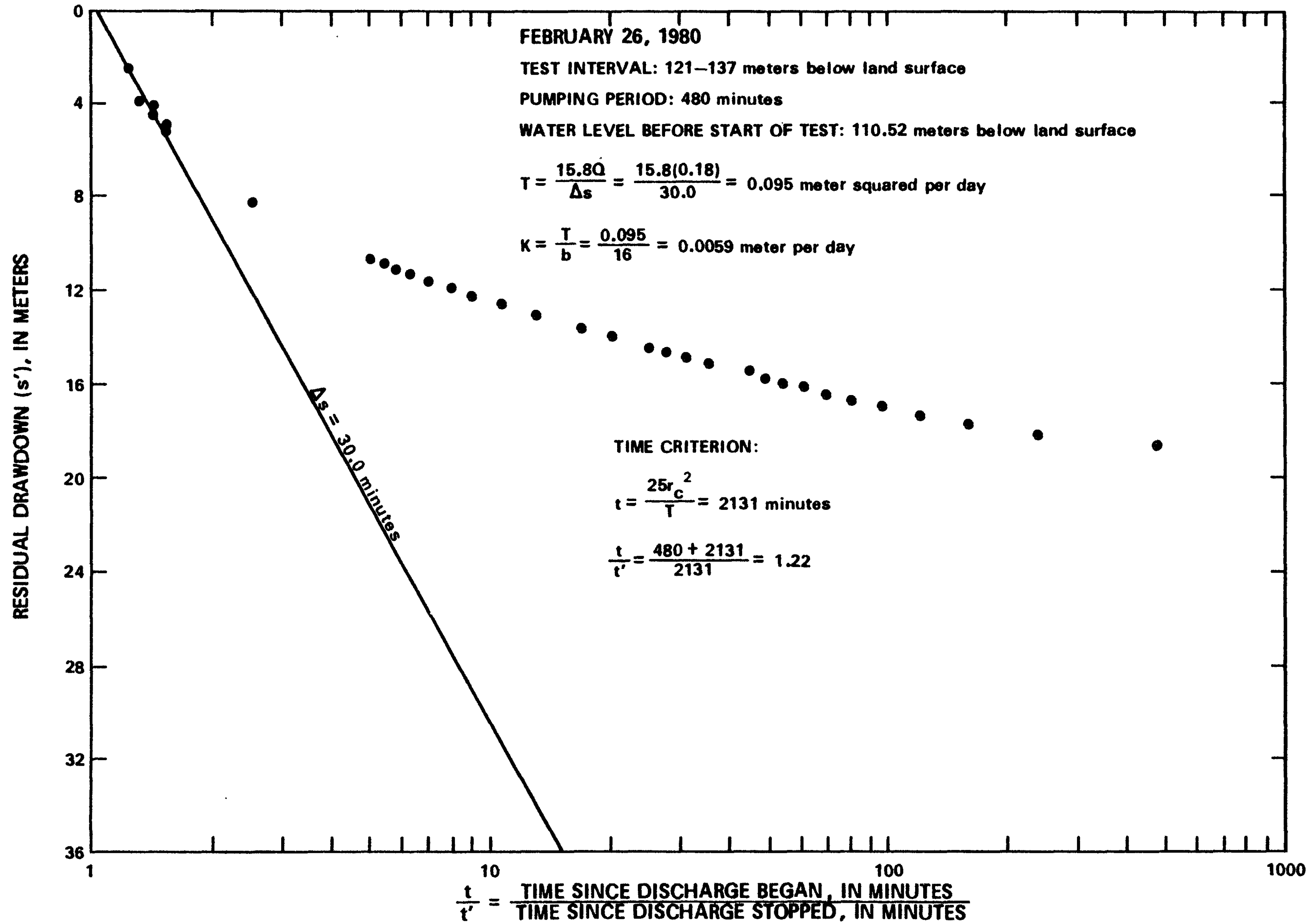


Figure 30.--Analysis of recovery of water level, pumping test, well DOE-9.

