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Geohydrology of the Rattlesnake Ridge Interbed in the Gable Mountain Pond Area

S.R. Strait
B.A. Moore

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S. R. Strait
Basalt Waste Isolation Project

B. A. Moore
Health, Safety and Environment

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December 1982

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DISCLM-2.CHP (1-91)

Document Number RHO-ST-38

Title: GEOHYDROLOGY OF THE RATTLESNAKE RIDGE INTERBED IN THE GABLE MOUNTAIN POND AREA

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Program Office		Date

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A-6000-084 (R-12-80)

ABSTRACT

Liquid waste disposal practices at the U.S. Department of Energy's Hanford Site include the discharge of low-level radioactive liquid waste to cribs, trenches, and surface ponds. A study was conducted to develop a conceptual ground-water flow model and characterize the current distribution of radionuclides in the ground water of the Rattlesnake Ridge interbed at one of these facilities, the Gable Mountain Pond (facility 216-A-25). Specially constructed wells were drilled in the vicinity of Gable Mountain Pond to obtain radionuclide distribution data and hydrologic properties of the aquifer. The acquired data were analyzed to determine concentrations of anions, cations, selected radionuclides and ground-water flow patterns. Geologic mechanisms which may be responsible for the determined concentration distribution were evaluated using borehole and subsurface geophysical techniques.

EXECUTIVE SUMMARY

The Hanford Final Environmental Statement* identified the need to investigate the possibility for downward migration of water from the unconfined aquifer into the uppermost confined aquifer on the Hanford Site. This study, conducted in support of the Surveillance and Maintenance Program, was designed to evaluate and quantify the potential for downward migration of water into the uppermost confined aquifer in the Gable Mountain Pond area.

The objectives of the study were to: evaluate the distribution and concentration of radionuclides within the uppermost confined aquifer, the Rattlesnake Ridge interbed; determine a mechanism for aquifer intercommunication; determine the hydrologic properties of the Rattlesnake Ridge interbed; and develop a conceptual model of ground-water flow in the Rattlesnake Ridge interbed.

To obtain aquifer intercommunication data, a series of seven wells were drilled for ground-water chemical analyses, hydrologic tests, sediment analyses, and ground-water monitoring. A multigeophysical investigation, including magnetics, gravity, and electrical resistivity techniques, was used to delineate potential pathways (erosional areas) to the upper confined aquifer.

Results of the study indicate that the highest detected radionuclide levels exist in the uppermost confined aquifer in the southern portion of the study area. However, the radionuclide levels in this area were determined to be several orders of magnitude below concentration guides for water in an uncontrolled area listed in Table II, in Chapter XI of U.S. Department of Energy Order 5480.1. The pathway for radionuclides entering the confined aquifer was found to be an area of erosion in the uppermost basalt flow, with the elevated ground-water

*U.S. Energy Research and Development Administration, Final Environmental Statement, Waste Management Operations, Hanford Reservation, Richland, Washington, ERDA-1538, Vol. 1 and 2 (December 1975).

surface providing the driving force to move water from the unconfined aquifer to the confined aquifer. Within the study area, the Rattlesnake Ridge interbed has a hydraulic conductivity of 0.75 to 25.1 ft/day and the groundwater in the aquifer flows to the southwest.

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INTRODUCTION

Aquifer intercommunication between the unconfined and upper confined aquifer systems is being studied in an area north of the 200 East Area and south of Gable Mountain on the Hanford Site in Washington State (Figure 1). The area has undergone local structural deformation associated with the nearby Gable Mountain anticline; subsequently the area was eroded by the ancestral Columbia River and/or glacial flood waters.

The waste disposal pond under study is the Gable Mountain Pond (facility 216-A-25), constructed in 1957 to receive process cooling water and waste condensates from several sources within the 200 East Area. West Lake, located approximately 1 mile northwest of the study area, is a naturally occurring pond that later increased in size owing to discharges to cribs, trenches, and surface ponds within the Separations Area. As the water table within the unconfined aquifer rose due to water disposal, the hydraulic head in the unconfined aquifer became greater than the head within the confined aquifer system, creating the hydraulic potential for downward migration of contaminated ground water. Within the West Lake area, paleochannels cut into the confining Elephant Mountain basalt flow are believed to have formed a connection between the two aquifer systems (Gephart et al., 1976). Therefore, it was concluded that the hydrologic and geologic characteristics in the Gable Mountain Pond area provide the potential for aquifer intercommunication.

The Gable Mountain Pond investigation had the following objectives:

- To evaluate the distribution and concentration of radionuclides within the uppermost confined aquifer, the Rattlesnake Ridge interbed
- To determine a mechanism for aquifer intercommunication
- To determine the hydrologic properties of the Rattlesnake Ridge interbed
- To develop a conceptual model for ground-water flow in the Rattlesnake Ridge interbed.

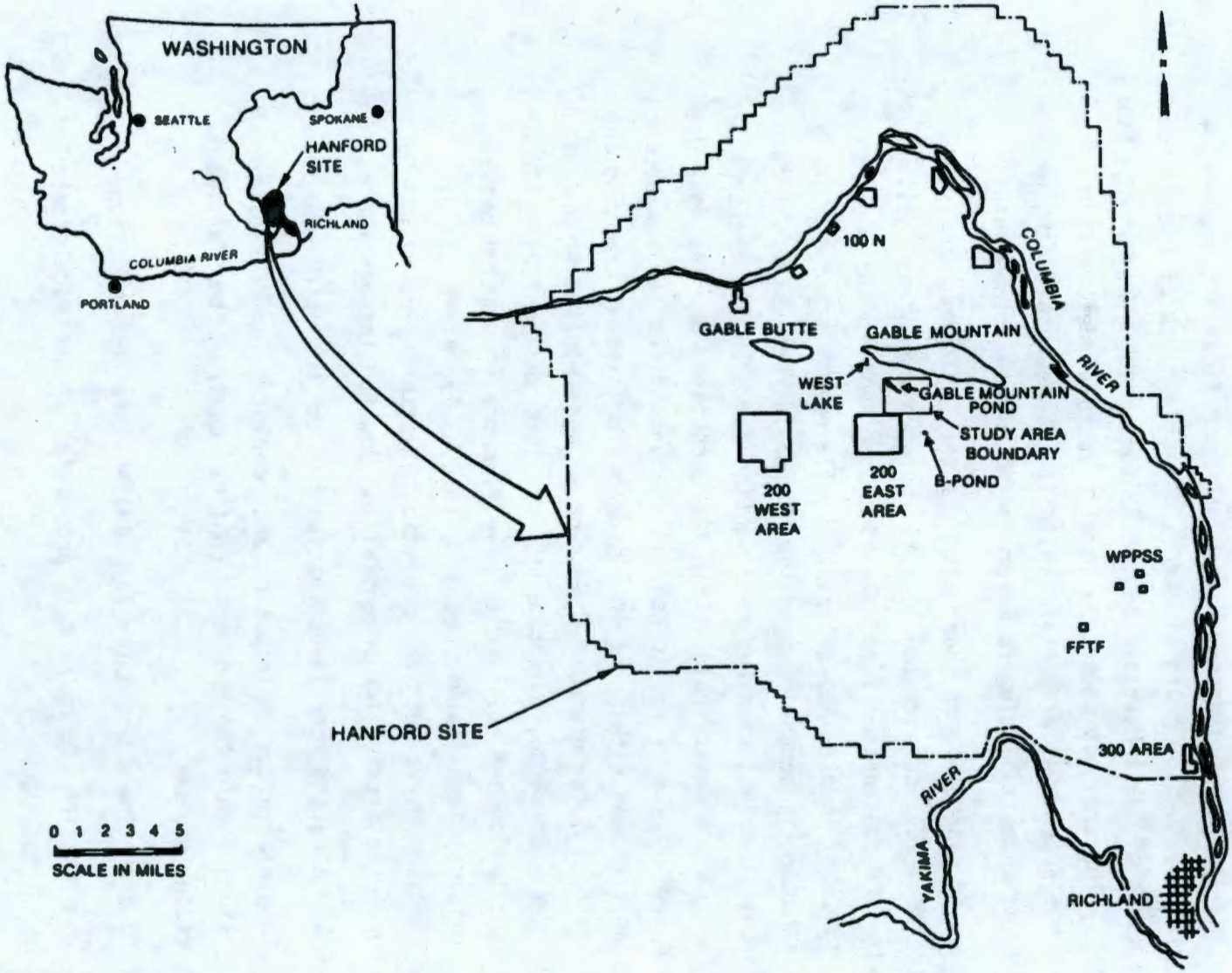


FIGURE 1. Location of the Gable Mountain Pond Study Area Within the State of Washington and the Hanford Site.

GABLE MOUNTAIN POND HISTORY

Gable Mountain Pond was constructed in 1957 and put into operation in December of that year. It now has a surface area of 71 acres, making it the largest of the Hanford ponds. Through 1981, the pond received a total of 5.65×10^{10} gallons of cooling water and steam condensate from various sources within the 200 East Area (Table 1). Gable Mountain Pond has received low-level radioactive liquid wastes, primarily ^{106}Ru, ^{90}Sr, and ^{137}Cs. Table 2 presents total discharges of radionuclides to Gable Mountain Pond through 1981. On June 1, 1964, a single unplanned release from a cooling coil in the PUREX Plant contributed about 100,000 curies of mixed fission products to Gable Mountain Pond and B-Pond. Following the incident, new inlet ditches were constructed and the water level in Gable Mountain Pond was maintained until the contamination level in the pond water decreased.

TABLE 1. Listing of Service Dates and Sources of Effluent to Gable Mountain Pond (from Sliger, 1982).

Service dates		Sources
From	To	
12/57	5/58	Received the process cooling water from the 202-A Building
5/58	11/67	Received the above effluents and the cooling water from the contact condenser in the 241-A-431 Building
11/67	1/68	Received the above effluents and the waste water from the 284-E Powerhouse
1/68	3/69	Received the above effluents, cooling water, and steam condensate from the 244-AR Vault
3/69	3/69	Valved out the pipeline to the contact condenser cooling water system
3/69	3/77	Received the process cooling water from the 202-A Building, the waste water from the 284-E Powerhouse, and the cooling water and steam condensate from the 244-AR Vault
3/77	12/81	Received the above effluents plus 242-A Evaporator-Crystallizer steam condensate and cooling water

TABLE 2. Inventory of Waste Discharged to Gable Mountain Pond Through December 31, 1981.*

Radionuclide	Waste inventory
^{241}Am (g)	$<0.163 \times 10^{-3}$
Beta (Ci)	0.945×10^{5}
^{144}Ce (Ci)	0.872×10^{-2}
^{60}Co (Ci)	$<0.440 \times 10^{2}$
^{137}Cs (Ci)	0.362×10^{3}
^{155}Eu (Ci)	0.409×10^{-2}
^{3}H (Ci)	$<0.708 \times 10^{1}$
Pu (g)	$<0.428 \times 10^{3}$
^{106}Ru (Ci)	$<0.740 \times 10^{3}$
^{90}Sr (Ci)	0.482×10^{3}
^{233}U (g)	$<0.459 \times 10^{3}$
^{238}U (kg)	$<0.126 \times 10^{5}$
Total volume (gal)	0.235×10^{12}

*From Sliger, 1982.

Prior to the development of the Separations Area, West Lake was an intermittent natural pond that appeared in the winter and spring when the water table was elevated. West Lake was used as a disposal site for sewage sludge from the early Hanford construction camp. High alkaline and phosphate levels, as well as the elevated pH values for West Lake, may be attributed to this use of West Lake. With cribs, trenches, and surface ponds receiving effluents, the water table rose, making West Lake a permanent feature.

Water samples are collected from Gable Mountain Pond and West Lake weekly and analyzed for gross beta and gross alpha activity. Concentration values for total beta and alpha are given in Table 3 (Wheeler and Law, 1980). Even though the gross beta and alpha concentrations for ^{90}Sr, ^{137}Cs, and ^{239}Pu are above background levels, they are below Table II, DOE Order 5480.1, Chapter XI, guidelines (U.S. Department of Energy, 1981).

TABLE 3. Water Samples from Gable Mountain Pond and West Lake for 1979.*

Sample site	Concentration in pCi/L			
	Total alpha		Total beta	
	Annual average	Monthly maximum	Annual average	Monthly maximum
216-A-25 Gable Mountain Pond inlet	<100	100	<40	40
216-A-25 Gable Mountain Pond north	<100	100	<40	60
West Lake	<500	1,100	300	1,900

NOTE: Hanford background levels taken from Houston and Blumer (1980)

$^{3}H = 290 \pm 450$ pCi/L

$^{60}Co = 0.79 \pm 3.0$ pCi/L

$^{90}Sr = 0.72 \pm 1.4$ pCi/L

$^{137}Cs = 0.10 \pm 0.73$ pCi/L

$^{239,240}Pu = 2 \times 10^{-4} \pm 4 \times 10^{-4}$ pCi/L

*From Wheeler and Law, 1980.

SITE DESCRIPTION

CLIMATOLOGY

The climate within the Hanford Site is largely influenced by topography and distance from the ocean, and the position of the high and low pressure systems in the Pacific Ocean. Storms from the Pacific Ocean are forced to rise over the Cascade Range to reach this area, resulting in mild temperatures and dry climate. The summers are generally sunny, warm, and dry with temperatures that can be greater than 100°F. Only 10% of the annual precipitation occurs during this time (Stone et al., 1972). However, the temperature can drop below zero in the winter, as the area is occasionally influenced by arctic air masses from Canada. Of the average annual precipitation of 6.25 inches (Stone et al., 1972), 37% falls in the winter months.

GEOLOGY

Regional

During the Miocene Epoch, basalts and interbedded sediments formed in portions of Washington, Oregon, and Idaho to become the Columbia River Basalt Group. During Columbia basalt volcanism, east-west trending folds developed, including the Umtanum-Gable Mountain structure that divides the Pasco Basin between the Cold Creek and Wahluke synclines (Figure 2). As a result of folding and subsidence of the Pasco Basin, fluvial and lacustrine sediments that were deposited in lakes and streams formed the Ringold Formation. Within the Quaternary Period, melt waters from glacial ice caused periodic and catastrophic flooding that eroded portions of the Ringold Formation and underlying basalts. As the melt waters receded, deposits of glaciofluvial sediments were left on the majority of the Hanford Site.

Gable Mountain Pond Area

The Gable Mountain Pond area is underlain by glaciofluvial sediments of the Hanford formation (informal name), fluvial and lacustrine

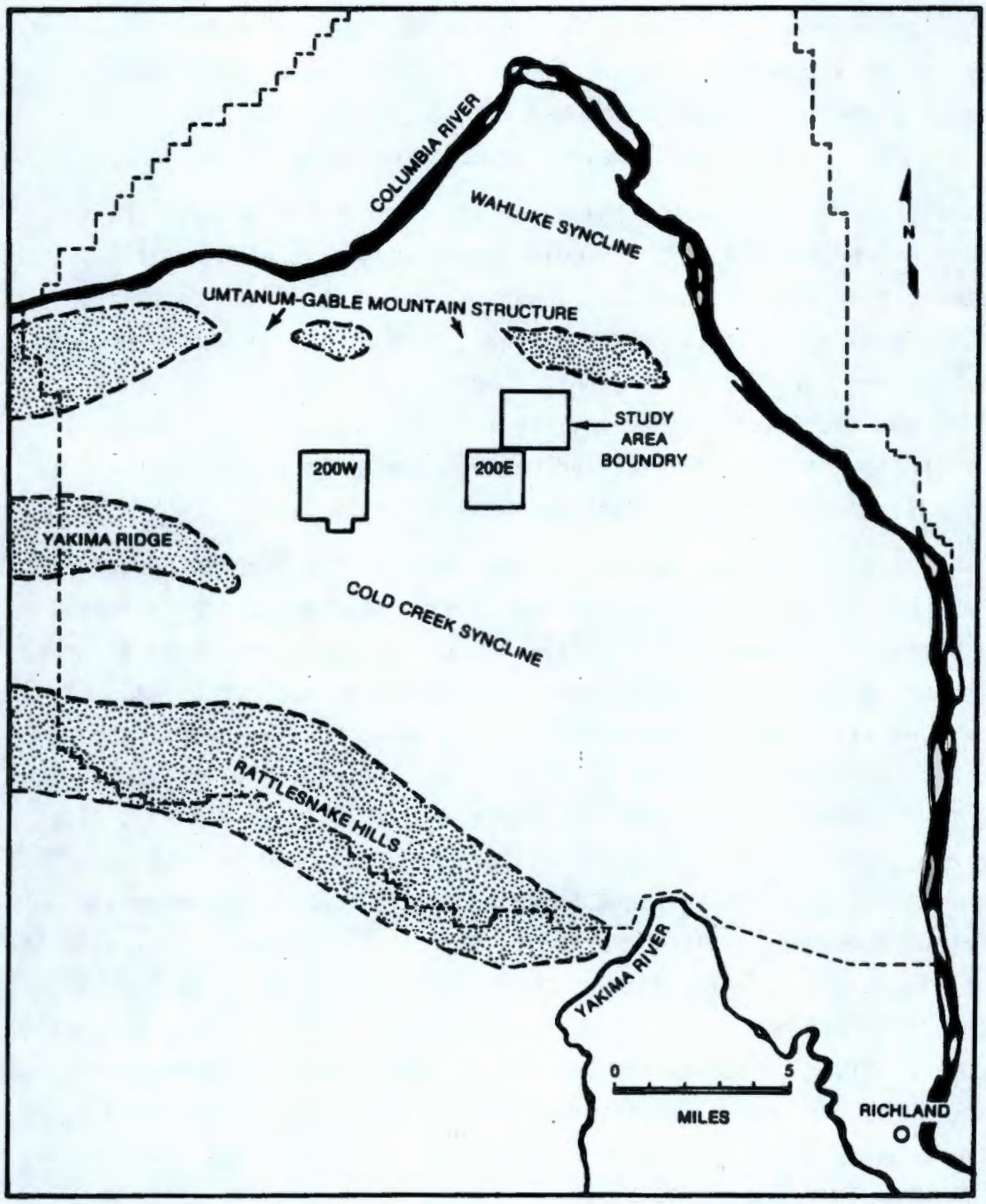


FIGURE 2. Location of Major Geomorphic Features in the Pasco Basin With Respect to the Study Area.

sediments of the Ringold Formation, plus the basalt flows and interbedded sediments of the Columbia River Basalt Group. Throughout the text, the Hanford formation and Ringold Formation are collectively referred to as unconsolidated sediments. This convention is adopted because formational thicknesses and lithologic characteristics vary greatly due to frequent changes in depositional mode.

Within the study area, the upper 900 feet of the Columbia River Basalt Group consists of the Saddle Mountains Basalt with basalt members, from the oldest to the youngest, which include: Umatilla, Asotin, Esquatzel (Gable Mountain flow), Pomona, and Elephant Mountain basalts; the interbedded sediments comprise the Mabton, Cold Creek, Selah, and Rattlesnake Ridge interbeds. Figure 3 shows the vertical distribution of the surficial sediments, basalt flows, and interbedded sediments as identified in wells within the study area.

Of primary concern to the current study is the Elephant Mountain basalt and the underlying Rattlesnake Ridge interbed, which represent the uppermost members in the Saddle Mountains Basalt in the study area. These members extend laterally throughout most of the Pasco Basin (Myers et al., 1979). Immediately around Gable Mountain Pond, the Elephant Mountain basalt has an average thickness of approximately 110 feet. The Elephant Mountain basalt contains little, if any, flow top due to erosion by the ancestral Columbia River and/or glacial melt waters. The Rattlesnake Ridge interbed lies between the Pomona and Elephant Mountain basalt and averages 46 feet in thickness in the Gable Mountain Pond area. The Rattlesnake Ridge interbed thins over Gable Mountain to between 5 and 18 feet in thickness (Fecht, 1978), suggesting minor uplifting of Gable Mountain during the deposition of the Rattlesnake Ridge interbed. The interbed consists of fine- to medium-grained arkosic sand, which is locally overlain by vitric tuff and clay ranging in thickness from 5 to 17 feet.

The geologic structure in the study area is dominated by Gable Mountain, which is an isolated, eastward extension of the Umtanum Ridge structure. North of the study area is the steep southern face of the Gable Mountain anticline. To the south the structure forms a gentle

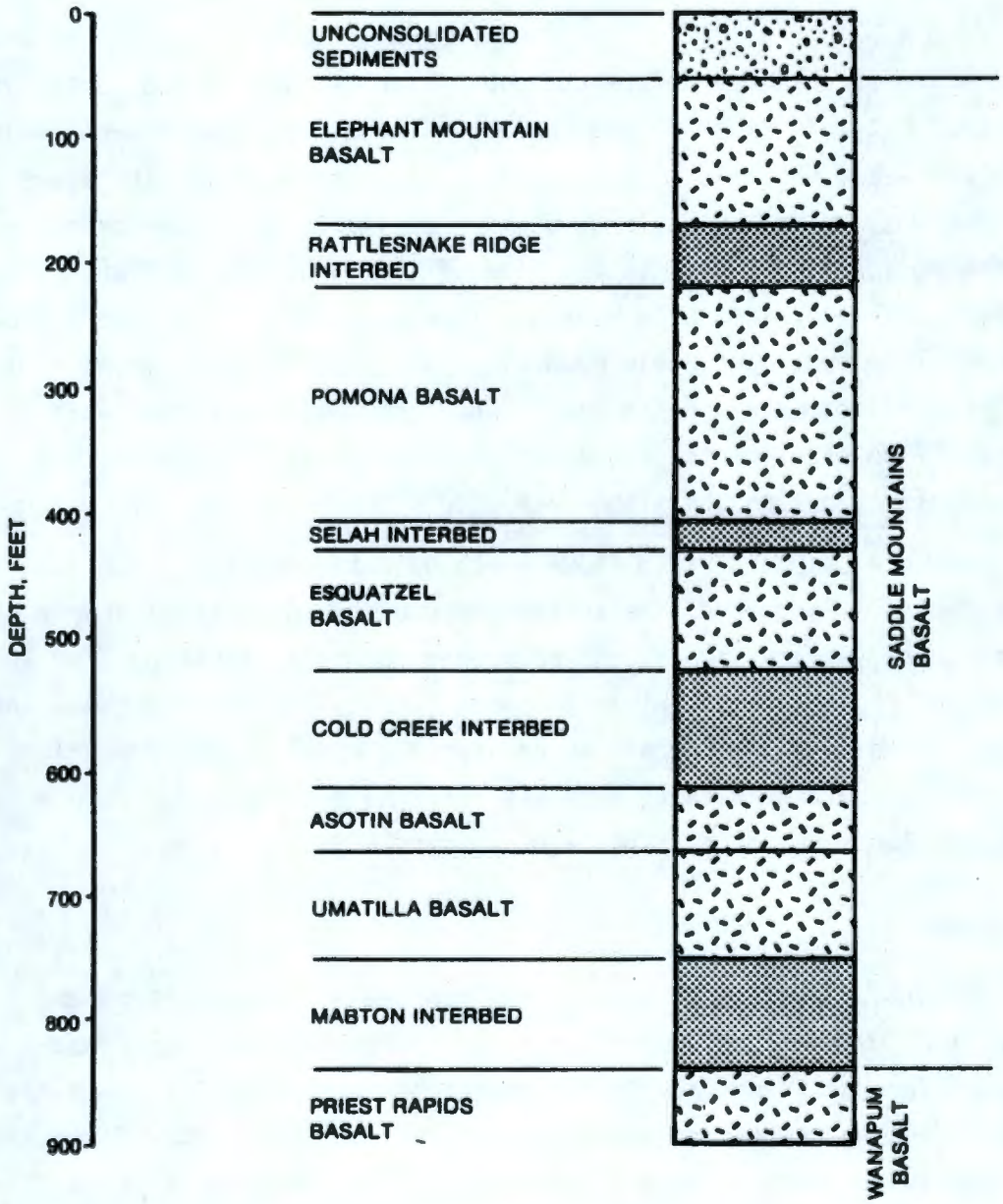


FIGURE 3. Stratigraphic Column Illustrating the Vertical Distribution of Unconsolidated Sediments, Basalt Flows, and Interbedded Sediments Within the Study Area.

slope of 2 degrees, and locally as high as 10 degrees, as it forms the northern limb of the Cold Creek syncline (Fecht, 1978). A small west-northwest trending parasitic fold or second order fold occurs approximately 1-1/2 miles south of Gable Mountain within the study area (Figure 4).

During or possibly before the deposition of Ringold sediments, the ancestral Columbia River flowed through a structural low between Gable Butte and Gable Mountain. This resulted in erosion of basalt layers near the western end of Gable Mountain. Sediments were then deposited on the erosional surface. In the time of the catastrophic floods of glacial melt water from Lake Missoula (Bretz, 1969), flood waters flowed between Gable Butte and Gable Mountain, causing additional erosion of the Ringold sediments and the Saddle Mountains Basalt in the Gable Mountain Pond area. Thick sequences of glaciofluvial sediments also were deposited during this time over much of the area.