Table 12.--*Results of pumping tests, wells DOE-4 through 9*

[m = meters; m/d = meters per day; m^2/d = square meters per day]

Well number	Interval tested (m)	Lithology of interval tested	Transmissivity (m^2/d)		Hydraulic conductivity (m/d)		Vertical hydraulic conductivity of confining beds between wells (m/d)	Data plotted in figures
			Calculated from drawdown using Jacob straight-line method	Calculated from recovery using Theis recovery method	Calculated from drawdown using Jacob straight-line method	Calculated from recovery using Theis recovery method	Calculated from Neuman-Witherspoon ratio method	
4	134-150	siltstone, claystone, shale and gypsum	0.21	0.57	0.013	0.036		12, 13, 14
							0.001 (wells 4 and 5)	18
5	110-125	fine sand, shale and gypsum	.061	.20	.0041	.013		15, 16, 17
6	133-148	siltstone, shale and gypsum	1.4	3.09	0.093	.206	---	19, 20, 21
7	118-133	limestone, siltstone, claystone, shale and gypsum	---	.0014	---	.000093	---	22, 23
8	145-160	siltstone, claystone and gypsum	0.12	.15	0.0080	.010		24, 25, 26
							0.00027 (wells 8 and 9)	27
9	121-137	siltstone, shale and gypsum	0.16	.095	0.010	.0059		28, 29, 30

The ratio of horizontal to vertical hydraulic conductivity was calculated to be 13 to 1 between wells DOE-4 and 5 and 37 to 1 between wells DOE-8 and 9 using the vertical hydraulic conductivities above and the values given in table 12 for horizonal hydraulic conductivities. The poor connection between wells DOE-6 and 7 suggests that the vertical hydraulic conductivity between them is very low so that the ratio of horizontal to vertical hydraulic conductivity is probably great between wells DOE-6 and 7.

POTENTIOMETRIC DATA

Land-surface altitudes at the wells, altitudes of the potentiometric surface, and depths to water are listed in table 13; the accuracy is ± 0.3 m. A contour map of the altitude of the potentiometric surface in the cap rock is presented in figure 31. Control for this contour map was water-level altitudes in deep wells DOE-1, 2, 4, 6, and 8; the shallow water-level data included in table 13 indicates a similar pattern of contours. At this locality the contours indicate that the potentiometric surface slopes down from both valley sides toward the center of Salt Valley. Several lines of evidence indicate that ground water is moving laterally through the cap rock from the western side of the valley toward the central part of the valley. First, the dissolved solids content of the well water increases along the flow path from probable recharge on the west side toward the center of the valley. Second, the uncorrected carbon-14 (^{14}C) age of the water increases along this same flow path. Third, the potentiometric data indicate that the head declines from the west side toward the center of the valley suggesting ground water movement in this direction. In the central part of the valley, the contours indicate that the gradient is to the northwest, along the axis of the valley. At the northern end of the valley the local gradient probably becomes the same as the regional gradient, which is toward the southwest, and ground water eventually is discharged into the Colorado River or its tributaries.

A downward vertical hydraulic gradient exists in the cap rock, as shown by the altitudes of the water levels in two of the three pairs of wells, DOE-4 and 5, and 6 and 7. Static water levels are approximately 1 to 4 m higher in the shallower wells than in the deeper wells at these sites, indicating a potential for downward movement of water. These head relationships could result from a slow rate of recharge from precipitation in the immediate area.

The clay beds are probably the dominating control in the vertical movement of water in the cap rock. Head gradient differences between wells screened in the top and near the base of the cap rock indicate that horizontal permeability is considerably greater than vertical permeability and some ground water probably discharges along the cap rock-salt interface.

Table 13.--*Altitude of wells and potentiometric surface; depth to static water level*

[m = meters above sea level or below land surface]

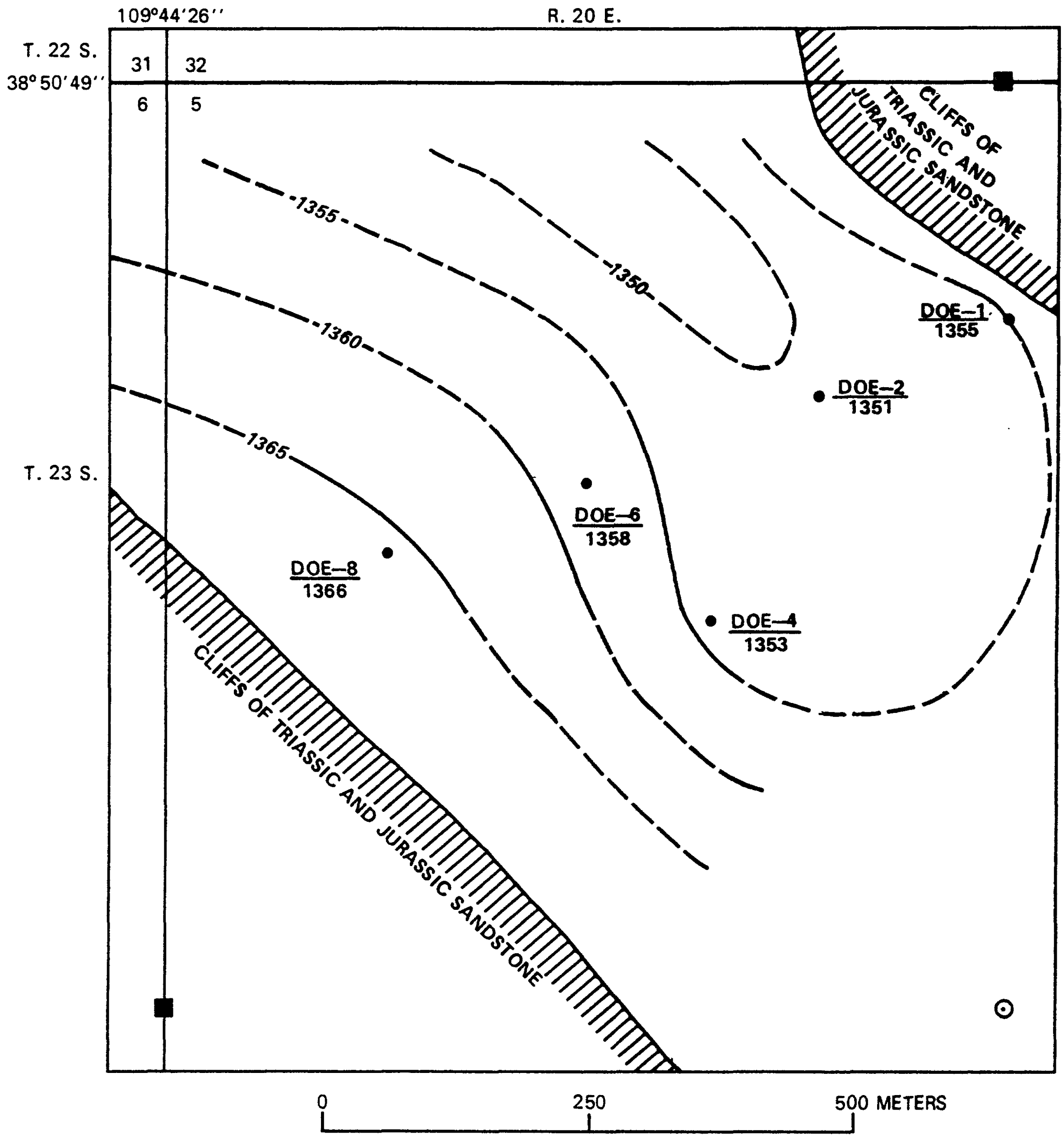
Well number	Altitude of top of casing (m)	Altitude of land-surface datum (m)	Altitude of potentiometric surface (m)	Depth to static water level below land-surface datum (m)
DOE-1[1/]	1,468.8	1,468.6	1,355.2	113.4
DOE-2[1/]	1,463.6	1,463.3	1,351.1	112.2
DOE-3[1/]	1,467.3	1,467.0	-------	-----
DOE-4[2/]	1,464.2	1,463.8	1,353.2	110.6
DOE-5[3/]	1,464.2	1,463.8	1,355.2	108.6
DOE-6[2/]	1,466.7	1,466.2	1,357.9	108.3
DOE-6A[4/]	-------	1,466.4	-------	-----
DOE-7[3/]	1,466.6	1,465.9	1,361.8	104.1
DOE-8[2/]	1,469.5	1,469.0	1,366.2	102.8
DOE-8A[4/]	-------	1,469.5	-------	-----
DOE-9[3/]	1,469.6	1,469.3	1,365.7	103.6
DOE-10A[4/]	-------	1,470.4	-------	-----

1/ From Rush and others, 1980.