Now, the Columbia River flows north of Gable Mountain. In the Gable Mountain Pond area, the surface morphology consists of coarse gravel bars, terrace slopes, and abandoned channels resulting from the torrential floods of glacial melt waters (Fecht, 1978). The sands and gravels containing the unconfined aquifer now overlie eroded portions of the Saddle Mountains Basalt, possibly creating a pathway for intercommunication into the confined aquifer system.

HYDROLOGY

The ground-water hydrology of the Hanford Site consists of two major flow systems: an upper unconfined system and lower confined system. The unconfined aquifer is contained in surficial unconsolidated deposits and/or members of the Ringold Formation and Hanford formation. The underlying confined aquifers consist of (1) the lower Ringold member, in other areas of the Hanford Site, and (2) sedimentary interbeds and interflow contacts between basalt units of the Columbia River Basalt Group, throughout the Hanford Site. Each flow system has a characteristic water chemistry indicative of the type of aquifer.

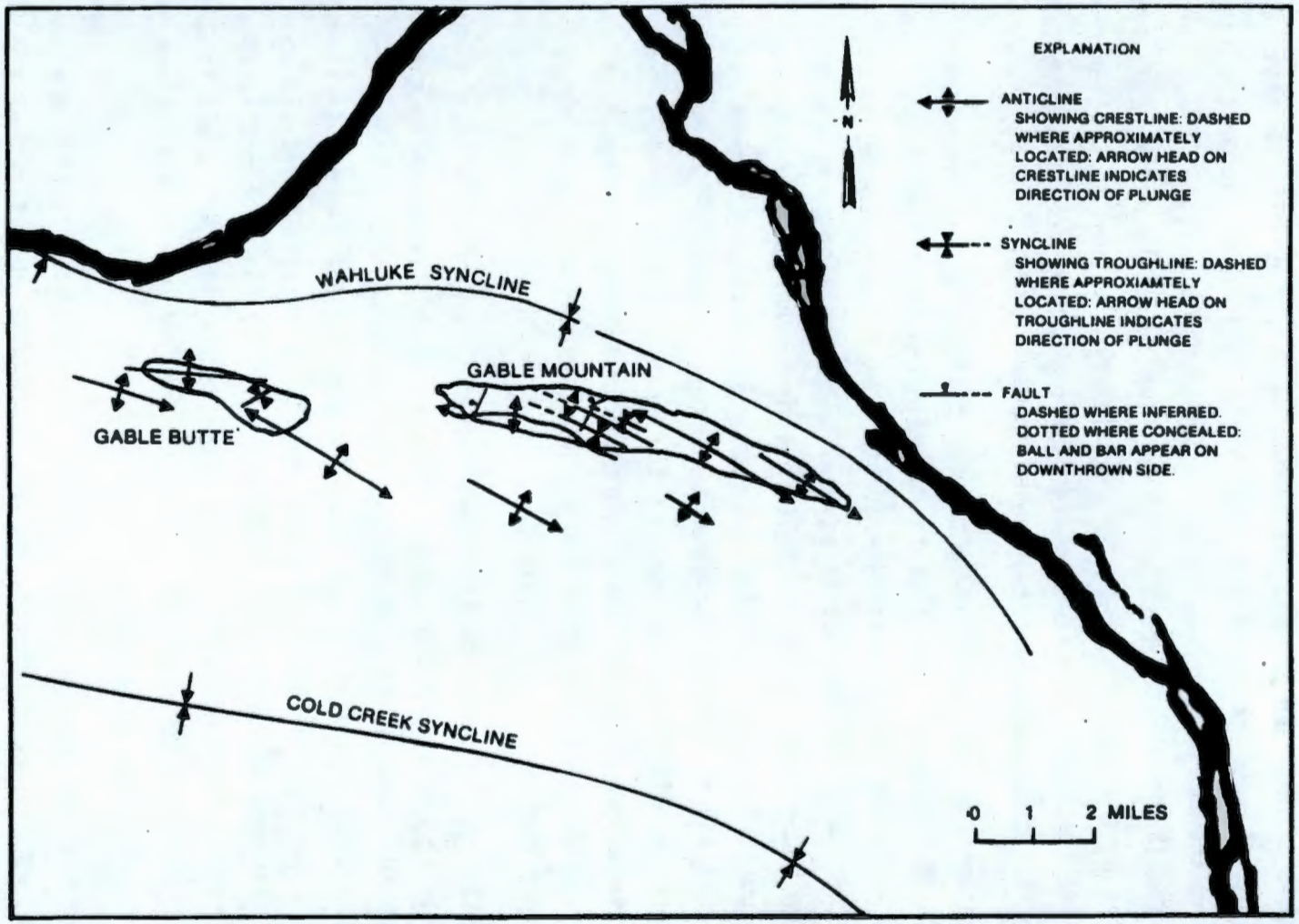


FIGURE 4. Generalized Geologic Structure in the Gable Mountain Area.

Unconfined Aquifer

The unconfined aquifer lies within the unconsolidated sediments of the Hanford formation and Ringold Formation. In the Gable Mountain Pond area, the base of the unconfined aquifer is defined as the basalt surface and the top is represented by the water-table surface. South of Gable Mountain Pond, the basalt surface lies above the water table, thus eliminating the unconfined aquifer in this area (Figure 5). In other locations, such as the western section of the study area, the unconfined aquifer is approximately 50 feet thick (Gephart et al., 1979).

Laterally, the unconfined aquifer encounters a no-flow boundary against the southern side of Gable Mountain and is otherwise continuous except where the basalt extends above the water table (see Figure 5). Natural recharge to the unconfined aquifer occurs along the western and southern boundaries of the Pasco Basin with discharge occurring along the Columbia River to the north and east. The hydraulic conductivity of the unconfined aquifer is variable, depending on the sediment size and the degree of limited cementation of the sands and gravels that comprise it. The Hanford formation has a hydraulic conductivity range from 500 to 20,000 ft/day and the Ringold Formation varies from 20 to 600 ft/day (Gephart et al., 1979).

Artificial recharge to the unconfined aquifer owing to liquid waste disposals to cribs, trenches, and surface ponds has resulted in a rise of the water table at this disposal site. In the Gable Mountain Pond area, the water table has risen approximately 20 feet since 1944 (Figure 6). The rise in the water table results in greater hydraulic potential for downward migration of ground water to the confined aquifer system if the confined aquifer has a lower hydraulic head. This is one of the conditions that must be met before aquifer intercommunication can occur from the unconfined to the confined aquifer system.

Chemical analyses are available for numerous wells within the unconfined aquifer as reported by Pacific Northwest Laboratory (PNL) (Eddy and Wilbur, 1980). Fifteen of these wells are located in or near the Gable Mountain Pond study area. The principle chemical constituents in

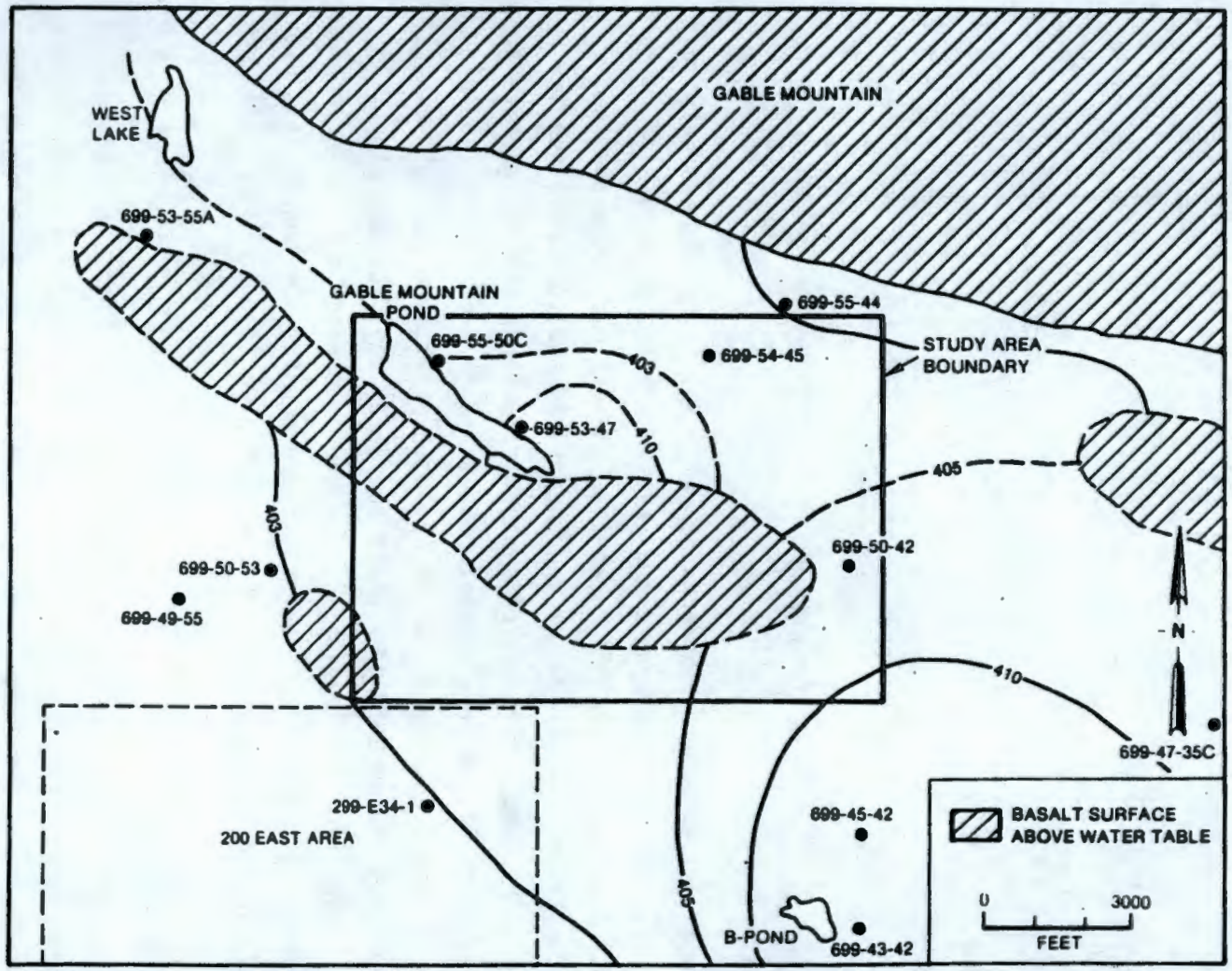


FIGURE 5. Water-Table Map in the Gable Mountain Pond Area, July 1980.

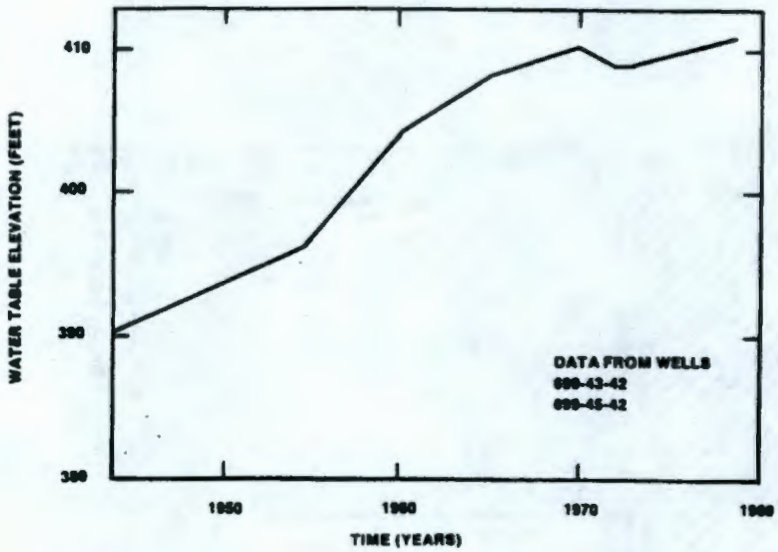


FIGURE 6. Average Water-Table Elevation in the Gable Mountain Pond Area.

the ground water include bicarbonate, calcium, magnesium, and sulfate, producing a calcium-bicarbonate and calcium-sulfate ground-water chemical type for the unconfined aquifer. A list of major chemical constituents and the ranges for the unconfined aquifer are given in Table 4. The best indicators of synthetic recharge are the nitrate and tritium levels in the ground water. They are present in the liquid waste discharges and are mobile in geologic materials. The nitrate levels within the unconfined aquifer decrease away from the disposal ponds (Figure 7). Tritium is incorporated into water molecules and therefore is not absorbed. The unconfined aquifer is contaminated with tritium throughout the Gable Mountain Pond area (Figure 8).

Confined Aquifers

The confined aquifers within the study area consist of sedimentary interbeds and/or interflow zones between dense columnar basalt in the Columbia River Basalt Group. The interbedded sediments generally have relatively low hydraulic conductivity except when they consist of sands to conglomerates. The main water-bearing portion of the interflow zones occurs within the upper portion of the flow where a network of interconnecting vesicles and fractures permits ground-water flow. The dense

portions of the basalt flows act as confining layers and have very low hydraulic conductivity. However, vertical cooling joints and fractures within the dense portion of a basalt flow can locally produce some degree of ground-water movement between confined aquifers (Gephart et al., 1979). The confined aquifers in the basalts extend laterally throughout most of the Pasco Basin except where the aquifers are eroded or are stratigraphically pinched out. The thickness of the confined aquifers varies from more than 170 feet in the Mabton interbed (the lowest confined aquifer in the Saddle Mountains Basalt) to a few inches in some basalt flow contacts.

TABLE 4. Range and Mean of Major Chemical Constituents Within the Unconfined Aquifer in the Hanford Site.*

Constituent	Concentration in mg/L	
	Range	Mean
Anions		
HCO_3^-	56 - 314	149
Cl^-	2.7 - 32	11
$SO_4^=$	2.7 - 99	43
NO_3^-	0.1 - 270	0.5
F^-	0.1 - 1.3	0.5
Cations		
Na^+	2.9 - 64	23
K^+	2.4 - 13	6.2
Ca^{++}	14 - 92	41
Mg^{++}	3.1 - 29	11

*From Gephart et al., 1979.

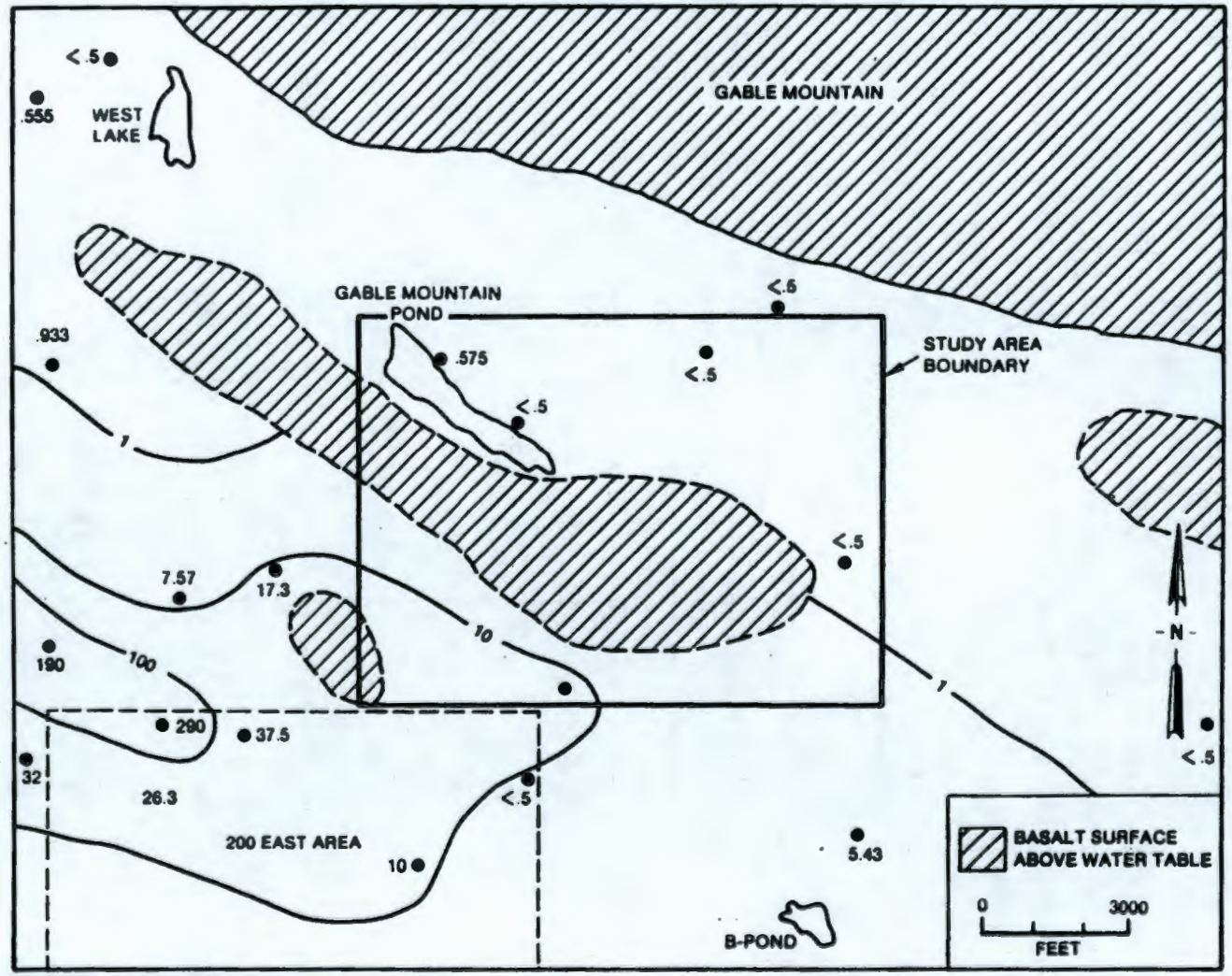


FIGURE 7. Nitrate Levels (ppm Nitrate) Within the Unconfined Aquifer in the Gable Mountain Pond Area.

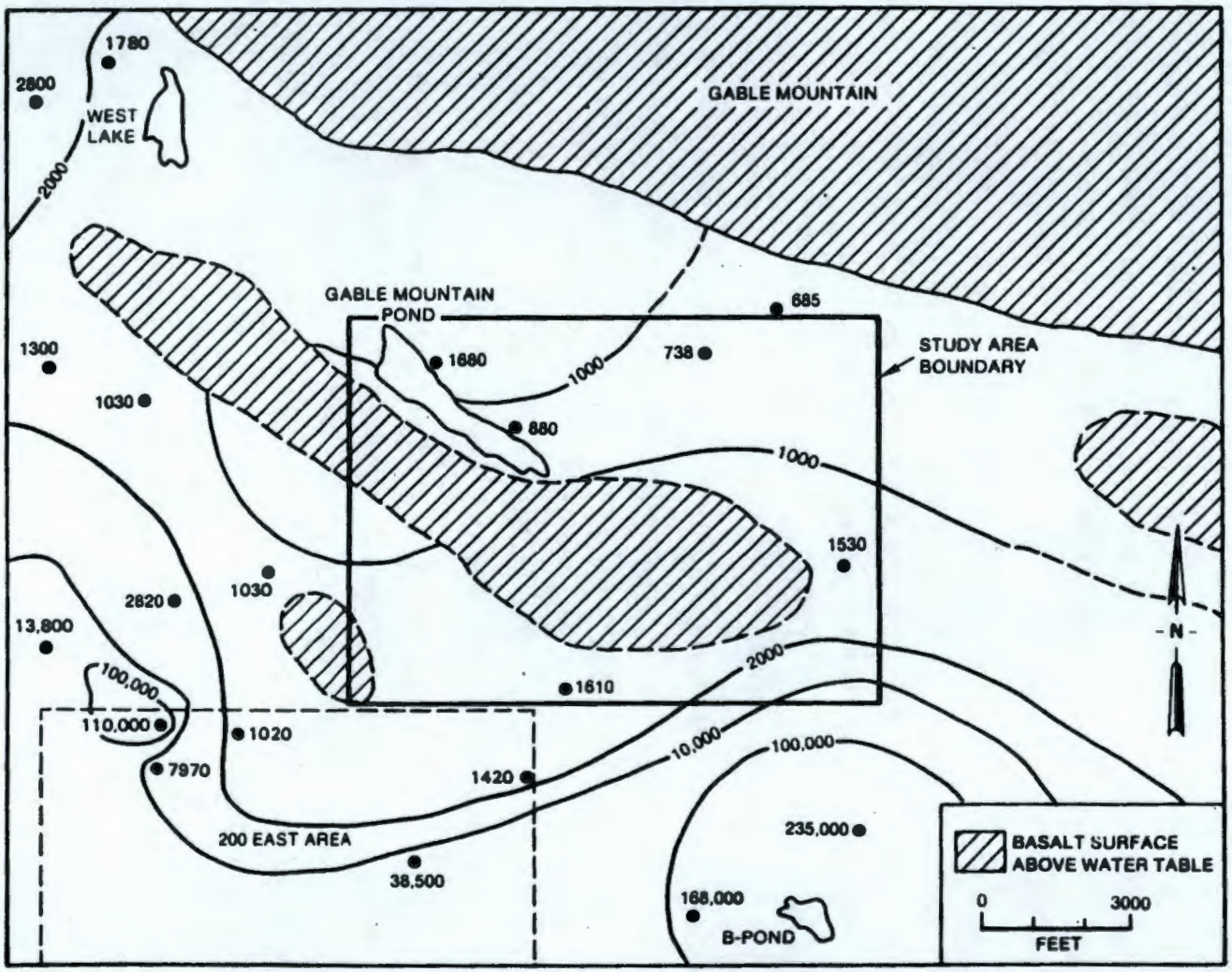


FIGURE 8. Tritium Levels (pCi/L) Within the Unconfined Aquifer in the Gable Mountain Pond Area.

The confined aquifer of major interest to this study is the Rattlesnake Ridge interbed and associated Pomona basalt flowtop. It is bounded to the north of the study area by the Umtanum-Gable Mountain structure (see Figure 2). To the west, the Rattlesnake Ridge interbed is bounded, in part, by paleochannels that eroded portions of the Saddle Mountains Basalt. To the south and east of Gable Mountain Pond, the Rattlesnake Ridge interbed extends laterally outside the Hanford Site (Myers et al., 1979).

Under most conditions, confined aquifers are under hydrostatic pressure, causing the water level to rise above the level of the aquifer and forming a potentiometric surface for that particular aquifer. The hydraulic head for the aquifer is influenced by the elevation of the source of recharge (anticlinal ridges), hydraulic conductivity of the aquifer, and the regional ground-water flow.

Hydraulic conductivity values for the Saddle Mountains Basalt aquifers were obtained primarily by pumping tests conducted at selected Hanford Site wells. Those tests indicated a hydraulic conductivity ranging from 0.1 to 100 ft/day for the sedimentary interbeds. The basalt interflow zones contain a much higher hydraulic conductivity, ranging from 100 to 2,000 ft/day (Gephart et al., 1979).

Table 5 lists the average of major chemical constituents for the ground water within the Mabton interbed. The Mabton interbed is used to represent the overall hydrochemistry of the confined aquifer system of the Saddle Mountains Basalt because it is extensive throughout the Pasco Basin and contains the most reported analyses (Gephart et al., 1979). The confined aquifer system is of a sodium-bicarbonate chemical type and contains much lower total dissolved solids than the unconfined aquifer. The confined aquifer is also characteristically low in nitrate.

TABLE 5. Mean and Range of Major Chemical Constituents Within Ground Water of the Mabton Interbed.[a]

Constituent	Concentration in mg/L	
	Range[b]	Mean[b]
Anions		
HCO_3^-	169 - 267	217
Cl^-	4.3 - 63	20
$SO_4^=$	0.3 - 18	4.0
NO_3^-	<0.5	<0.5
F^-	0.1 - 8	2.2
Cations		
Na^+	36 - 122	83
K^+	7.7 - 14	11
Ca^{++}	0.5 - 22	4.7
Mg^{++}	0.1 - 12	1.8

[a]From Gephart et al., 1979.
[b]Sampled from 11 wells.

PREVIOUS INVESTIGATIONS

Brown and Ruppert (1950) first reported radionuclide contamination within the unconfined aquifer system below both Separation Areas. Alpha activity ranged from less than 10 dis/min/L to 1,100 dis/min/L; beta activity ranged from less than 20 pCi/L to 4,300 pCi/L. This contamination occurred through past disposal of low-level liquid radioactive wastes, which were discharged to the surface and subsurface at waste disposal sites within the Separations Area. This practice of disposal is continued at present at a reduced rate. The lateral extent and distribution of radionuclide contamination within the unconfined aquifer is monitored and reported annually by PNL (Eddy and Wilbur, 1980) and Rockwell Hanford Operations (Rockwell) (Wheeler and Law, 1980). Even though information concerning the chemical composition and radionuclide concentration within the confined aquifers has been gathered since 1978, these data are sparse throughout the Hanford Site.

Eliason (1967) documented contamination of the lower member of the Ringold Formation, near the southeast corner of the 200 East Area. In this locality, the lower member of the Ringold Formation is considered a confined aquifer due to overlying clay. Here, maximum average beta and tritium activity levels of 1,820 pCi/L and 20 pCi/L, respectively, were reported. Significant activity levels were not established in the text prepared by Eliason (1967); however, contamination of the confined aquifer was concluded.

Ledgerwood and Deju (1976) investigated the Mabton interbed, the lowest confined aquifer in the Saddle Mountains Basalt, using existing data. From the well data, an area of potential intercommunication was suggested between the contaminated unconfined aquifer and the underlying confined aquifer system within the Gable Mountain Pond - West Lake area. Gephart et al. (1976) did a study on the effect of the water table on the expansion of B-Pond. Chemistries of surface, unconfined, and confined waters in existing ponds and wells in the Gable Mountain Pond area were examined. It was also suggested from this study that aquifer intercommunication exists in the Gable Mountain Pond area.

The geology of the Gable Mountain - Gable Butte area was studied by Fecht (1978). The erosion of the basalt surface by glacial flood waters (Bretz, 1969) and the development of paleochannels in the Gable Mountain Pond - West Lake area were discussed, as well as the structure, stratigraphy, and geomorphology of the area.

Previous gravity investigations within the Gable Mountain Pond - West Lake area suggested the presence of a buried erosional channel at Gable Gap, the valley between Gable Mountain and Gable Butte (Richard, 1976).

All the previously published information on the Gable Mountain Pond area merely suggests the potential for intercommunication between aquifers. No studies were conducted to determine the extent of radionuclide contamination in the confined aquifer. With the potential for intercommunication and the lateral extent of the confined aquifer outside the Hanford Site, it is necessary to determine the impact from the Gable Mountain Pond area on the contamination of the upper confined aquifer.

CURRENT STUDY

INTRODUCTION

An areal hydrologic study was designed to investigate and define areas of possible intercommunication in the Gable Mountain Pond area. Seven research wells were drilled to characterize the upper confined aquifer through sediment analysis, borehole geophysics, hydrologic testing and ground-water chemistry. Surface geophysical profiles extending from the wells were established to determine areas of possible erosion into the upper basalts that would provide a pathway for aquifer intercommunication.

WELL CONSTRUCTION

To characterize the Rattlesnake Ridge interbed, seven research wells were drilled in the Gable Mountain Pond study area (Figure 9). The wells are located in a cross-grid spacing one-quarter to one-half mile apart, southeast of Gable Mountain Pond. All wells are located using the Hanford Site coordinate system (McGhan and Damschen, 1977). Since each of the seven wells has basically the same construction, only a generalized description of the well construction will be given. Specific construction details for each well are summarized in Table 6.

Of primary concern in the construction of each well was the isolation of ground water within the Rattlesnake Ridge interbed from the overlying unconfined aquifer. To achieve this, several steps were followed during well construction. A 10-inch-cased entrance hole was drilled by cable tool methods through the unconsolidated sediments to the top of the Elephant Mountain basalt. A 10-inch-uncased hole was then drilled by air rotary methods through the Elephant Mountain basalt to the top of the Rattlesnake Ridge interbed with the exception of well 699-47-50, which was was drilled with the cable tool method. At this point, a 6- or 8-inch casing was cemented the entire length of the well to seal all ground water from the well. To insure proper cementing, approximately 9 cubic feet of cement were placed at the bottom of the well inside the casing. The casing was then lifted 20 feet,

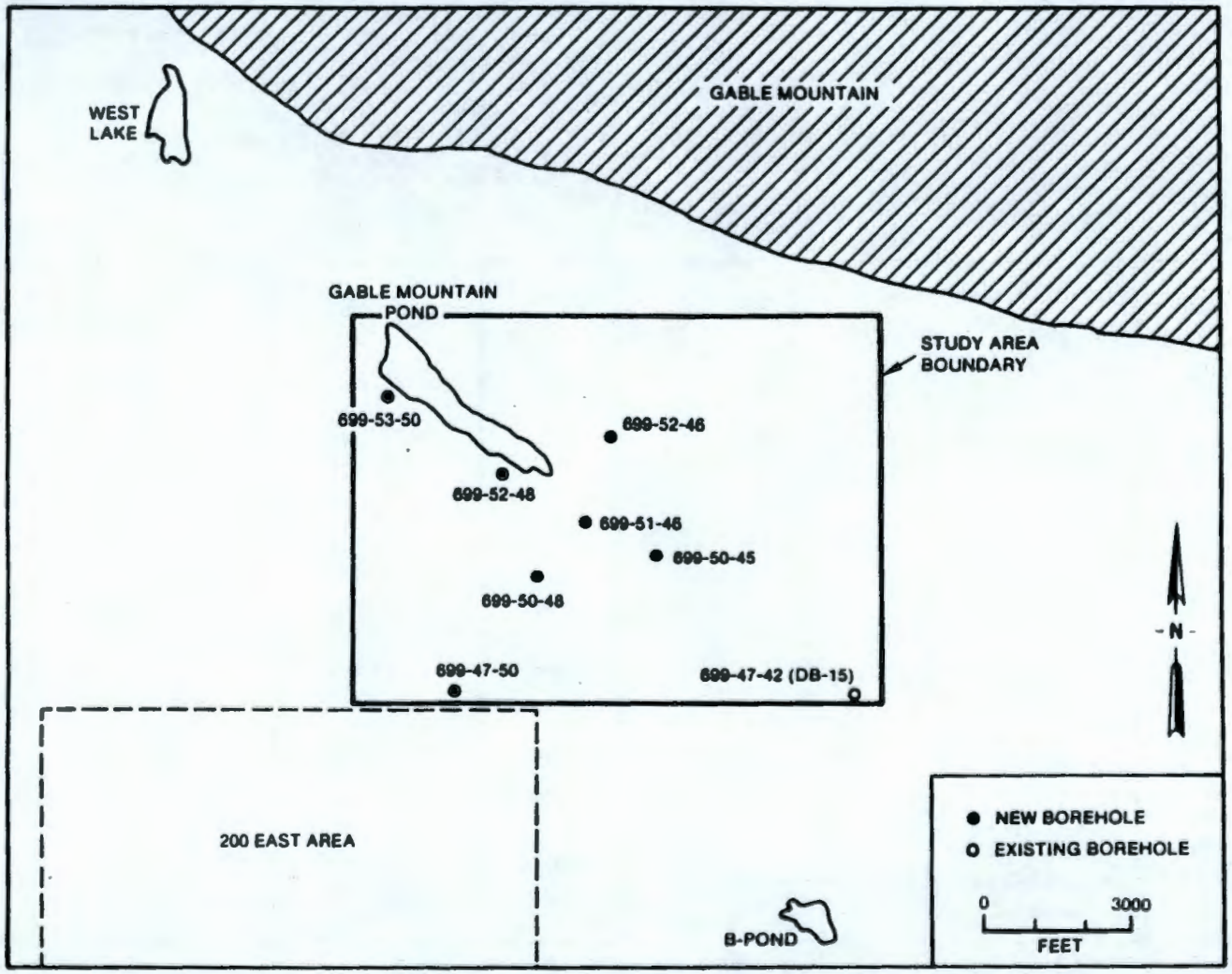


FIGURE 9. Location of Research Wells in the Gable Mountain Pond Study Area and Existing Well 699-47-42 (DB-15).

TABLE 6. Summary of Well Construction Detail for Gable Mountain Pond Area Research Wells.

Well	Hanford coordinates	Elevation MSL (ft)	Total depth (ft)	Casing		Screened interval and slot size (ft)	Date completed
				Size (in.)	Length (ft)		
699-52-48	N51,556.10 W48,076.32	466.06	197	8	149	145-195 (10 slot)	4/01/80
699-53-50	N53,218.59 W50,195.85	444.21	194	8	145	145-194 (10 slot)	4/14/80
699-51-46	N50,914.69 W46,414.34	444.63	168	8	120	120-163 (10 slot)	4/22/80
699-52-46	N52,196.03 W45,706.00	455.61	225	8	170	170-225 (10 slot)	5/07/80
699-50-45	N50,149.89 W44,992.17	451.41	178	6	133	133-178 (10 slot)	5/21/80
699-50-48	N49,980.41 W47,557.88	550.39	250	6	213	213-250 (20 slot)	6/06/80
699-47-50	N47,266.35 W49,507.91	583.87	295	6	260	260-295 (20 slot)	6/20/80

allowing the still-wet cement to fill the annular space behind the casing before lowering the casing back to the bottom of the well. The remaining annular space up to the ground surface was filled with cement by pouring the material in from the surface. Therefore, when cementing was completed, a seal existed at the bottom and top of the well to insure isolation of the Rattlesnake Ridge interbed. The quality of the cement was verified by cement bond (sonic-amplitude) logging as discussed in the Borehole Geophysical Logging section. A 6-inch hole was cable-tool drilled through the Rattlesnake Ridge interbed to the top of the Pomona basalt. Throughout the Rattlesnake Ridge interbed, a 6-inch telescoping well screen assembly (10 or 20 slot) was installed and a packer placed on top of the screen assembly to secure the screen to the casing.

SEDIMENT ANALYSIS

During the drilling of the seven research wells, sediment samples were collected for sieve analysis at 5-foot intervals throughout the Rattlesnake Ridge interbed. This was completed to define the lithologic character of the interbed and to compare grain size relations to borehole geophysical log responses.

The granulometric data used in this report were obtained by sieving. During this procedure, approximately 150 grams of the sediment sample are shaken through a group of nine sieves by a mechanical shaker. The group of sieves have wire mesh openings in accordance with the Wentworth grade-scale divisions, with openings ranging from 0.037 to 4.0 millimeters. Once the sample has been shaken (approximately 15 minutes), the disaggregate retained by each screen is weighed and recorded. The sediment is then classified according to a modified Folk classification scheme, which places more importance on the sand and the silt with its clay fractions (Fecht et al., 1978).

The results of the sieve analysis are presented in Appendix A as the percentages of mud (silt and clay), sand, and gravel content. The associated natural gamma log is also presented for each well. The Rattlesnake Ridge interbed predominantly consists of silty sand and

slightly silty sand. In most wells, silt and clay content increases in the upper portion of the interbed. This is also shown by the increase in natural gamma radiation in association with increased percentages of silt, clay, and ash content, as discussed in the next section.

BOREHOLE GEOPHYSICAL LOGGING

Borehole geophysical logs, as used in the investigation of the Rattlesnake Ridge interbed in the Gable Mountain Pond area, can be interpreted to determine lithology, formation resistivity, porosity, and relative bulk density. They may also be useful in determining the source, movement, and fluid temperature of the ground water (Keys and MacCary, 1971). In addition, well construction details can be ascertained from borehole geophysical logging, such as the bonding and location of the cement, and the size and depth of the casing.

Investigative Techniques

Eight geophysical functions were used to assist in the characterization of the upper confined aquifer system in the Gable Mountain Pond area (Table 7). Each of these logs (excluding the fluid temperature) was run prior to the installation of the screen through the Rattlesnake Ridge interbed to prevent any dampening of geophysical responses by the screen. To obtain more representative ground-water temperatures, the fluid temperature log was performed on all wells after hydrologic testing had been completed.

Lithologic Identification

Borehole geophysical logs are used to identify the depth and thickness of specific stratigraphic zones and to examine the basic rock characteristics within geologic units. The radiation logs (natural gamma, neutron-neutron, and gamma-gamma) are used to distinguish between basalt and interbedded sediment. The Elephant Mountain basalt exhibits uniform natural radiation, low porosity, and high density throughout its entire depth. It appears that the erosion by the ancestral Columbia

TABLE 7. Borehole Geophysical Functions Used for the Gable Mountain Pond Study.

Geophysical function	Basic use	Remarks
Spontaneous potential	Identification of interbed characteristics Zone thickness and depths	
Resistivity	Stratigraphic correlations Zone thickness and depths Mud infiltrate zones	
Fluid temperature	Locate sources of ground-water contribution into borehole Identify direction of ground-water circulation in borehole Pressure corrections for head measurements Geothermal gradient	
Caliper	Locating borehole breakouts and changes in borehole diameter Identifying liner sections Locating large rock fractures	
Natural gamma	Indicators of lithology Stratigraphic correlations	
Neutron-neutron	Moisture content Bulk porosity Stratigraphic correlations	Neutron source (Am-Be)
Gamma-gamma	Bulk density	Gamma source (^{137}Cs)
Sonic/cement bond log	Cement bonding between rock and casing Bulk porosity	

River and/or glacial melt waters has removed the vesicular flow top of the Elephant Mountain basalt. The Rattlesnake Ridge interbed characteristically has higher, more variable natural gamma response, lower density, and higher porosity. The depths of geologic units (as determined from the borehole geophysical logs) penetrated in the seven research wells are presented in Table 8. The flow top of the Pomona basalt was not detected in the geophysical logs because of the basalt's proximity to the borehole bottom.

TABLE 8. Geologic Units Penetrated in the Research Wells.

Well	Unconsolidated sediments		Elephant Mountain basalt		Rattlesnake Ridge interbed	
	Depth (ft)	Thickness (ft)	Depth (ft)	Thickness (ft)	Depth (ft)	Thickness (ft)
699-52-48	0-28	28	28-145	117	145-195	50
699-53-50	0-36	36	36-145	109	145-195	50
699-51-46	0-12	12	12-120	108	120-165	45
699-52-46	0-50	50	50-165	115	165-225	60
699-50-45	0-37	37	37-133	96	133-178	45
699-50-48	0-112	112	112-212	100	212-250	38
699-47-50	0-215	215	215-260	45	260-295	35

The natural gamma log is used to determine the lithologic character within the Rattlesnake Ridge interbed. A fine-grained 5- to 7-foot-thick layer was identified in the upper portion of the interbed (Figures 10 and 11). It exhibits high gamma radiation (>300 counts/second) from thorium, which naturally occurs in most fine-grained (clay) sediments. The existence of the fine-grained layer in the Gable Mountain Pond area is anomalous for the Rattlesnake Ridge interbed throughout the Hanford Site. Its presence in this area could be related to the topographic high which existed in the Gable Mountain - Gable Butte area during the deposition of the Rattlesnake Ridge interbed (Fecht, 1978). The remainder of the interbed (18 to 55 feet) consists of silt and sand and produces a much lower (100 to 150 counts/second) natural gamma response.

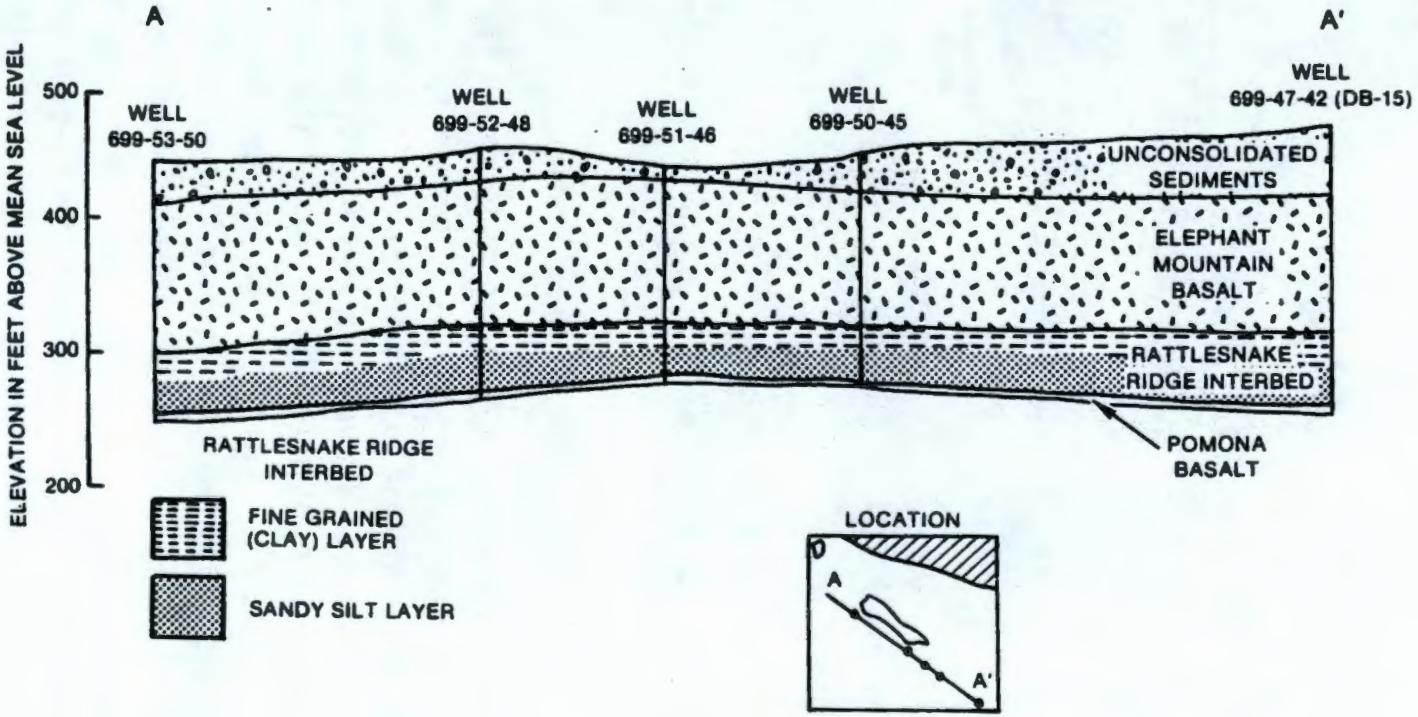


FIGURE 10. Geologic Cross Section Through Line A-A' in the Gable Mountain Pond Study Area.

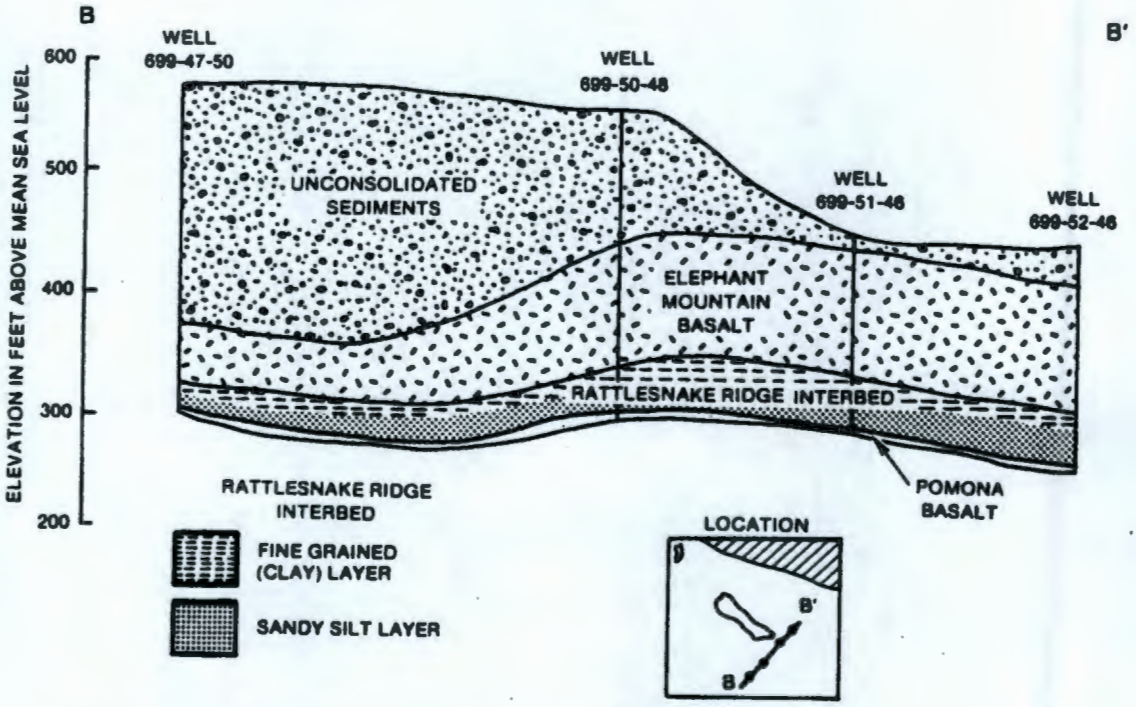


FIGURE 11. Geologic Cross Section Through Line B-B' in the Gable Mountain Pond Study Area.

Aquifer Isolation

The cement bond (sonic-amplitude) log was performed on five of the seven research wells to determine the quality of the cement. Equipment malfunction prohibited cement bond logging on two of the wells. An example of the cement bond log is given with well 699-53-50 (Figure 12). The well exhibits good bonding in the lower 16 feet of the cased portion, resulting in sonic signal attenuation and low wave amplitude. The remainder of the cement varies from poor to good bonding from 130 feet in depth to at least the water surface and reflects the method of cementation (see well construction). Therefore, good isolation of the Rattlesnake Ridge interbed exists as a result of good cement bonding in the lower and upper portions of the casing. The cement bond logs for the other wells are in Appendix B.

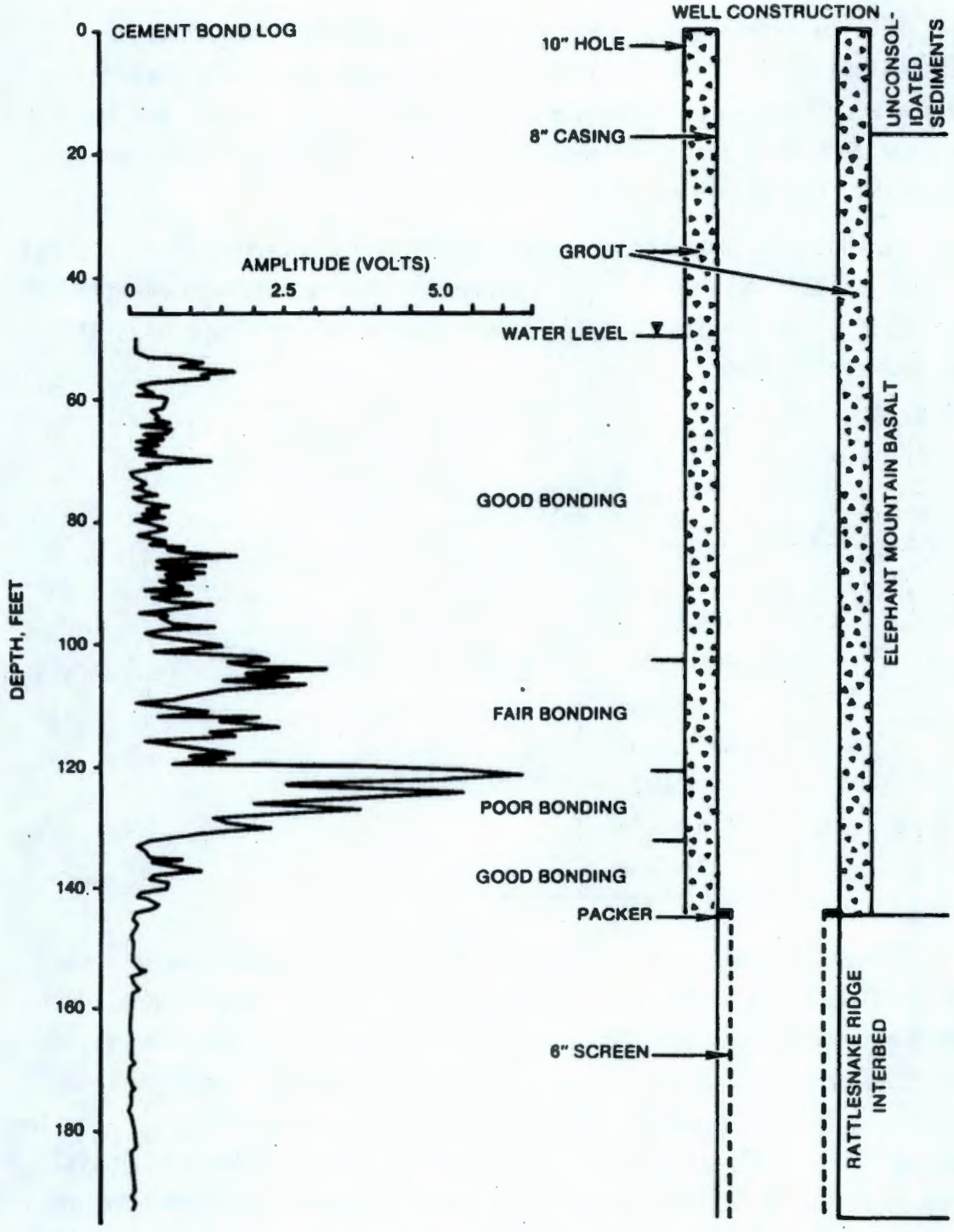


FIGURE 12. Cement Bond Log and Well Construction for Well 699-53-50.