2/ Deep well.

3/ Shallow well.

4/ Abandoned well.



EXPLANATION

DOE–4 / 1353 — TEST WELL—Upper number is well number. Lower number is altitude of static water level, in meters above sea level.

1365 — POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface in cap rock. Dashed where estimated. Contour interval 5 meters. Datum is sea level.

QUARTER-SECTION MARKER

CENTER OF SECTION

Figure 31.--Altitude of potentiometric surface.

CHEMICAL QUALITY OF WATER

First monitoring of water quality was conducted during the cleaning and developing of wells prior to pumping tests. Specific-conductance readings and detergent concentration of the pumped water were analyzed to determine whether mostly formation water or a mixture of formation water and drilling fluids was being pumped. These results are shown in table 14, and the amount of water pumped from each well prior to sampling is shown in table 15.

The following summary, condensed from table 14, shows ranges and means of major ions in six samples analyzed in the laboratory (concentrations are in milligrams per liter; specific conductance is in micromhos per centimeter at 25° Celsius):

	Dissolved solids	Specific conductance	Sodium (Na)	Potassium (K)
Range	3,940-16,900	3,530-23,200	240-4,600	13-99
Mean	6,500	7,910	1,370	38

	Calcium (Ca)	Magnesium (Mg)	Bicarbonate (HCO_3)	Chloride (Cl)	Sulfate (SO_4)
Range	450-790	180-460	210-660	230-6,700	1,800-3,500
Mean	560	340	490	1,500	2,700

Concentrations of sodium, potassium, and chloride ranged widely. The largest values for sodium and chloride were in samples from deep wells DOE-4 and DOE-6; these wells probably are hydraulically connected to the top of the salt sequence, at the base of the cap rock.

Dominant ions in water from wells DOE-4 and 6 were calcium, magnesium, sodium, chloride, bicarbonate, and sulfate. Dominant ions in water from wells DOE-8 and 9 were calcium and sulfate. Dominant ions in water from well DOE-5 were calcium, magnesium, sodium, bicarbonate, and sulfate. Dominant ions in water from well DOE-7 were calcium, magnesium, sodium, and sulfate. The effect of gypsum in the cap rock was manifested in all the samples by relatively large calcium and sulfate concentrations. Magnesium concentration also was relatively large in all the samples; it was least in water from wells DOE-8 and 9.

In well DOE-4, specific conductance of the drilling fluid returned at a depth of 144.8 m ranged from 3,000 to 5,500 μmho (micromhos per centimeter at 25° Celsius). At a depth of 157.6 m, the specific conductance of the drilling fluid was 6,900 μmho. At total depth of 161.2 m, a specific-conductance reading of the drilling fluid was 13,500 μmho.

Table 14.--*Analytical results for water samples from wells DOE-4 through 9*

[m = meter; °C = degree Celsius; mg/L = milligrsm per liter; µg/L = microgram per liter; µmho = micromho per centimeter st 25 degrees Celsius; pCi/L = picocurie per liter]

Well number	Date of collection	Screened interval below surface	Temperature	Bicarbonate (HCO_3)	Aluminum (Al)	Calcium (Ca)	Magnesium (mg)	Sodium (Na)	Potassium (K)	Sulfate (SO_4)	Chloride (Cl)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Lithium (Li)
		(m)	(°C)	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	µg/L
DOE-4	1-31-80	134-150	15	660	30	790	440	4,600	35	3,500	6,700	27	140	200	440
DOE-5	3-12-80	110-125	12	570	10	550	400	410	16	2,900	320	28	230	480	320
DOE-6	1-08-80	133-148	14	550	50	450	340	1,200	20	2,800	1,200	23	80	30	350
DOE-7	1-23-80	118-133	14	---	30	470	460	410	13	3,000	270	--	810	370	460
DOE-8	2-20-80	145-160	14	370	30	570	210	240	99	2,100	310	21	1,000	100	100
DOE-9	2-26-80	121-137	16	320	20	500	180	---	44	1,800	230	24	3,200	80	100