Hydrogeologic Properties

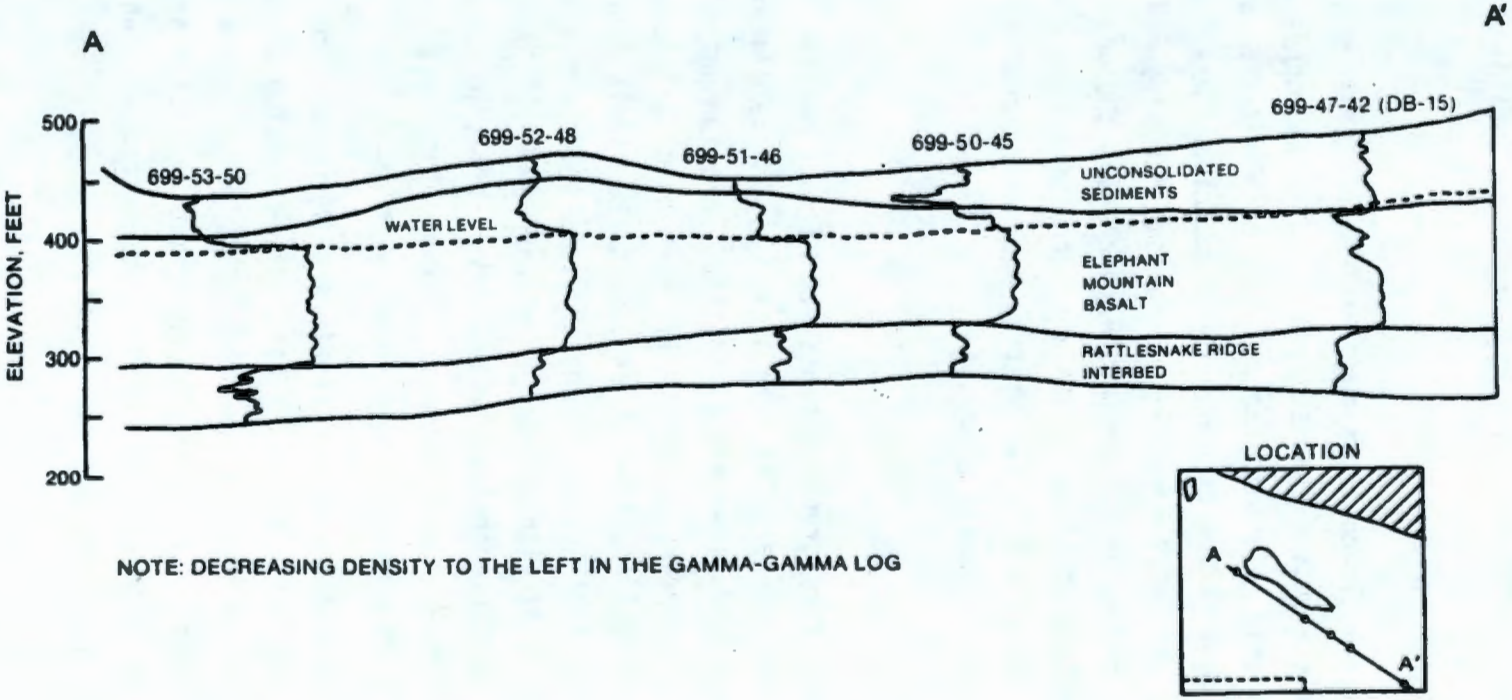
In situ hydrologic properties can be obtained from calibrated geophysical logs. However, only the fluid temperature and resistivity logs are calibrated to allow quantitative analysis. The radiation logs do provide good qualitative analysis and are important for examining variations in rock properties.

Fluid temperatures of the Rattlesnake Ridge interbed were obtained and are listed in Table 9. Temperature variations occur in relation to the depth of the aquifer and indicate a geothermal gradient of 2.9°F per 100 feet of depth.

TABLE 9. Fluid Temperature for the Middle of the Rattlesnake Ridge Interbed in the Gable Mountain Pond Area.

Well	Fluid temperature (°F)
699-52-48	62.2
699-53-50	62.2
699-51-46	61.7
699-52-46	64.0
699-50-45	62.2
699-50-48	65.1
699-47-50	64.9

A qualitative examination of the bulk density (gamma-gamma probe) of the Elephant Mountain basalt denotes a very dense basalt throughout the area underlying Gable Mountain Pond. However, the gamma-gamma log indicates the development of two basalt flows with an interflow zone separating them in borehole 699-47-42 (DB-15) as is evident from the low density interflow zone near the center of the Elephant Mountain basalt (Figure 13). The existence of this interflow zone, which also is present in borehole 699-17-47 (DB-13) (Gephart et al., 1979) may be important since it provides an additional confined aquifer (closer to the unconfined aquifer than the Rattlesnake Ridge interbed) for the possible



NOTE: DECREASING DENSITY TO THE LEFT IN THE GAMMA-GAMMA LOG

FIGURE 13. Gamma-Gamma Log Correlations Indicating Decreasing Bulk Densities of the Elephant Mountain Basalt Near Well 699-47-42 (DB-15).

lateral migration of radionuclides. However, the lateral extent of this interflow zone and the presence or absence of radionuclides is unknown.

SURFACE GEOPHYSICS

To evaluate the geologic controls and areal extent of intercommunication in the Gable Mountain Pond study area, a multigeophysical investigation was designed to extend control data obtained from hydrologic test holes. A combination of geophysical techniques was found to be useful in studying the Gable Mountain Pond area. Magnetic and gravity methods were employed to gain information concerning the depth and location of basalt surface erosional areas and structures. Electrical resistivity depth soundings aid in delineating hydrostratigraphic units and determining approximate basalt elevations.

Experimental Design

The sampling scheme for surveying consisted of four profile lines. A linear sampling design was selected over a grid system to minimize field efforts. A primary baseline was established in alignment with research wells. Three secondary baselines lie perpendicular to the northwest-trending primary line, thereby extending the sample network beyond West Lake toward Gable Gap. Figure 14 depicts the orientation and location of survey lines with respect to research wells. The primary line provides geologic control for secondary lines in the form of well logs and borehole surveys. Secondary survey lines were positioned to obtain data in areas not penetrated by wells.

Stations were located and ground elevations determined along profile lines at intervals of 164 feet. This station density is sufficient to provide a station spacing less than 1,312 feet, one-half the expected width of the bedrock channel. The experimental design applied to this study will allow major bedrock features to be resolved, while higher frequency features will be treated as noise.

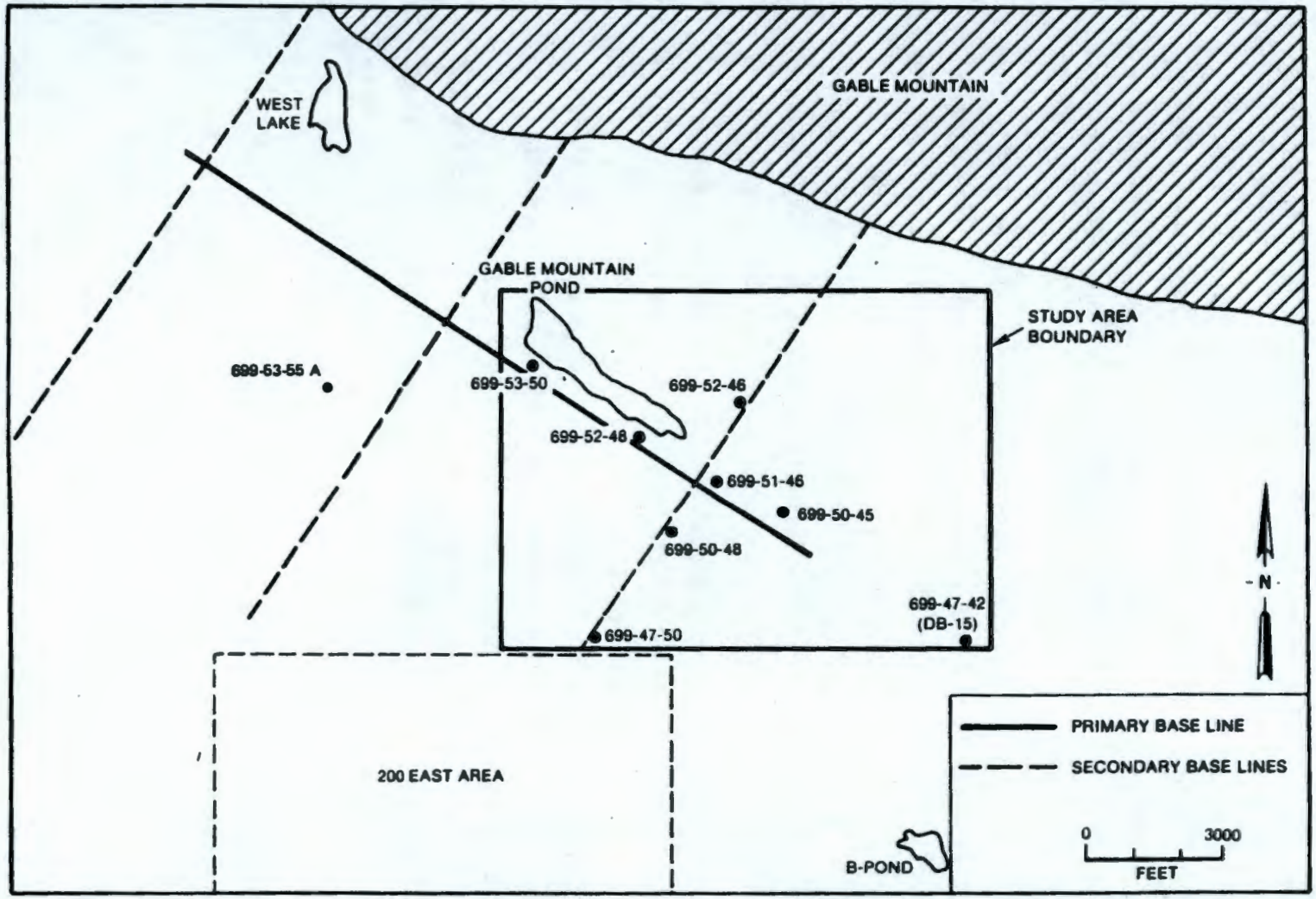


FIGURE 14. Location of Geophysical Survey Lines.

Investigative Techniques

Electrical Resistivity Depth Soundings. Direct current resistivity surveys measure the variation in electrical properties of rock materials with depth. For this study, variations in earth resistivity were analyzed to approximate basalt surface elevations where well data were scarce. Since resistivity values are dependent upon the amount, distribution, and quality of water in a formation, saturation content may be partly inferred.

Resistivity depth soundings were completed at 656- or 1,312-foot intervals along profile lines and at research well locations using a Soiltest resistivity meter. The Schlumberger electrode configuration was selected for surveying since it yields greater probing depth and resolution. By inducing a current to the ground and measuring the potential drop across an earth section, apparent resistivity values may be calculated for a given electrode separation, and configuration.

Resistivity values were plotted against electrode separation on log-log paper to produce a sounding curve. Sounding curves were automatically interpreted based on their similarity in shape to Dar Zarrouk curves (Zohdy, 1974). A geoelectric section is obtained, which consists of several layers that correlate to lithologic or hydrologic units. Table 10 compares basalt elevations determined by resistivity with those known in five reference wells located on Figure 15. Elevations determined by resistivity methods differ slightly from lithologic boundaries due to instrument errors. The geoelectric model was found to estimate accurately the basalt surface.

Gravity Profiling. Gravity profiles were designed and oriented to detect bedrock topography anomalies characteristic of incised channels and near-surface structures. Gravity variations measured from one location to the next are caused by lateral changes in density of earth materials. For example, erosional channels discovered locally are expressed as gravity lows. This is because glaciofluvial sediments filling the channel are less dense than the surrounding basalt.

TABLE 10. Basalt Elevations Determined by Vertical Electrical Soundings (VES) Compared With Those Known at Reference Well Locations.

Well	Reference well basalt elevation (ft)	Approximate basalt elevation from VES (ft)
699-53-50	409	406
699-52-48	438	434
699-51-46	433	431
699-50-45	414	421
699-52-46	405	398

A total of 294 stations were observed on four profile lines using a Worden gravity meter. Drift stations were reoccupied hourly to allow for corrections attributed to earth tide and instrument drift. A base station was secured at United States Geological Survey (U.S.G.S.) bench mark W 56 (1949) where absolute gravity was determined, providing a single reference point for the survey net.

Field values were corrected for drift, latitude, station elevation, and the influence of nearby topography. The objective in reducing data to absolute gravity is to isolate lateral variations in density by obtaining true Bouguer values. Bouguer values are then subjected to a simple trend surface analysis. The regional gravity gradient decreases linearly to the northwest; therefore, it is approximated by a first order equation and subtracted from corrected gravity data, leaving residual anomaly values. Removal of the regional gradient is mandatory in assessing the shape, density, and location of the anomaly's source.

Magnetic Profiling. Magnetic profiles were designed to measure variations in the gradient, direction, or intensity of the earth's magnetic field. The majority of magnetic variations in the study locality are remnant anomalies, or the result of permanent magnetization of iron-rich basalt units. This surveying method was employed to aid in mapping the location, extent, and structure of the upper Saddle Mountain basalts. The reversed magnetic character of the Pomona basalt contrasts to other

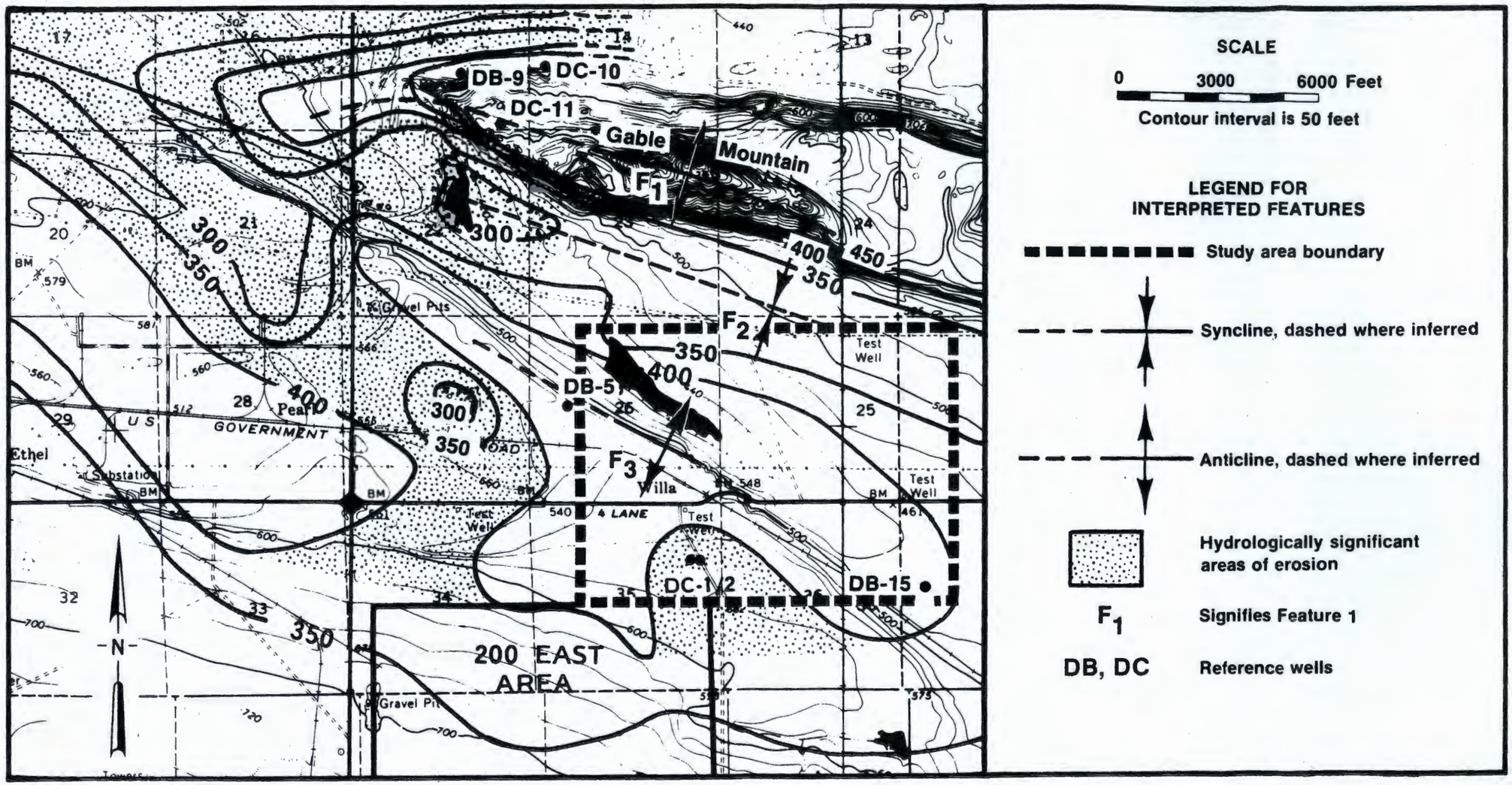


FIGURE 15. Top of Basalt Map Constructed by Multigeophysical Correlation of Electrical Resistivity, Gravity, and Magnetic Data Sets.

flows in the area that are normally or transitionally polarized. Consequently, its surficial presence may produce high amplitude magnetic depressions used to infer the basalt geologic configuration.

Magnetic measurements were taken along profile lines at 164-foot intervals with a Geometric model G-816 proton precision magnetometer. Surveys were conducted on days of minimal magnetic disturbance as reported by meteorological stations. Diurnal variations of the earth's magnetic field were corrected by hourly reoccupation of drift station. All readings were then tied to a reference site for qualitative comparison and interpretation. The effect on readings due to secular and global variations of the magnetic field are considered negligible for the resolution of this study.

Results

Introduction. Figure 15 is a top of basalt map constructed by multi-geophysical interpretation of all data sets. Electrical resistivity and data from DB, DC, and research wells are used primarily to estimate basalt surface elevations between the terrace (500-foot contour line) and south flank of Gable Mountain. On the terrace where the sedimentary overburden is thicker, well data and gravity profile trends are used exclusively in estimating basalt surface elevations. Resolving power of the Soiltest resistivity equipment decreases significantly as overburden thicknesses increase.

The surface of basalt depicted in Figure 15 reflects both the structural configuration and surface erosion of the upper Saddle Mountains Basalts. Structures include three features: feature 1 (F_1), the western Gable Mountain anticline; feature 2 (F_2), a buried syncline; and feature 3 (F_3), a buried anticline. Areas of erosion where there is a potential for aquifer intercommunication are also depicted, as inferred from geophysical surveys and well data.

Structures. Fecht's (1978) structure contour map depicts an anticlinal axis coincident with the eastern crest of Gable Mountain. Ground geophysical surveys support the subsurface extension of this feature north-

west toward Gable Gap, illustrated as F_1 on Figure 15. Total magnetic field data (Washington Public Power Supply System, 1977) are anomalously high in this region, suggesting local erosion of the Elephant Mountain and Pomona basalts. Erosion has exposed the Gable Mountain basalt, flanked by the Pomona basalt to either side, to overlying glaciofluvial sediments. Well data corroborate this interpretation. Evidence strongly suggests that the western Gable Mountain anticline was breached by the ancestral Columbia River and/or proglacial flood waters, exposing the confined aquifer system to the unconfined aquifer.

Research well data and gravity profiling of the Gable Mountain Pond area suggest the presence of a northwest-trending, buried syncline directly south of the western Gable Mountain anticline. This structure is depicted on Figure 15 as F_2. Upward curvature of the structure is observed on gravity profiles within one-quarter mile of the anticlinal axis (F_1), which the syncline closely parallels. The syncline's geophysical expression is obscured at West Lake by an erosional surface; hence, its direction and extent in this locality remain unresolved.

High ground and low-resolution airborne geophysical surveys confirm the presence of a subsurface anticline to the south of Gable Mountain Pond depicted in Figure 15 as F_3. The total magnetic field intensity map (Washington Public Power Supply System, 1977) indicates a high intensity dome coincident with the anticlinal fold axis located by Fecht (1978). The presence of this high intensity anomaly is not attributed totally to structural aspects of the area.

Fecht (1978) proposed that the buried anticline trends and plunges to the southeast. Gravity profiling between Gable Mountain and the 200 East Area suggests that maximum curvature of the anticline is isolated to the Gable Mountain Pond area. To the northwest, gravity and geologic profiles completed perpendicular to the structure show that it flattens or that the crest has been eroded. Insufficient data exist to determine an absolute axial trend or plunge direction. However, geophysical interpretations confirm an asymmetrical, northwest-trending anticlinal fold.

Erosional Surfaces. Extensive erosion in the Gable Butte - Gable Mountain area owing to late Pleistocene catastrophic flooding has been documented by Fecht (1978). Figure 15 illustrates the areas of erosion that are of hydrologic significance. Magnetic profiling at West Lake indicates that the Elephant Mountain basalt is eroded fully, exposing the Pomona basalt to the unconfined aquifer. Erosion of the Elephant Mountain basalt suggests formation in a high-energy fluvial environment. As great volumes of water were forced to move between Gable Butte and Gable Mountain, a plunge pool may have formed behind the breached anticline, referenced as F_1 on Figure 15.

To the south of Gable Mountain and across the subsurface anticline, minor areal erosion of the basalt surface is evident since the Elephant Mountain basalt flow top has been stripped off approximately 13 feet. However, local areas of more intense erosion are evident. For example, in well 699-53-55A (see Figure 14) the Elephant Mountain basalt is completely eroded away, and in well 699-47-50, 65 feet of the flow is gone.

Fecht (1978) assumed that these more intensely eroded areas defined a southeast branch of the erosional channel identified at Gable Gap. He illustrated the channel as a continuous feature connecting these points of deeper erosion. However, high resolution gravity and magnetic surveying between well localities do not detect the expression of such a buried erosional channel. Geophysical evidence suggests that these erosional surfaces are isolated and discontinuous. While it is possible that they are related by the same formational processes and may be penecontemporaneous, there is no doubt that they may be interpreted as a continuous feature. As an alternative, these deeply eroded areas should be referred to as "anomalies" until additional information is available to clarify interpretations.

HYDROLOGIC TESTING

To determine the hydrologic properties and the direction of groundwater flow in the Rattlesnake Ridge interbed in the Gable Mountain Pond area, hydrologic testing was performed on each of the seven research wells. The testing procedures included pump testing for determining

aquifer transmissivity and hydraulic conductivity, barometric efficiency, and hydraulic head measurements to determine ground-water flow direction. These factors were combined to characterize hydrologically the Rattlesnake Ridge interbed.

Pump Testing

Constant discharge pumping tests were performed following the development of each well. The development procedures involved overpumping (Johnson, 1975) with an air-lifting arrangement to bring coarse material adjacent to the screen. The well development was also used to estimate the aquifer's yield. Following well development, a one-half-horsepower submersible pump was installed in six of the seven wells; a five-horsepower submersible pump was installed in well 699-52-46. Water levels were monitored prior to pumping to assure that static conditions were reached. Each well was then pumped for approximately 24 hours with the discharge rate measured by a 1-inch Arad flow meter and a 60-degree V-notch weir. Drawdown water levels were measured using a Sinco Electro-Piezometer, an electric sounding tape, and steel tape. On termination of each test, recovery water levels were monitored manually until approximately 95% recovered. At that time, a Stevens water-level recorder was installed on the well to record continuously the late-time recovery water levels and obtain barometric water-level fluctuations for analysis of the barometric efficiency of the aquifer.

The straight-line analysis was used to determine transmissivity from the drawdown data (Cooper and Jacob, 1946) and recovery data (Theis, 1935) from the pumping well. To avoid head loss and other borehole effects, only late-time data were analyzed. Since no observation wells could be used due to the large distances between wells and the heterogeneity of the aquifer, a storativity value could not be computed with the pump test analysis. A summary of hydraulic properties of the Rattlesnake Ridge interbed is shown in Table 11. The semi-logarithmic plots and associated data are included in Appendix C.

TABLE 11. Summary of Hydraulic Properties of the Rattlesnake Ridge Interbed in Research Wells of the Gable Mountain Pond Study Area.