Table 14.--*Analytical results for water samples from wells DOE-4 through 9*--Continued

Strontium (Sr)	Uranium (U)	Hardness, noncarbonate	Hardness, total	Dissolved solids, sum	Dissolved solids, residue on evaporation at 180°C	Specific conductance, lab	Tritium (^3H)	Oxygen ($^{18}O/^{16}O$) ratio	Deuterium/protium ratio ($^2H/^1H$)	($^2H/^1H$) calculated[1]	pH, onsite	Carbon (C), organic	Detergents	Carbon-14 (^{14}C) age of water, uncorrected	Carbon ($^{13}C/^{12}C$) ratio[2]
µg/L	µg/L	mg/L	mg/L	mg/L	mg/L	µmho	pCi/L	----	----	----	Standard units	mg/L	mg/L	Years	----
17,000	<10.0	3,300	3,800	16,400	16,900	23,200	<200	-15.8	-123	-116	6.8	15	0.9	41,000	----
9,600	< 3.4	2,600	3,000	4,920	5,200	5,413	<200	-15.2	-115	-112	6.8	2.8	0.5	32,000	-9.4
11,000	< 1.2	2,100	2,500	6,320	6,660	5,280	<200	-15.4	-120	-113	6.9	1.6	0.1	>38,000	----
9,900	<10.7	2,700	2,800	4,680	5,380	5,549	<200	-16.4	-128	-121	7.4	9.2	1.6	----	----
11,000	< 0.8	2,000	2,300	3,740	3,940	4,479	<200	-15.2	-115	-112	6.9	12	0.2	17,000	-8.6
9,900	< 1.7	1,700	2,000	2,950	----	3,530	<200	-15.1	-114	-111	7.0	6.6	0.1	26,000	-8.6

1/ $^2H/^1H$ calculated from the equation $\delta^2H\ ^o/oo = 8\ \delta^{18}O^o/oo + 10$, called meteoric water line (Faure, 1977, p. 328).

2/ $^{13}C/^{12}C$ Ratio; deviation, in parts per thousand, from PDB (Peedee belemnite). Standard fossil from Peedee Formation of South Carolina.

Table 15.--*Summary of hydraulic testing*

[Water-level measurements are below land surface]

Well number	Depth to static water level (meters)	Duration of pumping test (minutes)	Pumping test rate (liters per second)	Total volume of water (liters)	Specific capacity (liters per second per meter)	Hydraulic conductivity (meters per day)
DOE-2	112.2	28	0.23	386	0.013	0.005
DOE-4	110.6	463	.06	6,722	.004	.036
DOE-5	108.6	40	.09	6,113	.0009	.013
DOE-6	108.3	420	.45	20,964	.039	.206
DOE-7	104.1	18,659	.001	1,601	.00005	.000093
DOE-8	102.8	180	.19	30,685	.006	.010
DOE-9	103.6	480	.18	12,093	.009	.0059

At a depth of 152.4 m in well DOE-6, specific conductance of the drilling fluid was 1,050 μmho. At the total depth of 160.6 m, the specific conductance of the drilling fluid was 170,000 μmho.

In well DOE-8, specific conductance of the returning fluid during drilling at a depth of 123 m was 13,300 μmho. At a depth of 142 m, the drilling fluid began to taste salty; at depths ranging from 145 m to 168 m, the conductance was 20,000 μmho. After the drilling was finished, the hole was bailed from a depth of 152 m; specific-conductance was 6,100 μmho.

Dissolved solids were greater in water from the deep wells than in water from the adjacent shallow wells. Onsite pH generally was about 7.0 for all wells (fig. 32). Iron concentrations were noticeably greater in water from wells DOE-8 and 9.

Laboratory determinations for detergent indicated uniformly small concentrations in all samples, indicating that samples were representative of formation water; however, the presence of even small concentrations of detergents reflects the extreme difficulty experienced in removing all drilling fluids from boreholes and surrounding rock. "Less than" tritium values determined by liquid scintillation indicate the absence of high-level nuclear contaminants that could have entered the cap rock via fallout in local precipitation.