Well	Discharge rate, Q (gal/min)	Transmissivity, T (ft^2/day)			Hydraulic conductivity, K (ft/day)		
		Drawdown[a]	Recovery[b]	Average	Drawdown[a]	Recovery[b]	Average
699-52-48	8.07	37.27	36.79	37.03	0.75	0.74	0.75
699-53-50	6.90	540.35	639.88	590.12	11.50	13.61	12.56
699-51-46	2.69	30.48	107.72	69.10	0.68	2.39	1.54
699-52-46	47.1	187.76	135.27	161.52	3.13	2.25	2.69
699-50-45	8.46	131.92	173.65	152.79	2.93	3.86	3.40
699-50-48	6.95	371.09	278.32	324.71	9.77	7.32	8.54
699-47-50	5.68	465.50	1000.81	733.16	13.30	20.02	16.66

[a]Cooper et al., 1946.

[b]Theis, 1935.

Barometric Efficiency

Changes in atmospheric pressure in wells penetrating a confined aquifer can produce sizable water-level fluctuations. The relationship is inverse; that is, increases in atmospheric pressure will produce decreases in water levels, and visa versa. If atmospheric pressure is expressed in terms of feet of water, the ratio of water-level change to pressure change denotes the barometric efficiency of the aquifer (Jacob, 1940). Barometric efficiency was determined for each well by monitoring the water-level fluctuations with a Stevens water-level recorder (Table 12).

TABLE 12. Barometric Efficiency of Rattlesnake Ridge Interbed in Research Wells of the Gable Mountain Pond Study Area.

Well	Barometer efficiency (%)
699-52-48	12.3
699-53-50	53.0
699-51-46	61.6
699-52-46	42.0
699-50-45	44.5
699-50-48	52.2
699-47-50	29.9

Potentiometric Surface

Through measurement of the static water level in each well on July 9, 1980, a potentiometric surface of the Rattlesnake Ridge interbed was plotted (Figure 16). The potentiometric surface indicates a declining hydraulic head toward the southwest that probably results from recharge from Gable Mountain. This produces ground-water flow to the southwest. Before this investigation, the ground-water flow direction was assumed to be directly to the southeast from the Gable Mountain Pond area. The exact extent of the southwestward migration of the ground

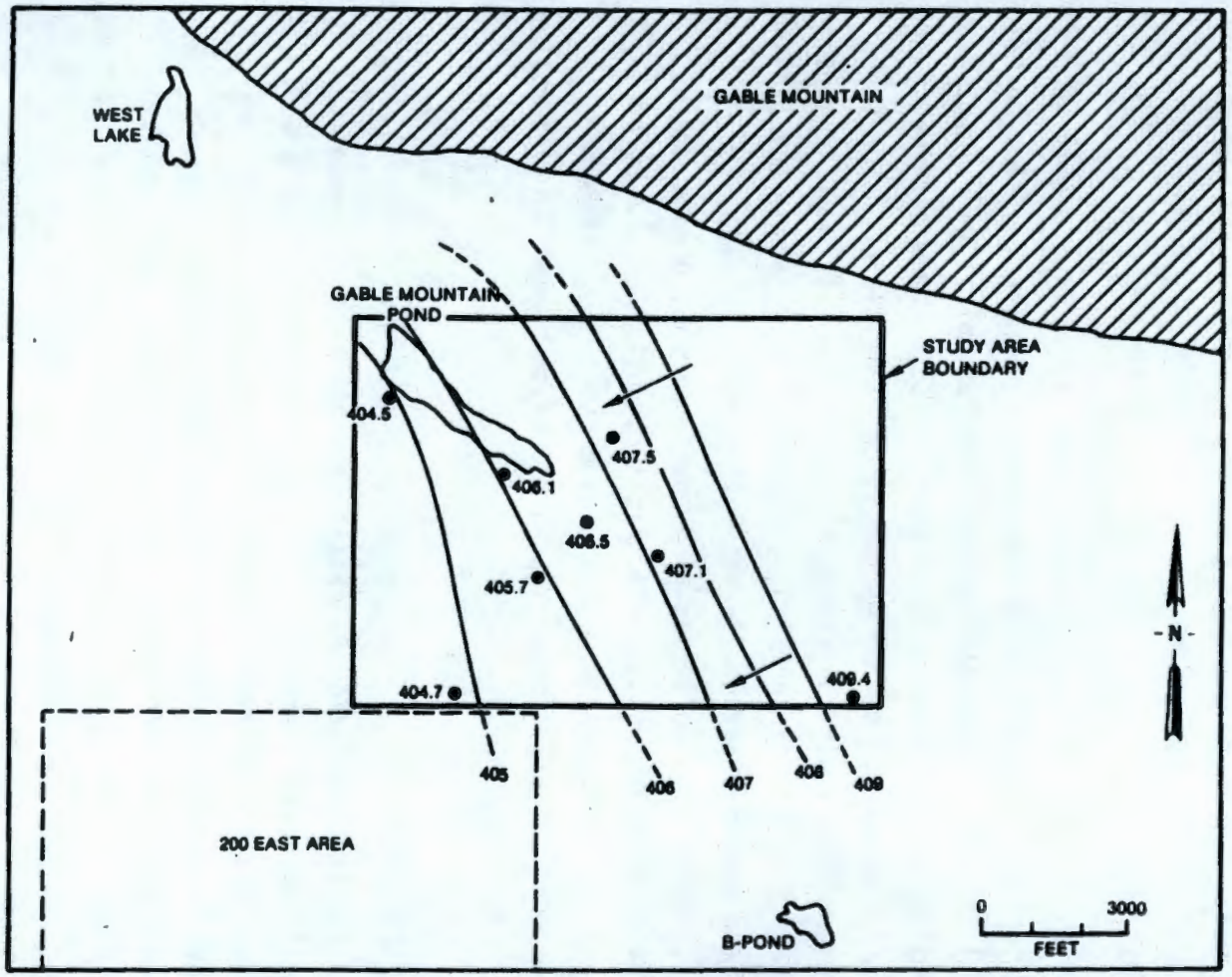


FIGURE 16. Potentiometric Surface (Feet Above Mean Sea Level) and Inferred Ground-Water Flow Directions of the Rattlesnake Ridge Interbed in the Gable Mountain Pond Study Area.

water is unknown, but it is presumed from the hydraulic heads of the Rattlesnake Ridge interbed in two boreholes outside the study area [699-17-47 (DB-13) and 699-25-80 (DB-14)] that the flow turns to the southeast, south of the Gable Mountain Pond area. See Figure 17 for the location of wells 699-17-47 and 699-25-80.

HYDROCHEMISTRY

Hydrochemistry data and isotopic analyses can be interpreted to evaluate the origin and source of ground water, ground-water flow paths, hydrochemical classification, and aquifer intercommunication. To attain this information, ground-water samples were collected from each well at the end of the pumping period for hydrochemical analysis of major ions, alkalinity, specific electrical conductivity, and pH. Isotopic analyses include tritium (^{3}H), deuterium (^{2}H), carbon-14 (^{14}C), iodine-129 (^{129}I), gamma scan, and oxygen-18:oxygen-16 ratio (^{18}O:^{16}O). In addition, ground-water samples were collected at 4-hour intervals during the pumping phase to monitor specific electrical conductivity and temperature. This ensured homogeneity of the ground water and, therefore, collection of representative samples prior to major ground-water sampling for chemical analysis.

Major Inorganic Composition

Aquifer intercommunication is easily detected by ground-water chemistry analyses because the unconfined and confined aquifer ground waters, excluding the Rattlesnake Ridge interbed, are of two distinct chemical types (calcium-bicarbonate and sodium-bicarbonate, respectively). Therefore, an indication of the ground-water source to the Rattlesnake Ridge interbed can be obtained by analyzing the major cations (Na^{+}, K^{+}, Ca^{++}, and Mg^{++}) and anions (HCO_3^{-}, NO_3^{-}, Cl^{-}, SO_4^{--}, and F^{-}) in the ground water.

A trilinear diagram (Figure 18) shows the chemical composition of ground water within the Rattlesnake Ridge interbed in the Gable Mountain Pond study area and surface water from Gable Mountain Pond and B-Pond.

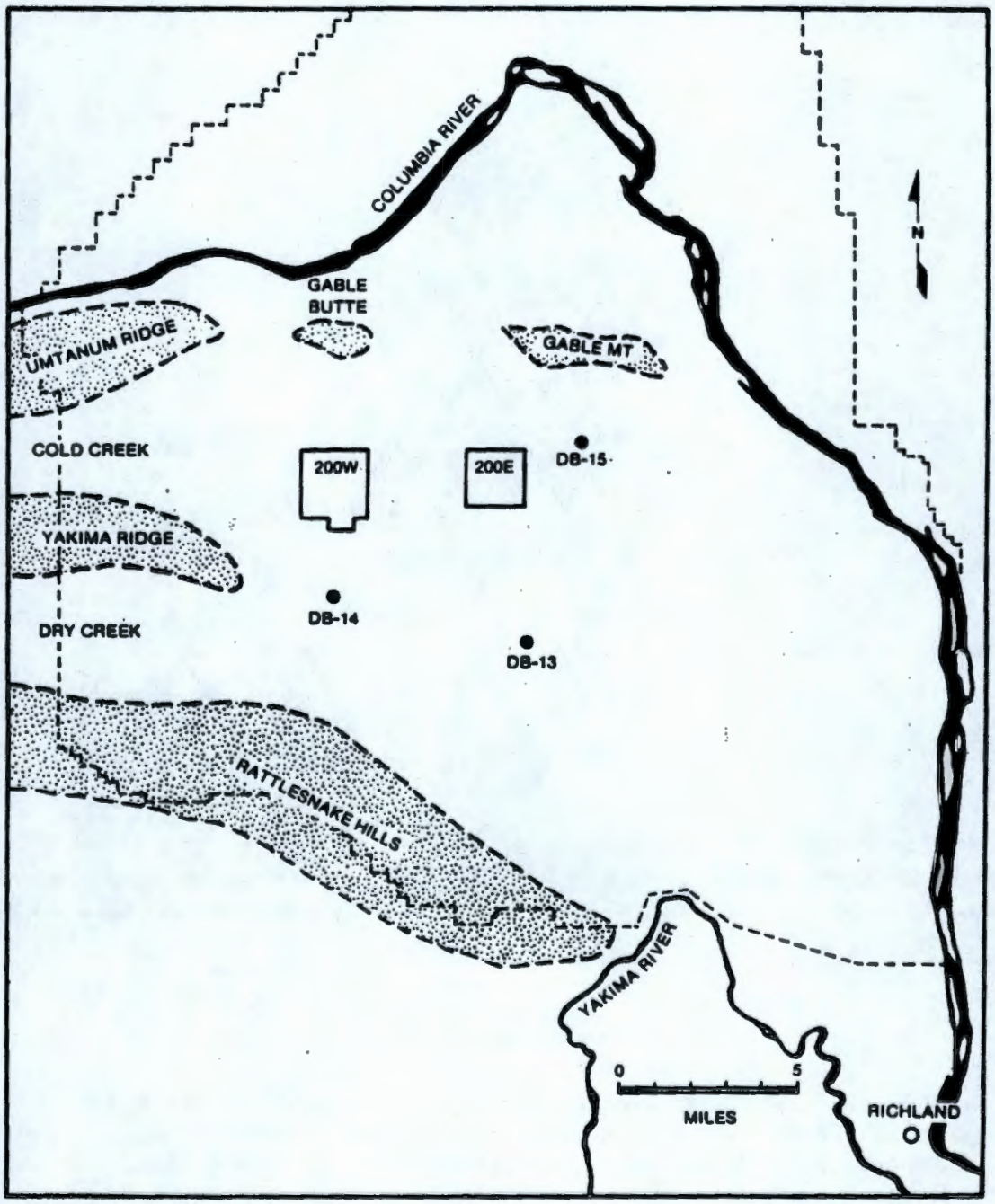


FIGURE 17. Location of Wells DB-13, DB-14, and DB-15.

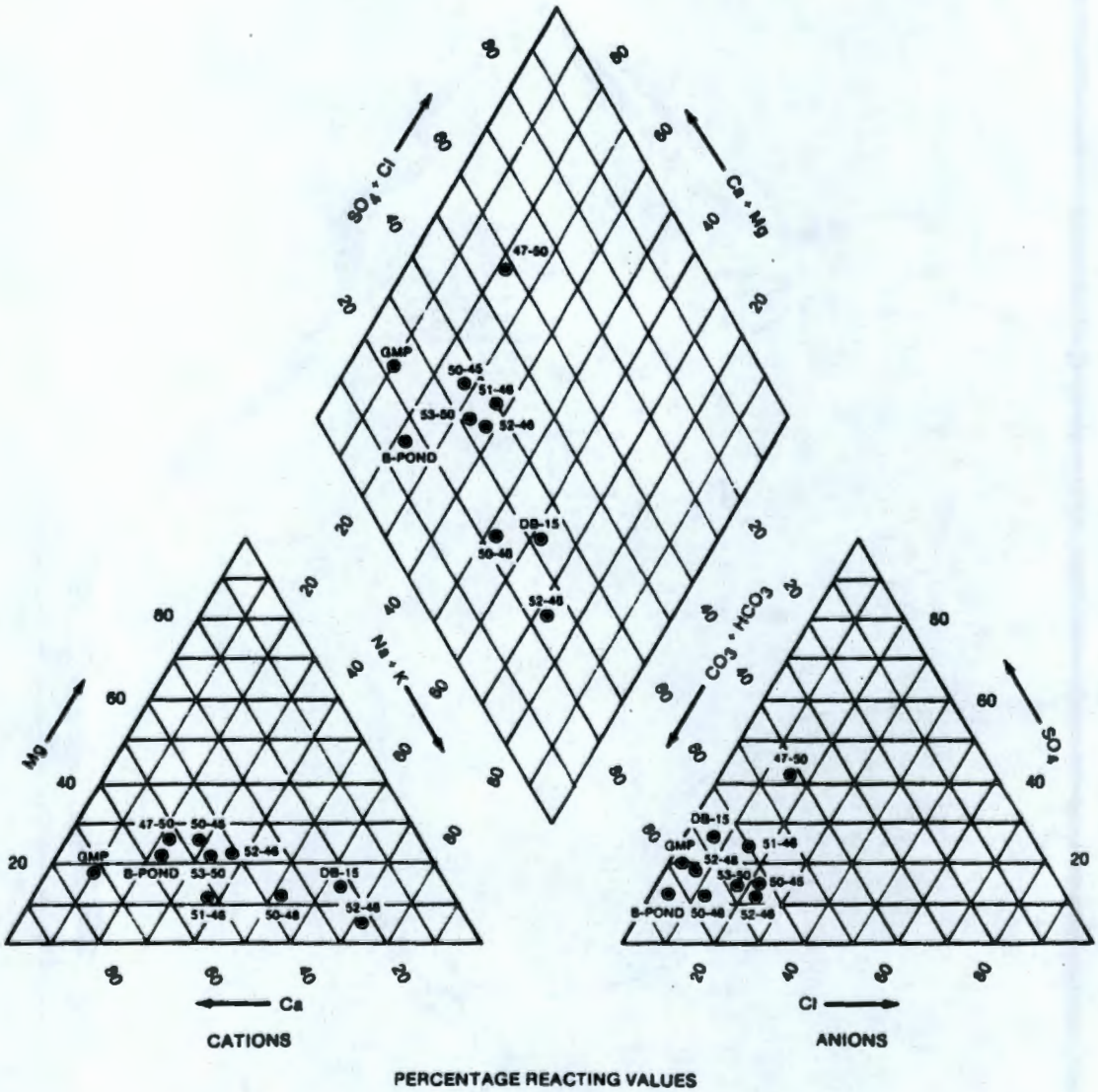


FIGURE 18. Trilinear Diagram Showing the Relationship of Major Chemical Constituents in Ground Water of the Rattlesnake Ridge Interbed, Well DB-15, Gable Mountain Pond (GMP), and B-Pond.

An overall chemical similarity exists between the ground water of the Rattlesnake Ridge interbed and the unconfined aquifer. This relationship is illustrated by examination of the trilinear diagrams in Figures 18 and 19. The data used in the construction of Figure 19 for the confined aquifer system (interflow zones and interbeds below the Rattlesnake Ridge interbed within the Saddle Mountains Basalt Formation) and the Rattlesnake Ridge interbed are from three core wells [699-17-47 (DB-13), 699-25-80 (DB-14), and 699-47-42 (DB-15) (see Figure 17)] and the unconfined aquifer data from wells throughout the Hanford Site. The diagram indicates similarity in chemistry between the unconfined aquifer and the Rattlesnake Ridge interbed with a significant overlapping of data envelopes. If no intercommunication were occurring, the Rattlesnake Ridge interbed chemistry would be more closely associated with the chemistry of the confined aquifer. The specific chemical constituents for each well and pond are listed in Table 13.

Isotopic Analysis

Tritium. The heavy isotope of hydrogen, ^{3}H, serves as an excellent ground-water tracer because it acts as part of the water molecule and is not sorbed by the aquifer material. Tritium is present in the ground-water environment of the Hanford Site largely as the result of past disposal of radioactive waste in cribs, trenches, and surface ponds.

The distribution of ^{3}H content in the Rattlesnake Ridge interbed is shown in Figure 20. Of primary interest are the elevated ^{3}H levels (up to 308.2 pCi/L) (0.01% of concentration guidelines, Table II of DOE Order 5480.1, Chapter XI) in well 699-47-50 located just north of the 200 East Area (see Figure 14). Much lower ^{3}H levels ranging from 0.06 to 1.79 pCi/L occur adjacent to Gable Mountain Pond.

Deuterium and Oxygen-18. Results of ^{2}H and ^{18}O analyses for ground-water samples from the Rattlesnake Ridge interbed and several surface water bodies are shown in Table 14 and Figures 21 and 22. Examination of Table 14 indicates a considerable range in isotopic composition for samples analyzed, probably due to varying degrees of intermixing of ground waters.

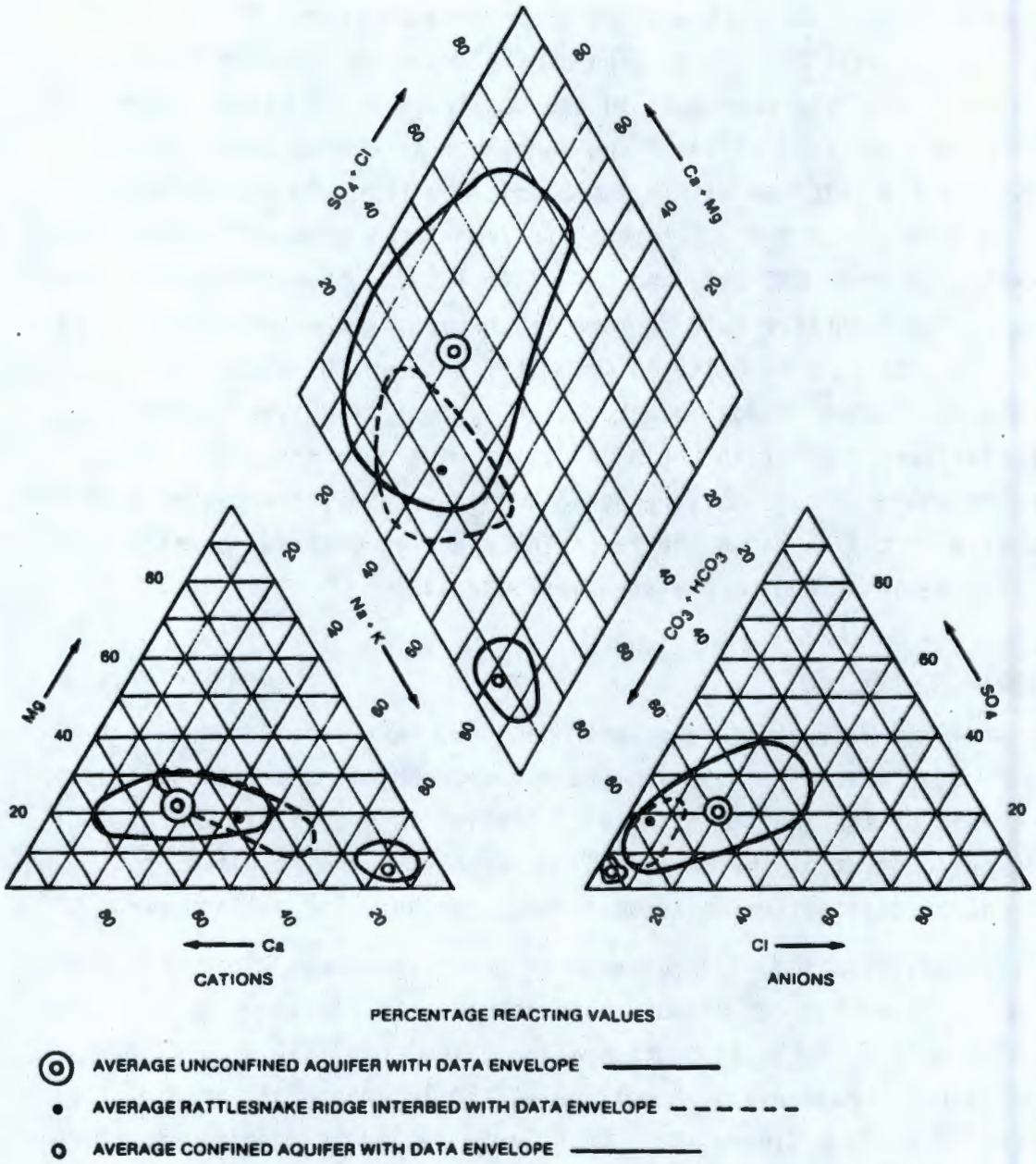


FIGURE 19. Average Chemical Composition of Ground Water Within the Unconfined Aquifer, Confined Aquifer System (Interflow Zones and Interbeds Below the Rattlesnake Ridge Interbed Within the Saddle Mountains Basalt Formation), and Rattlesnake Ridge Interbed.

TABLE 13. Inorganic Chemical Constituents of the Rattlesnake Ridge Interbed Taken from Research Wells, Well DB-15, Gable Mountain Pond, and B-Pond.

Source	Anions (mg/L)					Cations (mg/L)				pH	Specific electrical conductivity (μmhos/cm)
	HCO_3^-	Cl^-	SO_4^{--}	F^-	NO_3^-	Na^+	K^+	Ca^{++}	Mg^{++}		
699-52-48	160.7	4.99	35.27	0.71	--	51.70	6.69	14.43	3.06	7.4	330.7
699-53-50	131.2	20.99	18.93	0.42	1.05	20.39	7.12	28.98	8.63	7.2	306.8
699-51-46	104.3	16.98	32.85	0.46	1.18	20.00	9.31	32.02	4.23	8.9	254.9
699-52-46	130.6	25.95	21.02	0.46	0.43	16.51	4.23	33.63	9.19	7.4	313.4
699-50-45	115.3	22.97	20.52	0.49	0.93	16.39	5.71	30.02	10.21	7.4	301.1
699-50-48	162.0	16.98	16.78	0.80	0.12	30.39	10.99	22.08	4.23	7.5	320.3
699-47-50	128.7	30.95	107.3	0.57	7.63	20.39	7.39	55.31	14.66	7.5	521.6
DB-15	153.6	7.70	37.10	--	7.00	44.40	10.40	18.90	4.90	--	--
B-Pond	55.68	0.80	9.10	0.10	11.5	2.21	9.38	18.24	4.13	--	--
Gable Mtn. Pond (avg)	79.37	3.00	11.80	0.10	--	3.33	1.17	20.64	4.26	7.7	--

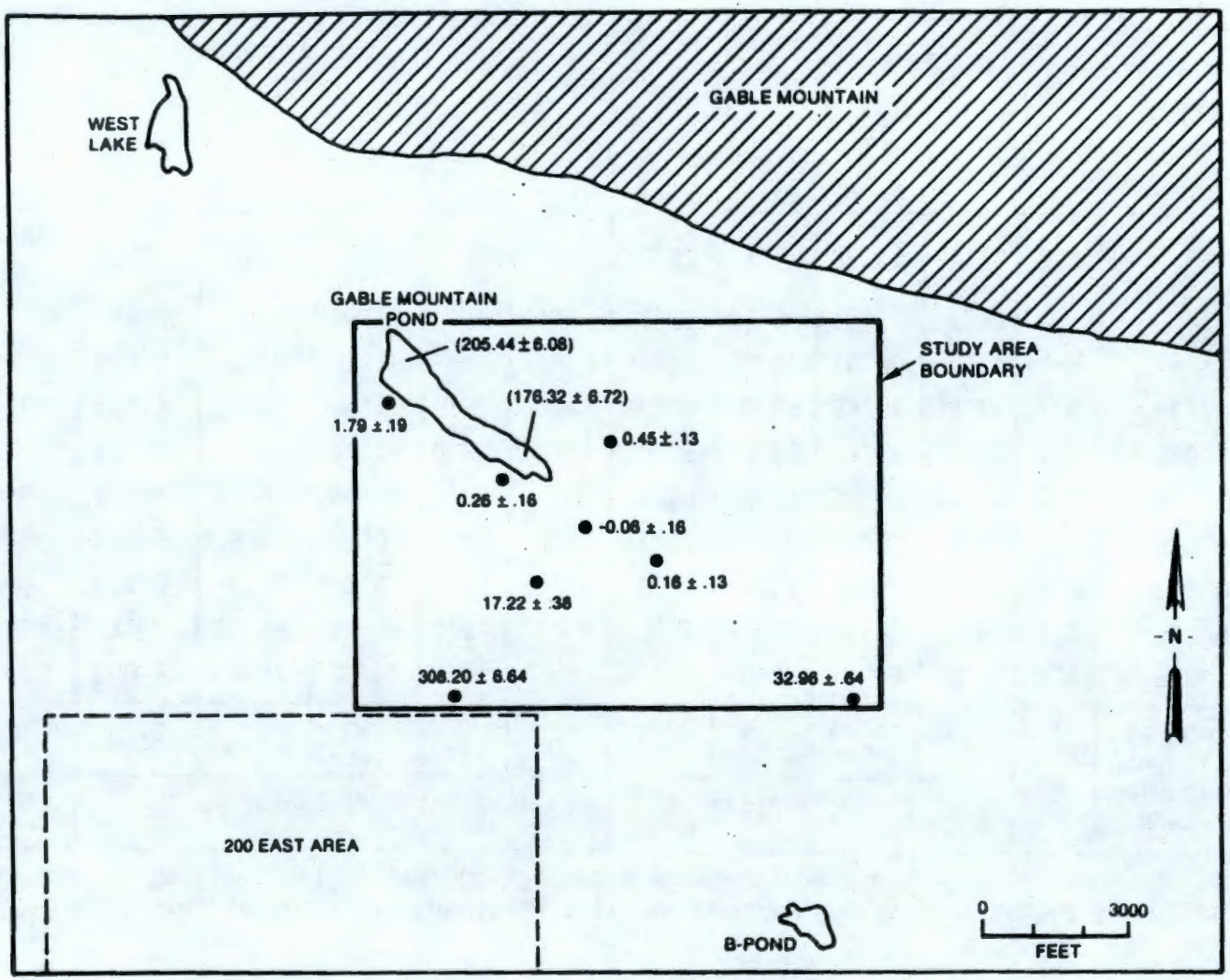


FIGURE 20. Tritium Levels (pCi/L) in the Rattlesnake Ridge Interbed, West Lake, Gable Mountain Pond, and B-Pond.