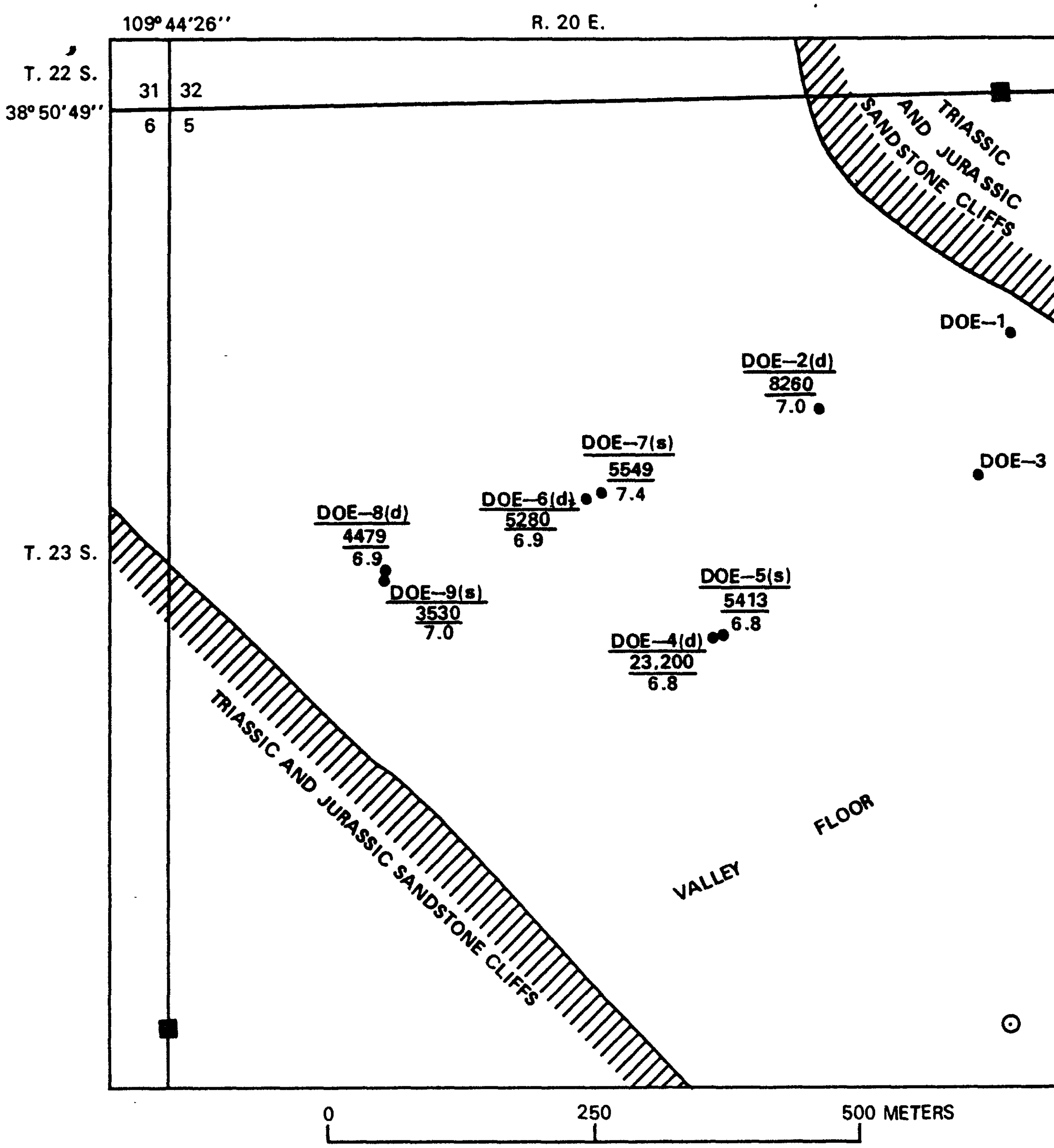
The ratios of the chief isotopes in water, oxygen ratio ($^{18}O/^{16}O$) and deuterium/protium ratio ($^{2}H/^{1}H$), indicate that the ground water in test wells DOE-4 through 9 was derived originally from precipitation. These ratios are in units of parts per thousand ($^{o}/oo$) differences, $\delta^{2}H^{o}/oo$ and $\delta^{18}O^{o}/oo$, relative to standard mean ocean water. In precipitation on continents, $\delta^{18}O$ ranges from 0 to $-25^{o}/oo$, and $\delta^{2}H$ ranges from 0 to $-150^{o}/oo$ (Freeze and Cherry, 1979, p. 138). In the ground-water analyses in table 14, $\delta^{18}O$ ranges only from -15.1 to -16.4, and ^{2}H ranges only from -114 to -128, indicating that the water is derived from precipitation. Moreover, the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios are surmised to be from precipitation because they satisfy the equation:

$$\delta^{2}H^{o}/oo = 8\delta\ ^{18}O^{o}/oo + 10$$

This equation is called the meteoric water line, and it was derived by H. Craig from surveys of global precipitation (Faure, 1977, p. 328; Freeze and Cherry, 1979, p. 139). A map showing both uncorrected carbon-14 (^{14}C) age of the water and the deuterium/protium ratio ($^{2}H/^{1}H$) is presented in figure 33. The uncorrected ages of the ground water that were derived from ^{14}C age dating range from 17,000 to 41,000 years.

ADDITIONAL STUDIES

The nine wells in Salt Valley, Grand County, Utah, used for geohydrologic investigations occur in an area of about 0.4 km^2. If Salt Valley continues to be a potential site for the storage of nuclear wastes, knowledge of the geohydrologic continuity of the cap rock needs to be extended over a larger area of the valley. The following need to be determined:



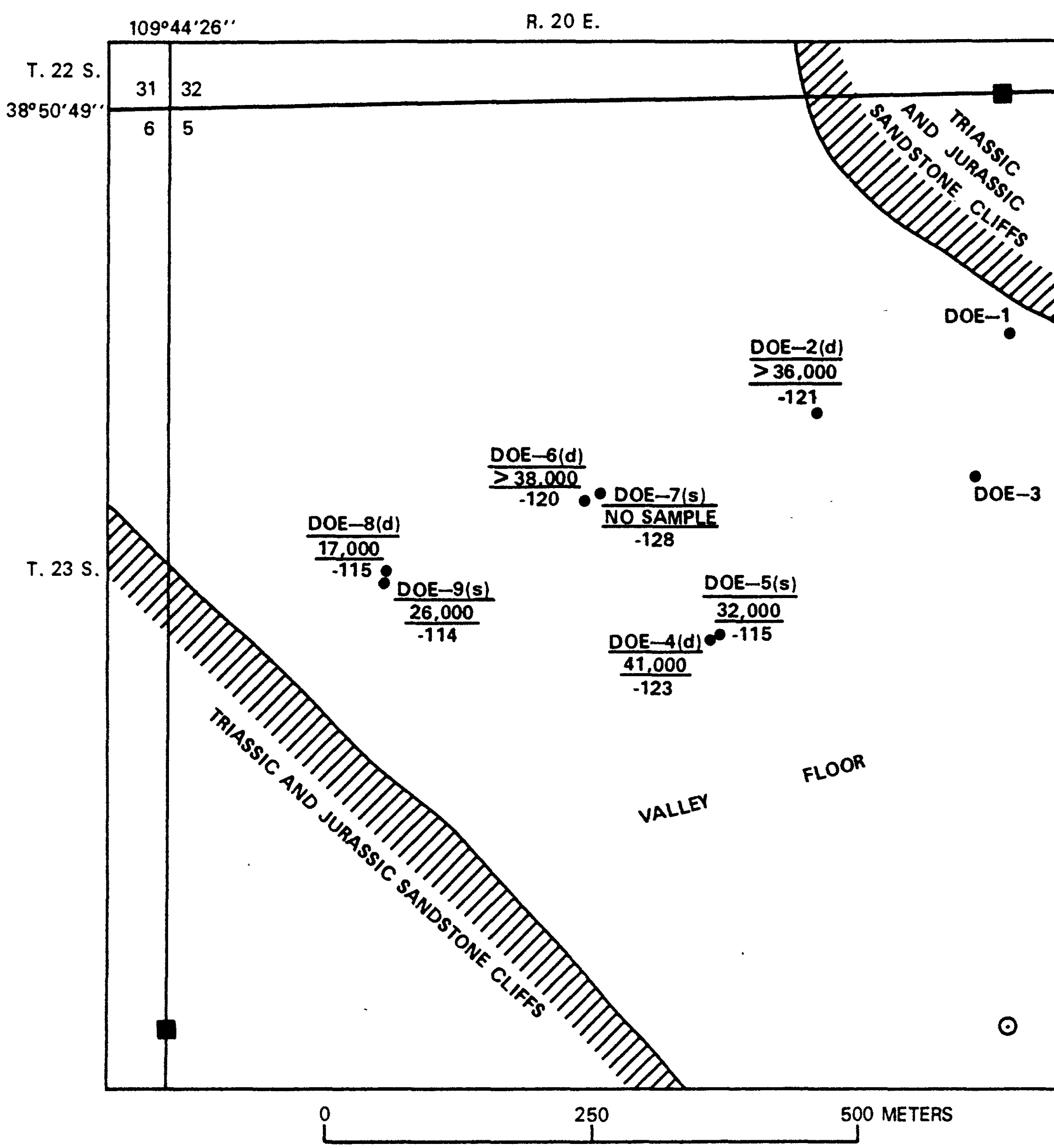
EXPLANATION

DOE–5(s)
5413
6.8 ● TEST WELL—Upper number is well number; (s) shallow well, (d) deep well. Middle number is laboratory specific conductance, in micromhos per centimeter at 25 degrees Celsius. Lower number in onsite pH, in standard units.

■ QUARTER–SECTION MARKER

⊙ CENTER OF SECTION

Figure 32.--Laboratory specific conductance and onsite pH of water samples.



EXPLANATION

DOE–5(s) / 32,000 / -115 ● TEST WELL—Upper number is well number; (s) shallow well, (d) deep well. Middle number is uncorrected carbon-14 age of water, in years. Lower number is deuterium/protium ratio.

■ QUARTER–SECTION MARKER

⊙ CENTER OF SECTION

Figure 33.--Uncorrected carbon-14 age of water and deuterium/protium ratio.

1. Hydrologic relationship of the flanking Mesozoic strata to the cap rock. This could be achieved by drilling and conducting hydraulic tests of wells on the flanks of Salt Valley. In addition to determining the hydrologic connection between rocks in the valley and on the flanking lithologies of Salt Valley, the collected data would provide a better definition of the flow direction and gradient of water in the cap rock throughout the length of the valley floor and their relation to the regional flow system.

2. Hydrologic relationships of the salt bed in the Paradox Member of the Hermosa Formation to the overlying and the underlying hydrogeologic units. The relationship to the overlying hydrogeologic units is known only locally; the relationship to the underlying hydrogeologic units is virtually unknown. To determine the relationship of the overlying and underlying hydrogeologic units to the cap rock, drilling of a deep hydrologic test well (3,700 m) to the Mississippian aquifer underlying the salt would be required. This aquifer would be tested as well as the salt, cap rock, and interbeds of the Paradox Member. Some additional hydrologic data might be obtained by testing existing deep wells that penetrate aquifers below the salt.

3. Hydraulic head, flow directions, and hydraulic gradient in the cap rock throughout the length of Salt Valley. This could be achieved by drilling shallow wells (150 m deep) at the northwest and southeast ends of Salt Valley.

4. Hydraulic properties of the salt-cap rock contact.

SUMMARY AND CONCLUSIONS

Geologic data obtained from drilling test holes DOE-4 through 9 indicate less than 20 m of buried relief along the cap-rock salt interface. The hydraulic conductivity of the saturated cap rock, determined from six pumping tests, ranges from 9.3×10^{-5} to 2.06×10^{-1} m/d as summarized in table 15. The unsaturated zone of the cap rock is more than 100 m thick.

Static water levels in these test holes indicate a general flow direction to the northwest in the northern end of Salt Valley. Outside the valley, this local gradient probably becomes the same as the regional gradient, which is toward the southwest, and ground water eventually is discharged into the Colorado River or its tributaries. The shallowest water level was 103 m below land surface at the edge of the valley; the deepest water level was 111 m below land surface near the center of the valley.

Chemical analyses show that water quality deteriorates toward the center of the valley and that the uncorrected age of the water increases toward the center of the valley, suggesting that recharge occurs on the western edge of Salt Valley.

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