TABLE 14. Results of ^2H and ^{18}O Analyses for Ground-Water Samples from the Rattlesnake Ridge Interbed Research Wells and Gable Mountain Pond.

Well	$\delta^{18}O$ ($\delta^{18}O$ SMOW)	δ^2H (δD SMOW)	t_α, ^{18}O (°F)	t_α, ^2H (°F)
699-52-48	-16.9	-145	23.52	17.53
699-53-50	-16.4	-141	24.80	18.82
699-51-46	-15.6	-139	26.85	19.47
699-52-46	-17.0	-137	23.25	20.10
699-50-45	-17.0	-136	23.25	20.43
699-50-48	-17.9	-149	20.95	16.25
699-48-50	-17.0	-139	23.25	19.47
GMP[a] (inlet)	-17.2	-129	22.75	22.68
GMP[a] (northwest)	-16.1	-124	25.57	24.28

[a]Gable Mountain Pond.

The ^2H and ^{18}O content are established during atmospheric precipitation of water and are highly dependent on temperature. While considerable variability may be evident locally, on a worldwide basis Dansgaard (1964) reported the following relationships between average annual ground temperature, t_α, (measured in °C) and ^2H and ^{18}O content:

$$\delta^{18}O = (0.7\ t_\alpha - 13.6)\ o/oo \qquad (1)$$

$$\delta^2H = (5.6\ t_\alpha - 100)\ o/oo \qquad (2)$$

Using Equations 1 and 2 and isotopic data listed in Table 14, an average annual ground temperature within the range of 18°F to 28°F is estimated for areas that recharge ground water within the Rattlesnake Ridge interbed. This qualitative temperature estimate is considerably lower than currently observed conditions. Ground water sampled from the Rattlesnake Ridge interbed may have recharged this geologic unit under climatic conditions considerably cooler than presently occurring at the Hanford Site.

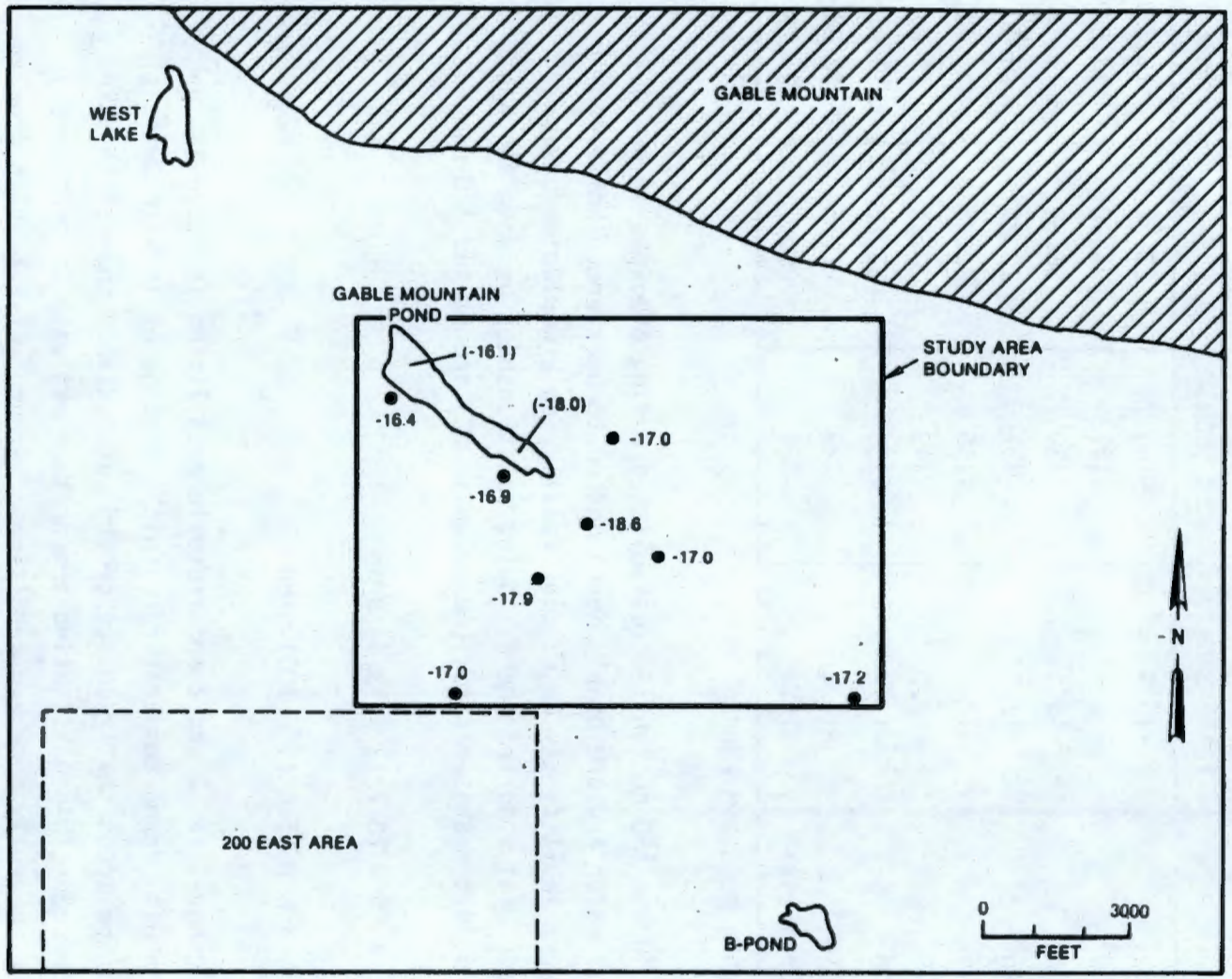


FIGURE 21. Oxygen-18 ($\delta^{18}O$ SMOW) Levels in the Rattlesnake Ridge Interbed, Gable Mountain Pond, and B-Pond.

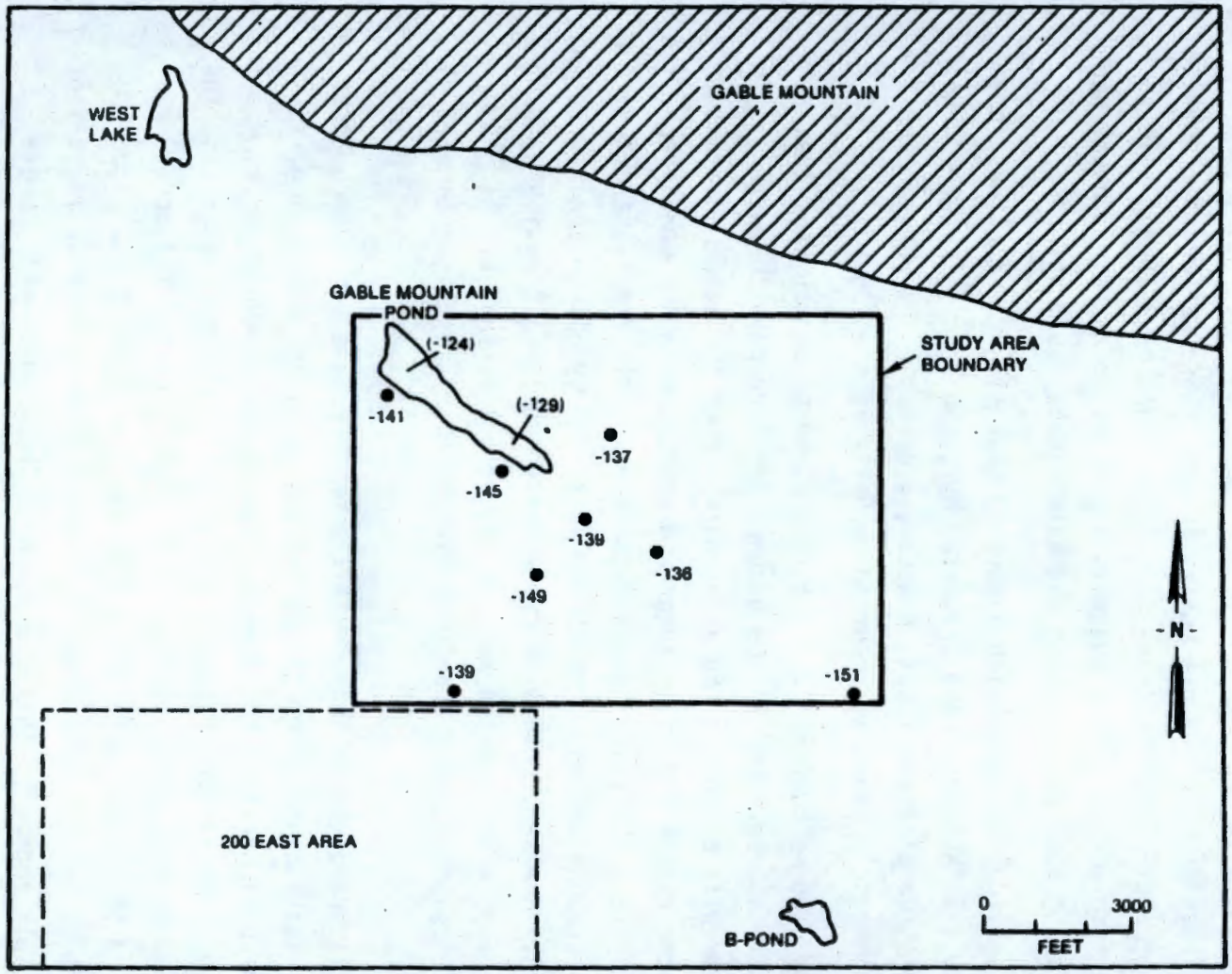


FIGURE 22. Deuterium (δD) Levels in the Rattlesnake Ridge Interbed and Gable Mountain Pond.

The relationship between ^{2}H and ^{18}O for research wells completed in the Rattlesnake Ridge interbed, other confined aquifers of the Saddle Mountains Basalt at borehole 699-47-42 (DB-15), Gable Mountain Pond, and B-Pond are shown in Figure 23. Examination of Figure 23 indicates considerable scatter in data for Rattlesnake Ridge interbed ground waters. These data points are mostly between those defined for confined aquifers of the Saddle Mountains Basalt at borehole DB-15 and selected nearby surface waters. This suggests a possible mixture of unconfined and confined ground water within the Rattlesnake Ridge interbed.

It is evident in examining Figure 23 that all ground waters shown fall below the "Meteoric Line" reported by Craig (1961) for ground water worldwide. The plotted values, however, are within the range of shifts from the "Meteoric Line" as reported by Fritz et al. (1979).

Carbon-14. The method of ^{14}C age dating is based on the fact that before water is recharged to the ground, the carbon in the water is in equilibrium with carbon in the atmosphere. Once the water enters the ground-water system and is no longer in contact with the atmosphere, the ^{14}C (half-life 5,700 years) decays with time. This creates a method for age dating ground waters up to 40,000 years old by conventional counting techniques. However, unless corrected by known ^{13}C:^{12}C ratios within sampled ground water and the host rock, ages determined by the ^{14}C method are relative and can only be used for comparison (Gephart et al., 1979).

The distribution of ages, with the error ranges, of ground water in the Rattlesnake Ridge interbed, as determined by ^{14}C age dating, is presented in Figure 24. The reported age of the ground water ranges from 7,190 to 15,640 years before present (B.P.). The youngest of the reported dates occurs in well 699-51-46 (7,190 years B.P.) and well 699-53-50 (7,280 years B.P.). However, well 699-47-50 (located just north of the 200 East Area) contains ground water that is 122% of modern. This indicates that the ratio of the ground-water sample activity of ^{14}C to a standard activity based on the reference year, 1950, is greater than 1, which indicates the ground-water age to be younger than 1950. or modern. Also, water from West Lake was ^{14}C-dated

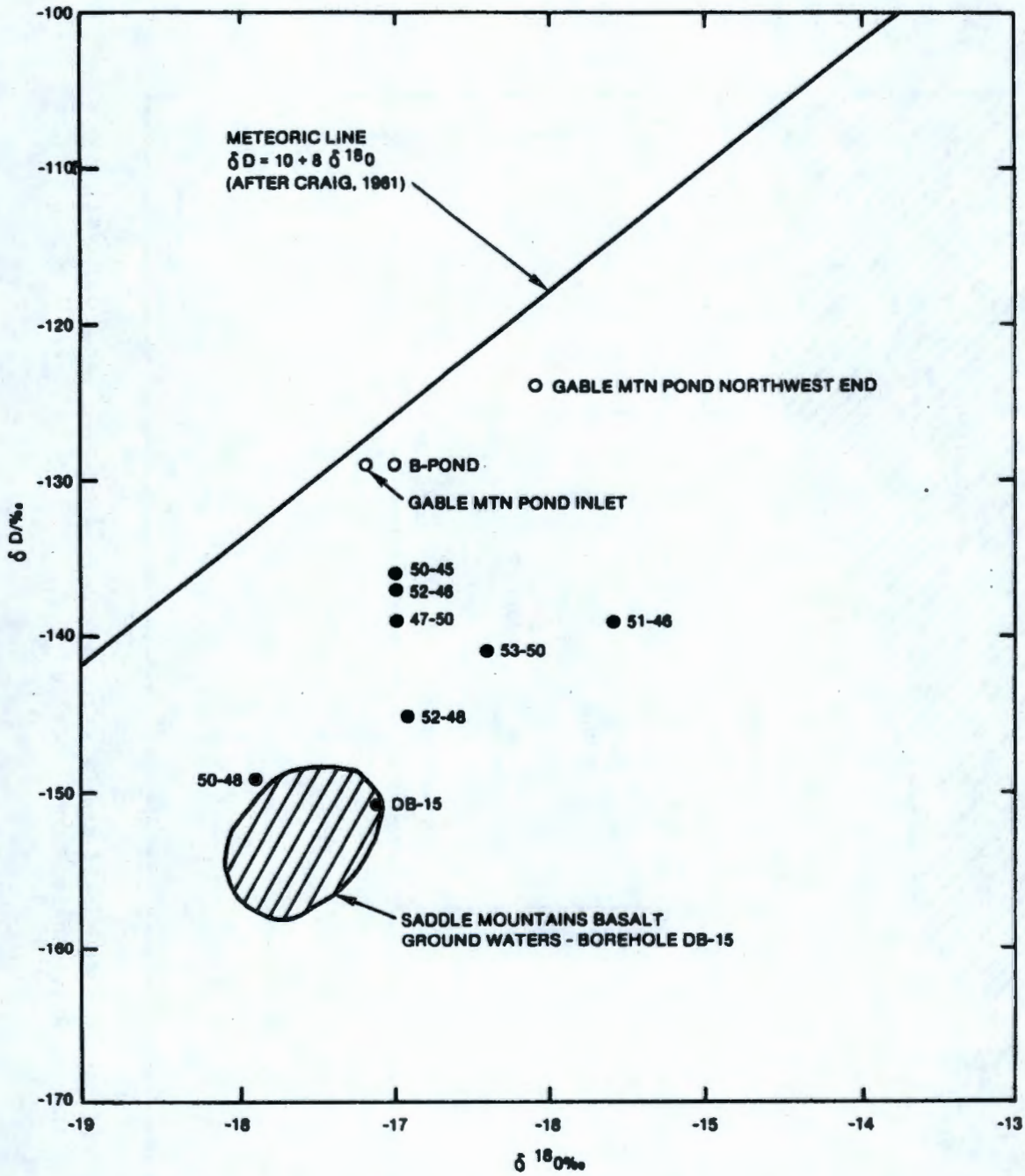


FIGURE 23. Oxygen-18 and Deuterium Relationship for Research Wells Completed in the Rattlesnake Ridge Interbed, DB-15, B-Pond, and Gable Mountain Pond.

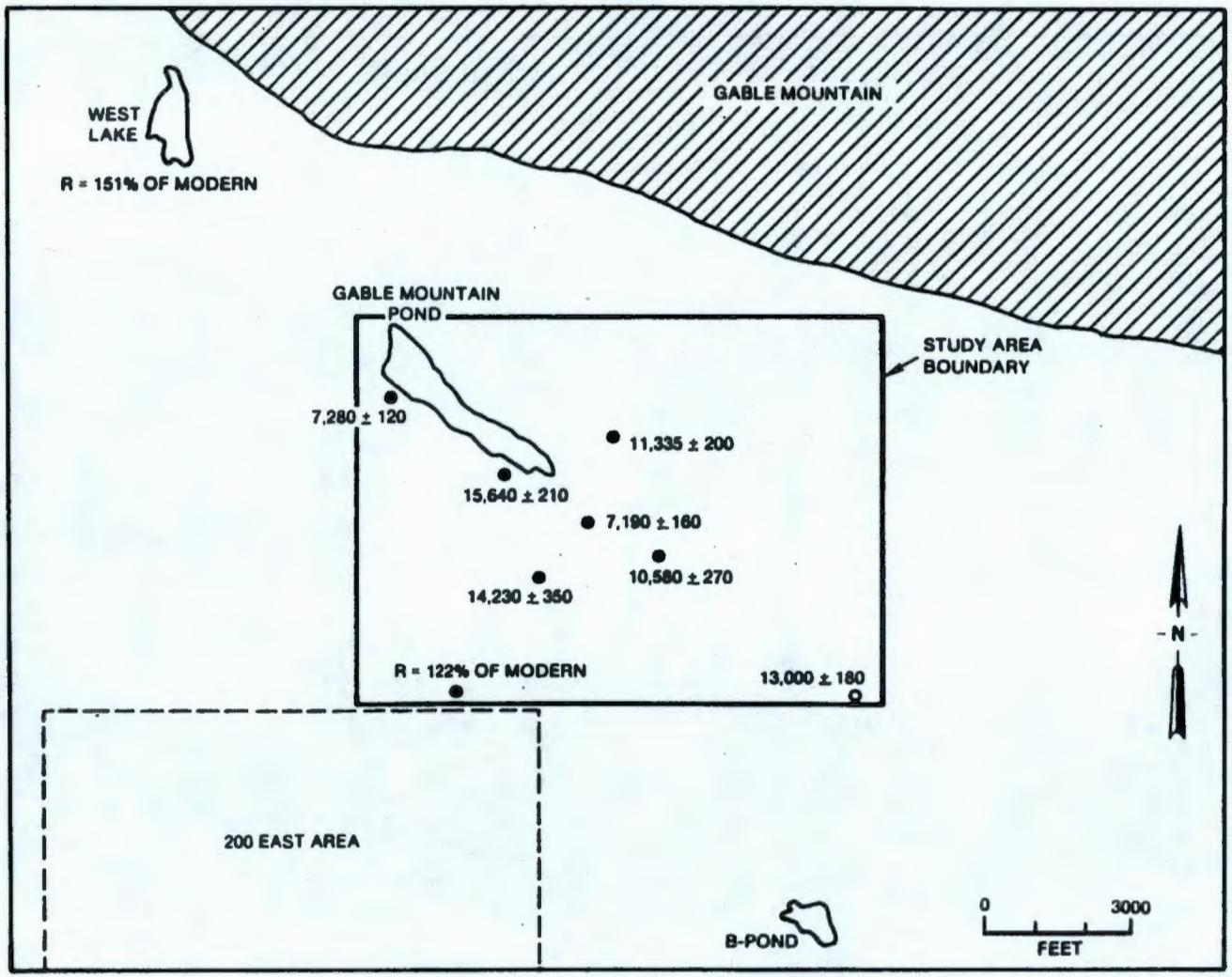


FIGURE 24. Carbon-14 Age Dates (Years Before Present) from West Lake and the Rattlesnake Ridge Interbed.

and determined to be 151% of modern. This water is considered modern since West Lake was not a permanent body of water until 1957.

Iodine-129 and Gamma Scan. Iodine-129 serves as a good tracer of ground-water movement because it is not readily absorbed by the aquifer material. It is also the only fission product of the iodine isotope with a sufficiently long half-life (1.6×10^7 years) to be useful as a tracer.

The ^{129}I levels (pCi/L) for the Rattlesnake Ridge interbed are presented in Figure 25. The ^{129}I levels under Gable Mountain Pond are relatively low, ranging from 3.8×10^{-5} to 9.5×10^{-5} pCi/L. South of Gable Mountain Pond, the ^{129}I levels increase to as high as 2.3×10^{-2} pCi/L.

No detectable ^{60}Co or ^{106}Ru levels were obtained in the gamma scan analysis.

DISCUSSION

Intercommunication Area

The area of aquifer intercommunication was determined by evaluating the hydrologic, hydrochemical, and geophysical data. The hydrologic data outline the areas of hydraulic potential for intercommunication, whereas hydrochemical and geophysical data indicate in which of these areas aquifer intercommunication occurs.

For aquifer intercommunication to occur, the hydraulic head of the unconfined aquifer must be greater than that of the confined aquifer. Hydraulic head provides the driving force for ground water to move downward to the Rattlesnake Ridge interbed. Areas where this condition is met are around the eastern end of Gable Mountain Pond and in the southeast portion of the study area, as shown in Figure 26.

The hydrochemical evidence is conclusive in indicating the area of aquifer intercommunication. The inorganic chemical constituents at well 699-47-50, located northeast of the 200 East Area, exhibit a strong similarity to that of the unconfined aquifer. In addition, the isotopic analyses indicate elevated ^{3}H (308.2 pCi/L) and ^{129}I (6.6×10^{-3} pCi/L)

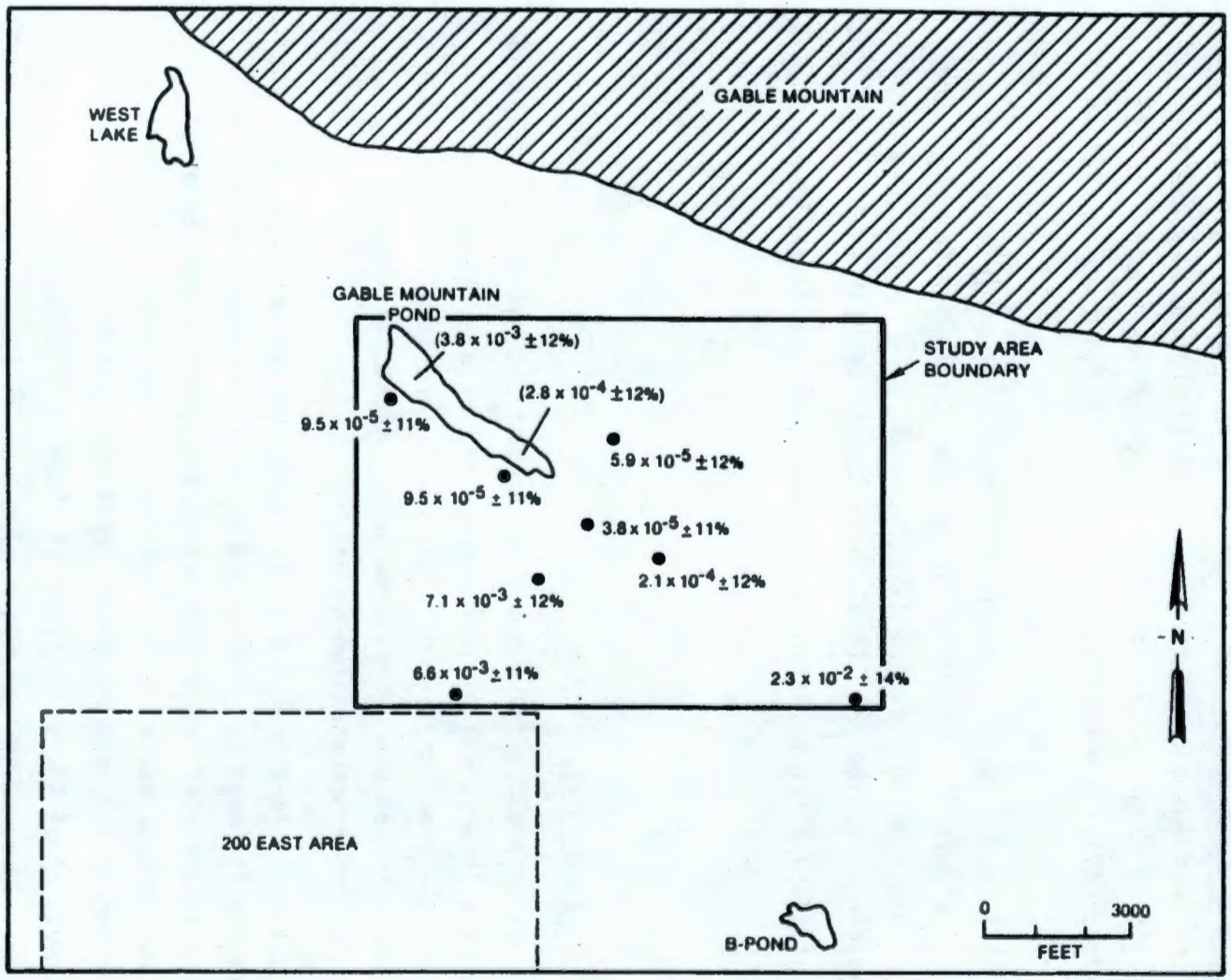


FIGURE 25. Iodine-129 Levels (pCi/L) in the Rattlesnake Ridge Interbed, Gable Mountain Pond, and West Lake.

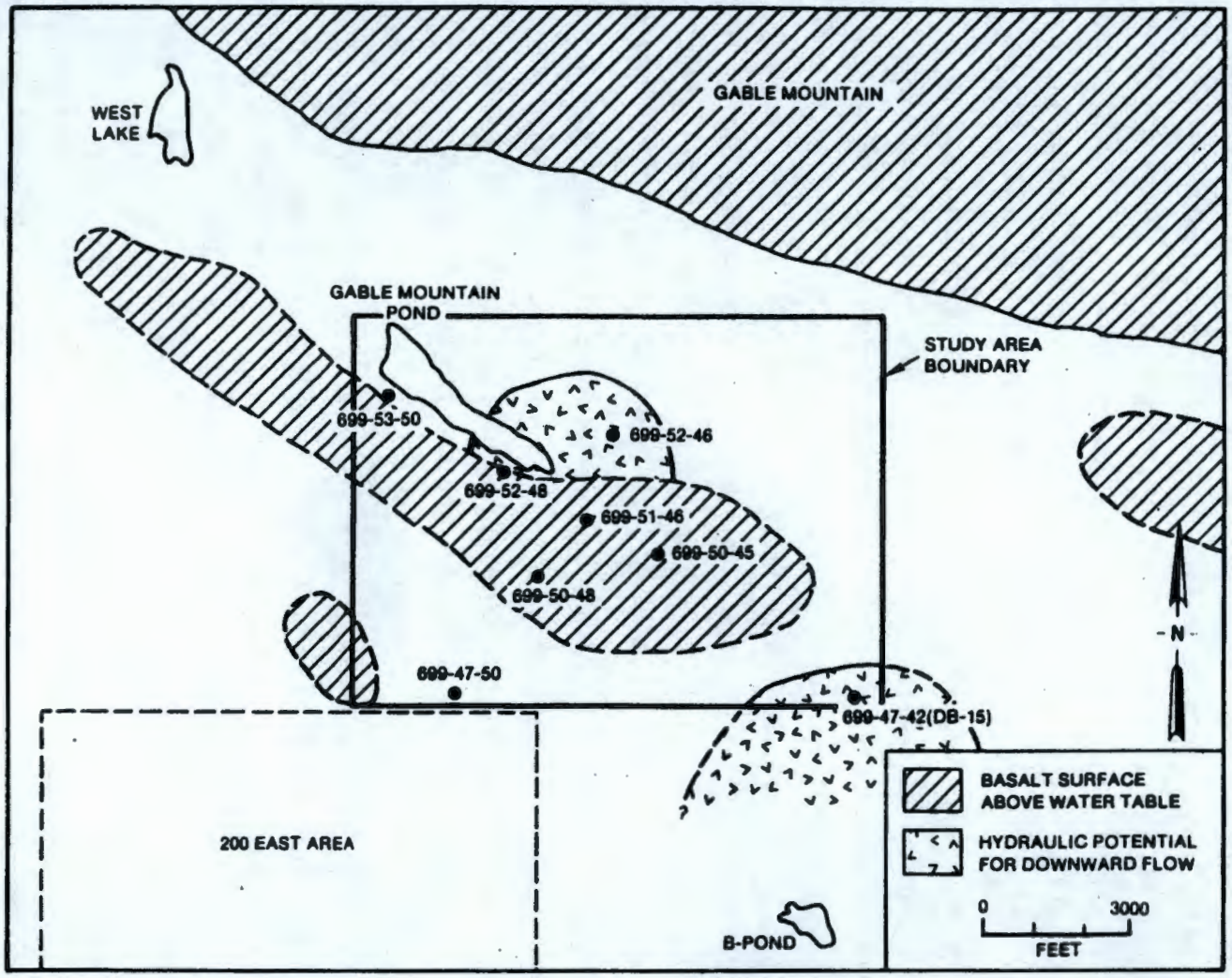


FIGURE 26. Areas of Hydraulic Potential for Aquifer Intercommunication Under Current Unconfined and Confined Aquifer Conditions.

concentrations in well 699-47-50. Very young ground water (less than 30 yr B.P.) is determined from ^{14}C age dating at this well. The ^{2}H and ^{18}O isotopes indicate intermixing of Rattlesnake Ridge interbed ground water with that of the unconfined aquifer in an area northeast of the 200 East Area. Borehole DB-15, located in the southeast corner of the study area, contains the highest ^{129}I concentration, which is 2.3×10^{-2} pCi/L. Therefore, the hydrochemical data indicate a high degree of similarity between the ground water of the Rattlesnake Ridge interbed and the unconfined aquifer northeast of the 200 East Area.

High-resolution magnetic and gravity surveys in the study area indicate significant erosion of the confining Elephant Mountain basalt coincident with the area of potential intercommunication in the southeast portion of the study area (see Figures 15 and 26). This is verified by geologic evidence, especially at well 699-47-50, where approximately 65 ft of Elephant Mountain basalt is eroded. Erosion of the confining Elephant Mountain basalt creates a possible avenue for ground water to reach the Rattlesnake Ridge interbed from the unconfined aquifer.

By integrating the hydrologic, hydrochemical, and geophysical data, the primary area of intercommunication appears to lie northeast of the 200 East Area. Here, the presence of a downward hydraulic gradient, elevated hydrochemical constituents, and erosion of Elephant Mountain basalt permit aquifer intercommunication.

Hydrochemical data indicate that mixing of unconfined aquifer and Rattlesnake Ridge interbed ground waters is undetectable near Gable Mountain Pond, although the hydraulic potential for intercommunication exists. Geophysical surveys detect no significant erosion of the Elephant Mountain basalt in this area. Therefore, no avenue exists for ground-water flow to the Rattlesnake Ridge interbed.

There is no direct evidence from this study to indicate that Gable Mountain Pond contributes significantly to radionuclide contamination of the Rattlesnake Ridge interbed. Although the hydraulic potential for downward migration is present in the area closer to Gable Mountain Pond (see Figure 26), hydrochemical data indicate a lower degree of chemical

similarity between the unconfined aquifer and Rattlesnake Ridge interbed than the southeastern portion of the study area. Isotopic data indicate that concentrations are very low around Gable Mountain Pond. For example, ^{14}C ages are significantly older here when compared to those samples taken from well 699-47-50. Some degree of intermixing is evident because the inorganic chemical constituents show a similarity between the unconfined aquifer and the Rattlesnake Ridge interbed. The geochemical information obtained in this study cannot be used to explain this observation; additional information is required.

Intercommunication Mechanism

The major mechanism for ground-water flow to the Rattlesnake Ridge interbed from the unconfined aquifer is where there is hydraulic potential for downward flow through areas of erosion in the Elephant Mountain basalt. As in the area of intercommunication northeast of the 200 East Area, unconfined aquifer ground water apparently enters the Rattlesnake Ridge interbed in an area of erosion.

Since no complete erosion of the overlying basalt flow has been located in the area northeast of the 200 East Area, the possibility exists that the unconfined ground water may migrate through the fractures and cooling joints of the overlying basalt. This mechanism may be facilitated by the partial erosion of the basalt and lack of overburden pressure on the fractures and joints. However, no direct evidence, such as vertical hydraulic conductivities, exists to verify this hypothesis.

CONCLUSIONS

The potential for aquifer intercommunication between the unconfined aquifer and the upper confined aquifer, the Rattlesnake Ridge interbed, was investigated in an area northeast of the 200 East Area that encompasses Gable Mountain Pond. A study was designed to determine the distribution and concentration of radionuclides in the Rattlesnake Ridge interbed within the study area and to determine a mechanism for aquifer intercommunication. This study was conducted by drilling seven wells into the Rattlesnake Ridge interbed and performing hydrologic tests, ground-water chemical analyses, borehole and surface geophysics, and sediment analyses. Conclusions of the study are summarized below.

- Gable Mountain Pond is not a significant source of aquifer intercommunication.
- The southeastern section of the study area has the proper combination of hydraulic potential and an erosional surface to permit aquifer intercommunication. Geophysical surveys and well data indicate an isolated basalt erosional surface as partly coincident with the elevated ground-water surface. Tritium and ^{129}I levels within the Rattlesnake Ridge interbed are elevated in the southeastern section of the study area.
- All water samples taken from the Rattlesnake Ridge interbed within the study area indicate that radionuclide concentrations are several orders of magnitude below concentration guides listed in Table II, DOE Order 5480.1, Chapter XI, for water in an uncontrolled area.
- The Rattlesnake Ridge interbed has a transmissivity value ranging from 37.0 to 590.1 ft^2/day and a hydraulic conductivity value ranging from 0.75 to 25.1 ft/day.
- The ground-water flow direction within the Rattlesnake Ridge interbed is to the southwest, as depicted in Figure 16.
- Based upon the evidence above, aquifer intercommunication should be investigated further outside the boundaries of this study.

ACKNOWLEDGEMENTS

We would like to thank Mr. H. C. Baze for maintaining the technical end of the field operations and assisting on the numerous pumping tests. Other people that assisted on pumping tests include: Mr. W. R. Brown, Mr. T. L. Jones, Mr. W. A. Jordan, and Mr. R. M. Smith. Dr. F. A. Spane also assisted in analyzing pump test data and ground-water chemistry data.

Thanks also go to the Basalt Waste Isolation Project for their use of surface geophysical equipment and computers in determining the extent of erosion in the Gable Mountain Pond area.

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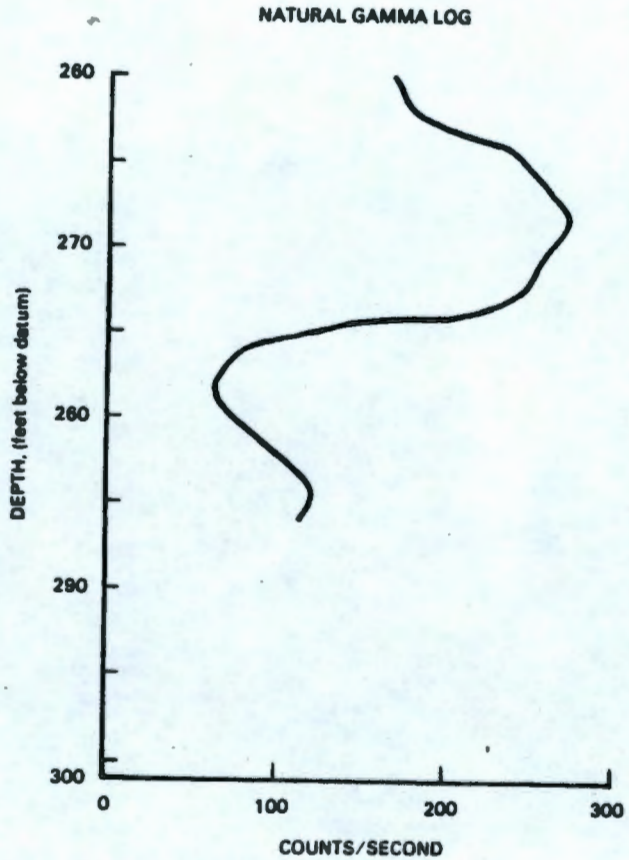
APPENDIX A

SIEVE ANALYSIS RESULTS

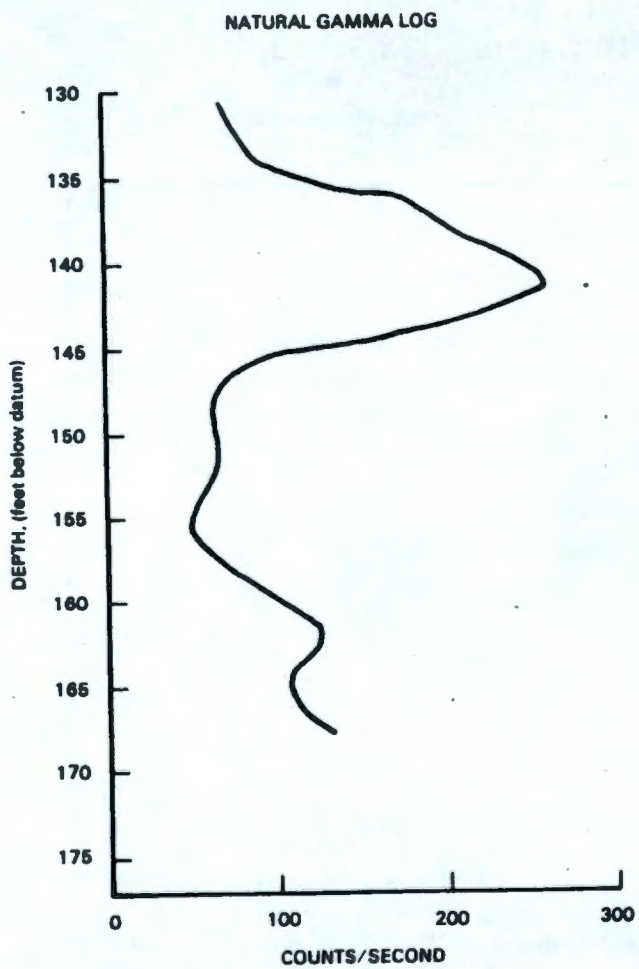
BOREHOLE: 699-47-50



SIEVE ANALYSIS			
% MUD	% SAND	% GRAVEL	CLASS
30.4	68.8	0.8	MS
27.5	71.9	0.6	MS
30.6	68.7	0.7	MS
41.9	56.3	1.8	MS
53.3	46.4	0.2	SM
36.7	60.9	2.3	MS
32.7	66.9	0.4	MS

FIGURE A-1. Sieve Analysis for Well 699-47-50.

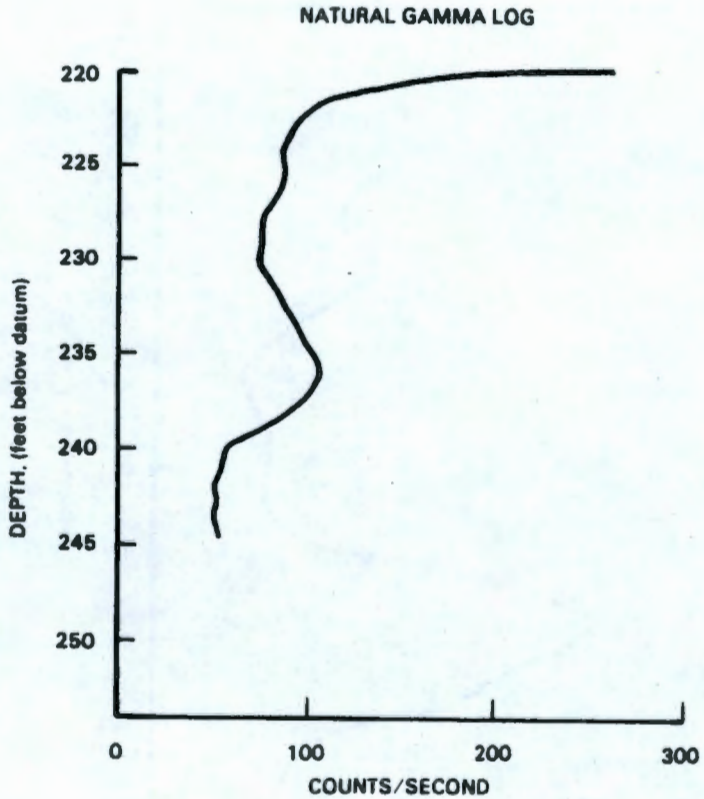
BOREHOLE: 699-50-45



SIEVE ANALYSIS			
% MUD	% SAND	% GRAVEL	CLASS
34.3	64.8	0.9	MS
59.3	40.7	0.1	SM
45.5	53.4	1.0	MS
44.8	51.1	4.1	MS
53.4	45.9	0.7	SM
54.0	45.7	0.3	SM
32.3	63.4	4.3	MS
17.0	81.4	1.6	(M) S
24.2	75.4	0.3	MS

FIGURE A-2. Sieve Analysis for Well 699-50-45.

BOREHOLE: 699-50-48

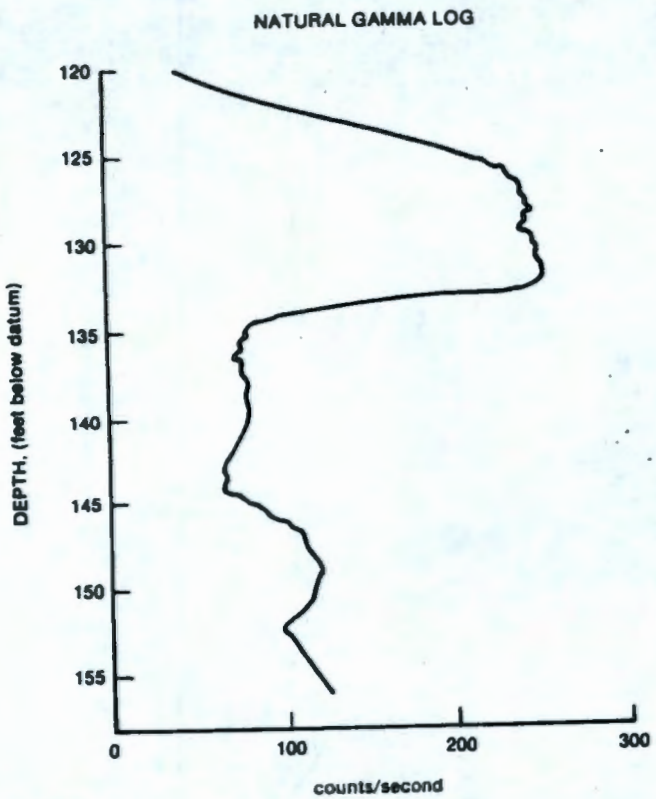


SIEVE ANALYSIS

% MUD	% SAND	% GRAVEL	CLASS
12.5	84.4	3.0	(M) S
14.2	81.9	4.0	(M)S
20.5	77.4	2.0	MS
25.4	72.4	2.2	MS
18.3	73.4	8.4	(G)MS
31.6	68.5	0.0	MS

FIGURE A-3. Sieve Analysis for Well 699-50-48.

BOREHOLE: 699-51-46

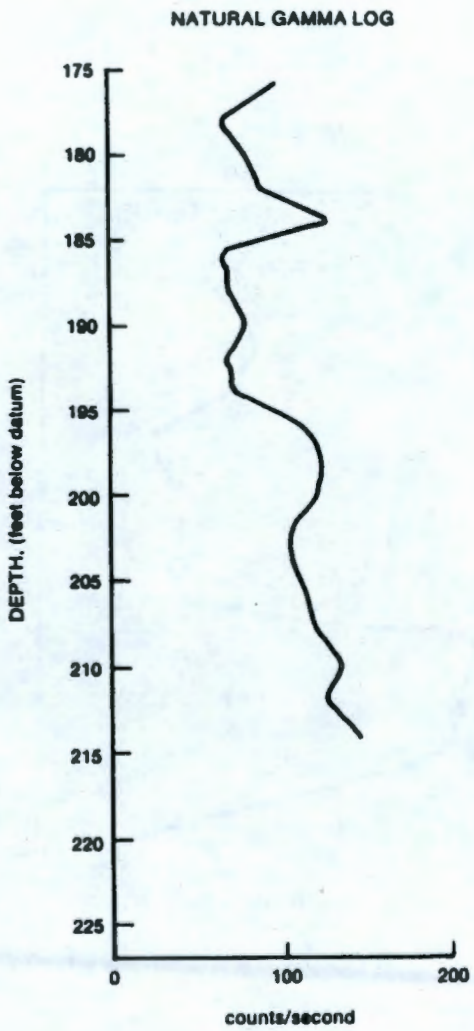


SIEVE ANALYSIS

% MUD	% SAND	% GRAVEL	CLASS
43.1	56.9	0.0	MS
49.2	50.2	0.6	MS
23.6	76.2	0.0	MS
37.4	62.4	0.2	MS
20.9	79.1	0.0	MS
30.6	69.4	0.1	MS
24.1	75.8	0.1	MS

FIGURE A-4. Sieve Analysis for Well 699-51-46.

BOREHOLE: 699-52-46

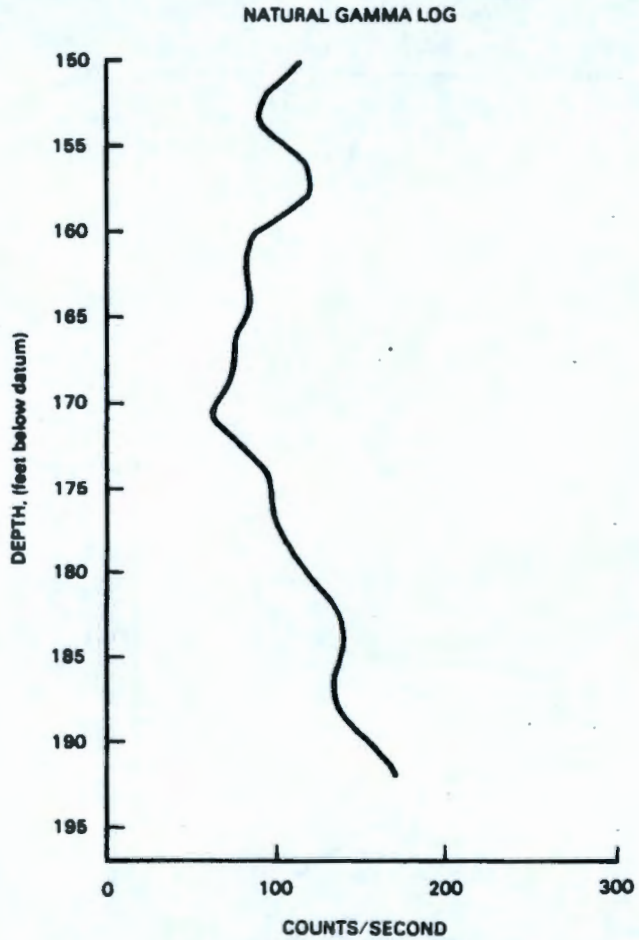


SIEVE ANALYSIS

% MUD	% SAND	% GRAVEL	CLASS
44.7	54.9	0.5	MS
23.7	76.1	0.1	MS
14.5	84.9	0.5	MS
17.6	82.4	0.0	MS
22.3	77.8	0.0	MS
24.8	75.1	0.0	MS
15.3	84.6	0.0	MS
18.5	81.5	0.0	MS
10.0	90.0	0.0	(M) S
10.7	83.7	5.6	(M) GS
11.1	88.9	0.0	MS

FIGURE A-5. Sieve Analysis for Well 699-52-46.

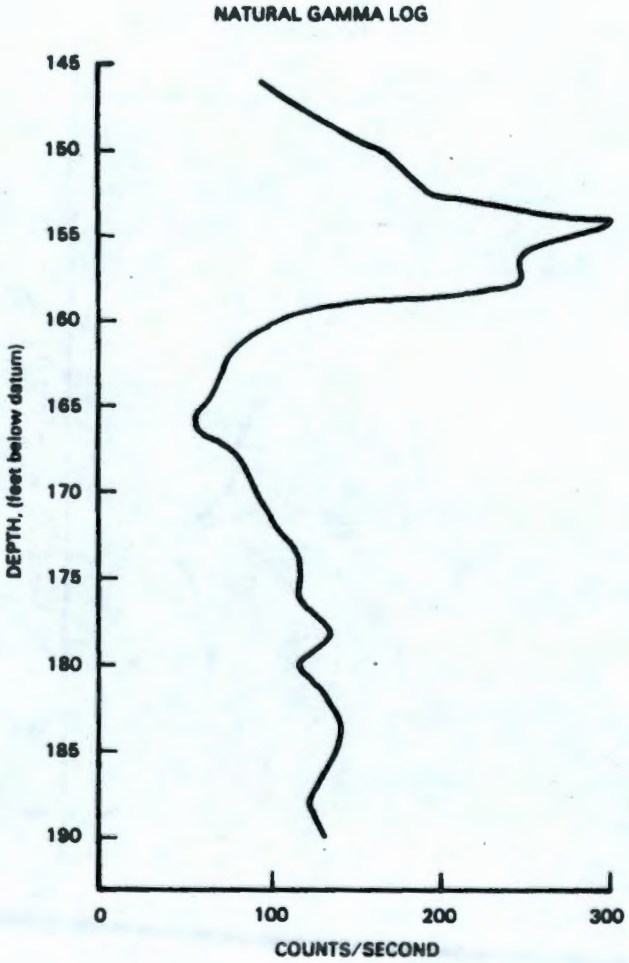
BOREHOLE: 699-52-48



SIEVE ANALYSIS % MUD	% SAND	% GRAVEL	CLASS
6.9	91.4	1.7	(M)S
16.0	80.7	3.3	MS
16.9	82.9	0.2	MS
19.6	79.9	0.5	MS
13.3	85.7	1.0	MS
5.6	87.9	6.5	(M) GS
9.0	90.2	0.8	(M) S
12.0	87.6	0.4	MS
5.4	93.9	0.7	(M) S

FIGURE A-6. Sieve Analysis for Well 699-52-48.

BOREHOLE: 699-53-50



SIEVE ANALYSIS % MUD	% SAND	% GRAVEL	CLASS
32.1	65.0	2.9	MS
27.2	68.4	4.4	(G) MS
41.5	58.4	0.1	MS
41.5	58.3	0.2	MS
24.8	75.1	0.1	MS
16.8	82.5	0.6	(M) S
16.5	83.4	0.1	(M) S
9.9	89.7	0.4	(M) S
22.3	77.6	0.1	MS

FIGURE A-7. Sieve Analysis for Well 699-53-50.

APPENDIX B

BOREHOLE GEOPHYSICAL LOGS

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-47-50
HANFORD COORDINATES: N47,266.35 W49,507.91
ELEVATION: 583.87 FEET ABOVE MEAN SEA LEVEL

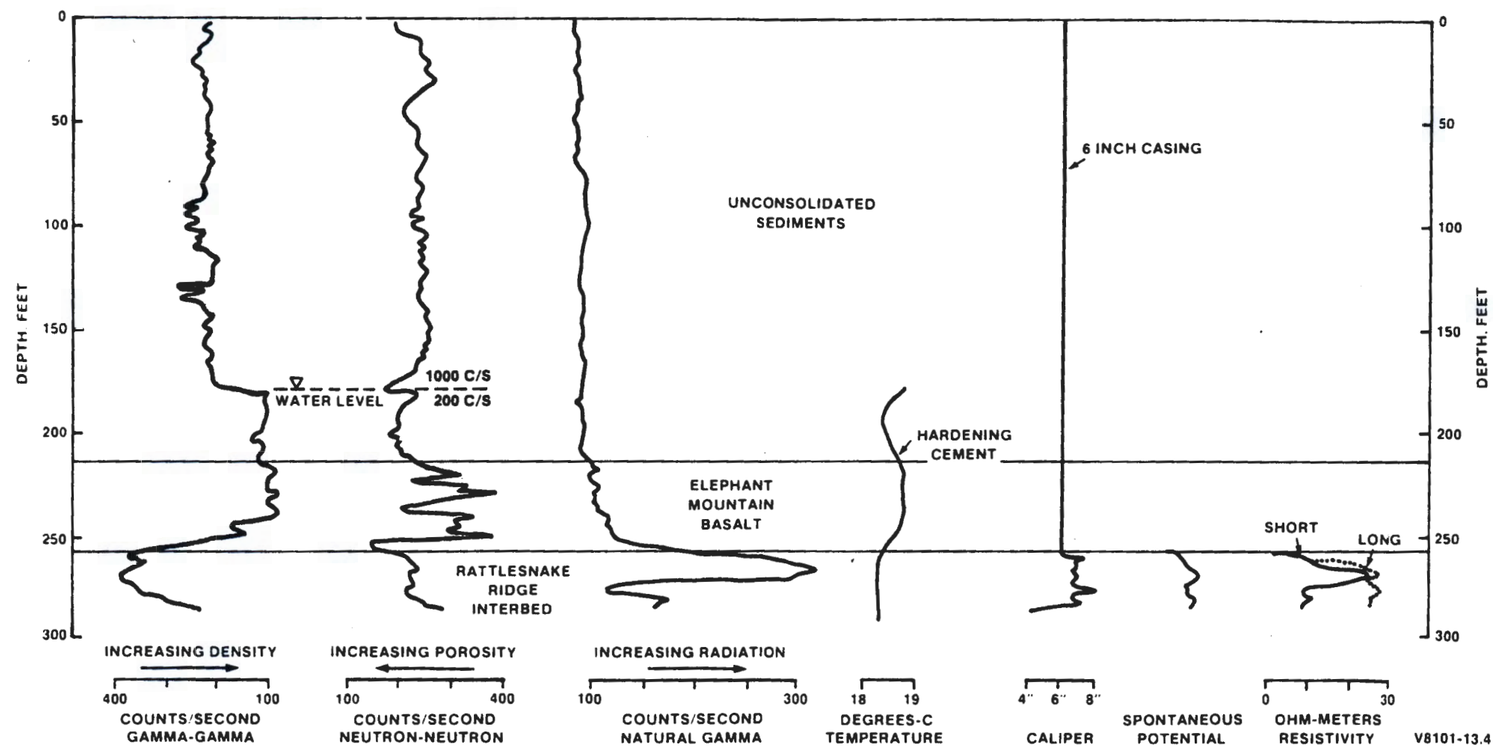


FIGURE B-1. Borehole Geophysical Logs for Well 699-47-50.

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-50-45
HANFORD COORDINATES: N50,149-89 W44,992.17
ELEVATION: 451.41 FEET ABOVE MEAN SEA LEVEL

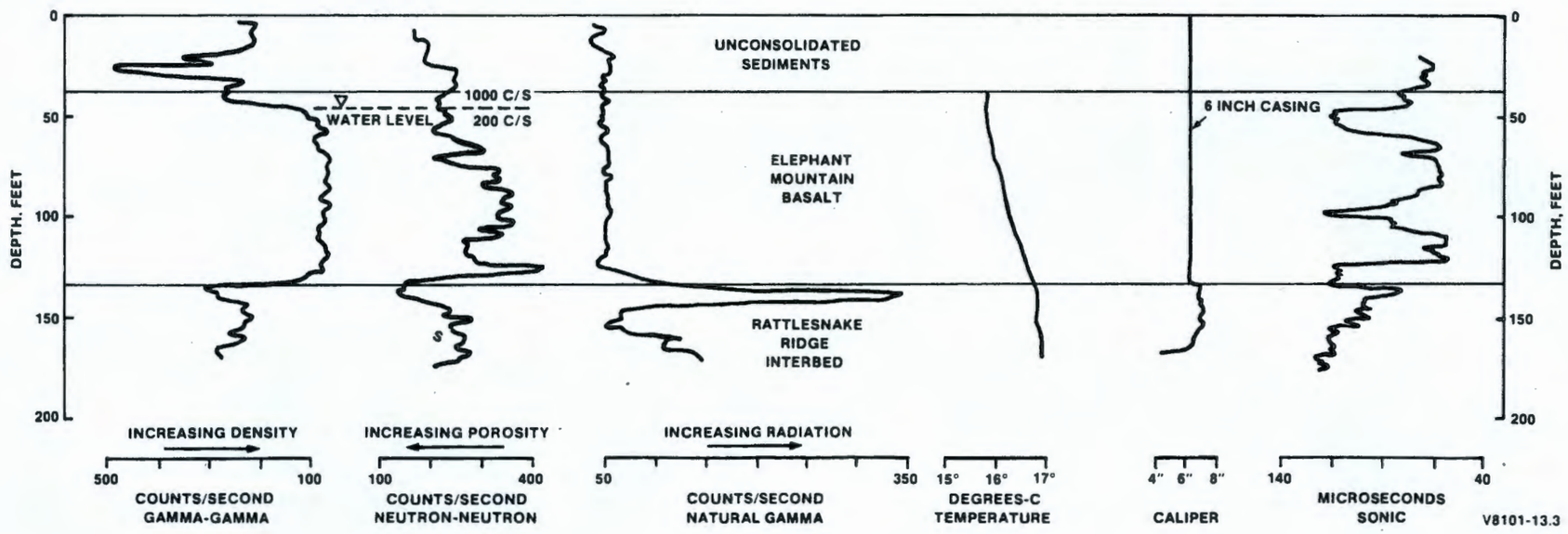


FIGURE B-2. Borehole Geophysical Logs for Well 699-50-45.

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-50-48
HANFORD COORDINATES: N49,980.41 W47,557.88
ELEVATION: 550.39 FEET ABOVE MEAN SEA LEVEL

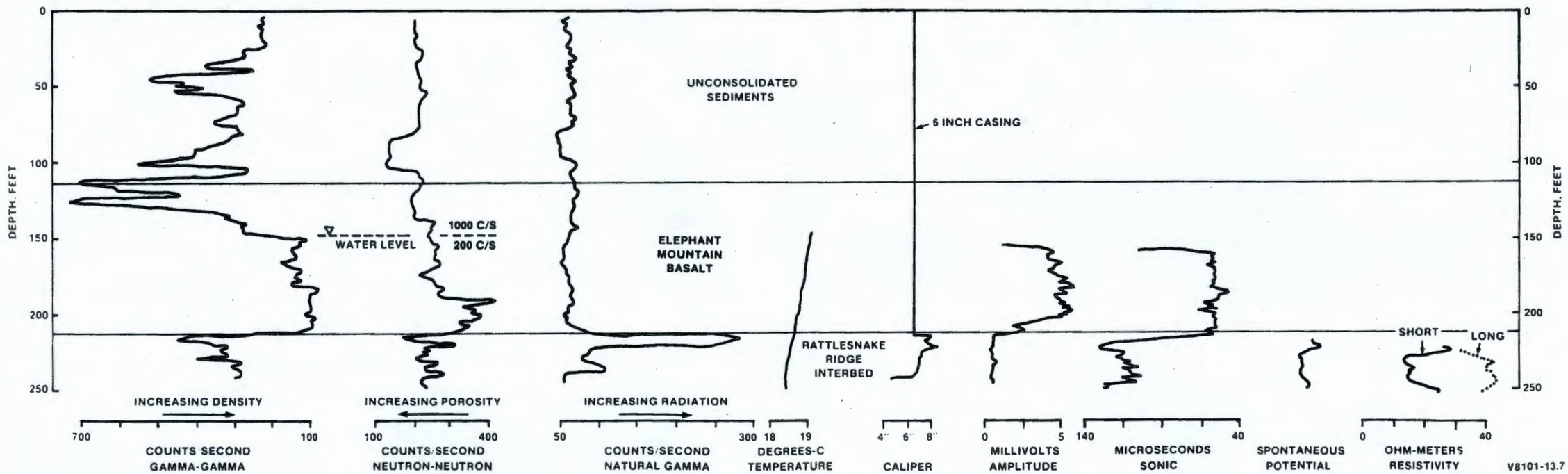


FIGURE B-3. Borehole Geophysical Logs for Well 699-50-48.

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-51-46
HANFORD COORDINATES: N50,914.69 W46,414.34
ELEVATION: 444.63 FEET ABOVE MEAN SEA LEVEL

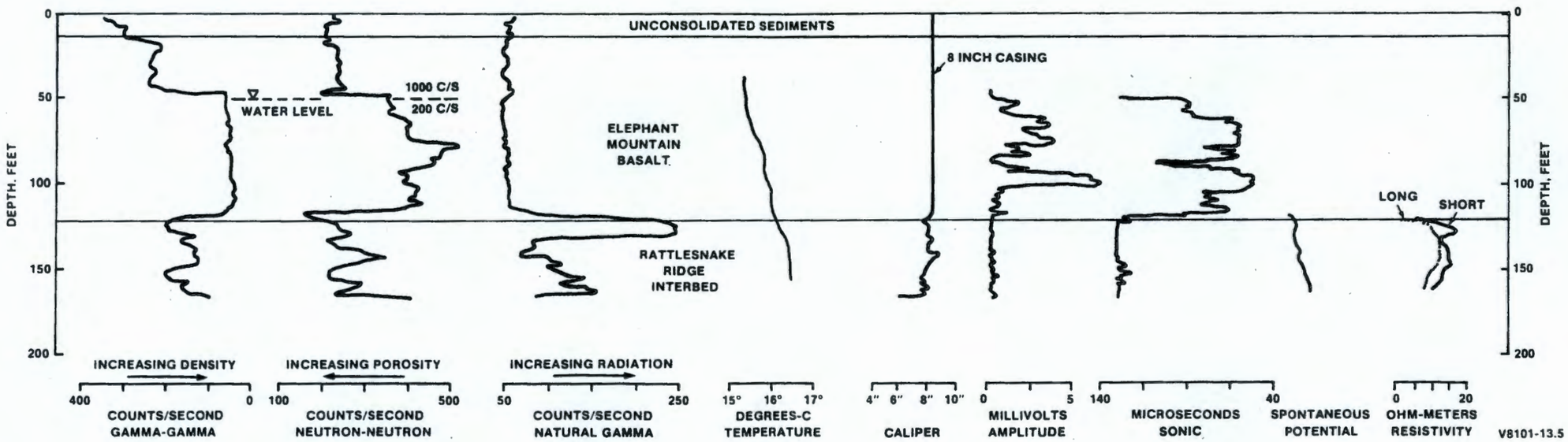


FIGURE B-4. Borehole Geophysical Logs for Well 699-51-46.

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-52-46
HANFORD COORDINATES: N52,196.03 W45,706.00
ELEVATION: 455.61 FEET ABOVE MEAN SEA LEVEL

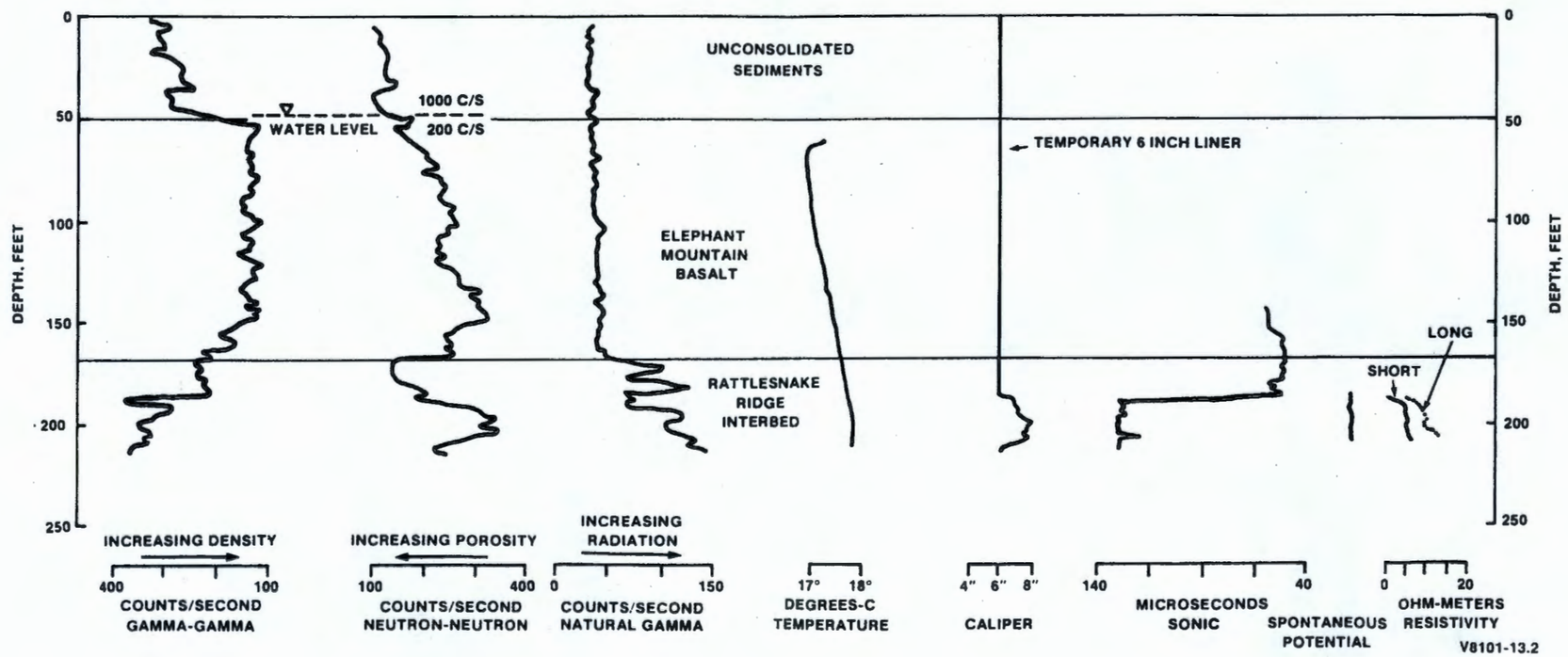


FIGURE B-5. Borehole Geophysical Logs for Well 699-52-46.

BOREHOLE GEOPHYSICAL LOGS
WELL: 699-52-48
HANFORD COORDINATES: N51,556.10 W48,076.32
ELEVATION: 466.06 FEET ABOVE MEAN SEA LEVEL

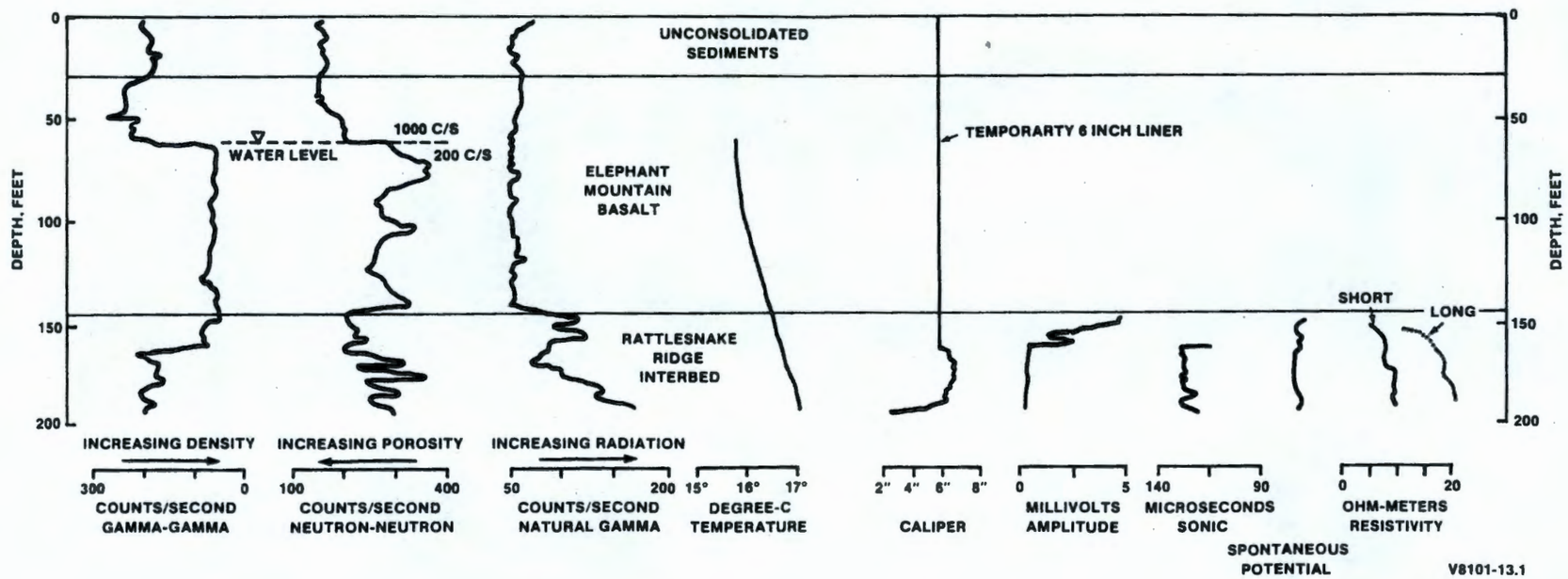


FIGURE B-6. Borehole Geophysical Logs for Well 699-52-48.

BOREHOLE GEOPHYSICAL LOGS
WELL: 669-53-50
HANFORD COORDINATES: N53,218.59 W50.195.85
ELEVATION: 444.21 FEET ABOVE MEAN SEA LEVEL

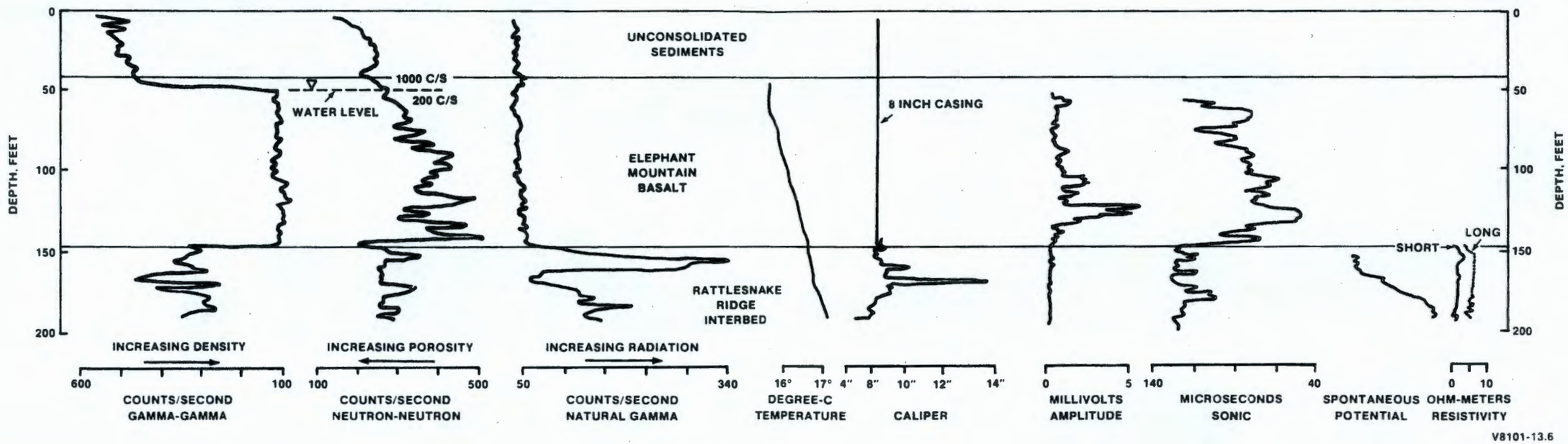


FIGURE B-7. Borehole Geophysical Logs for Well 699-53-50.

APPENDIX C

PLOTS OF HYDROLOGIC TEST DATA

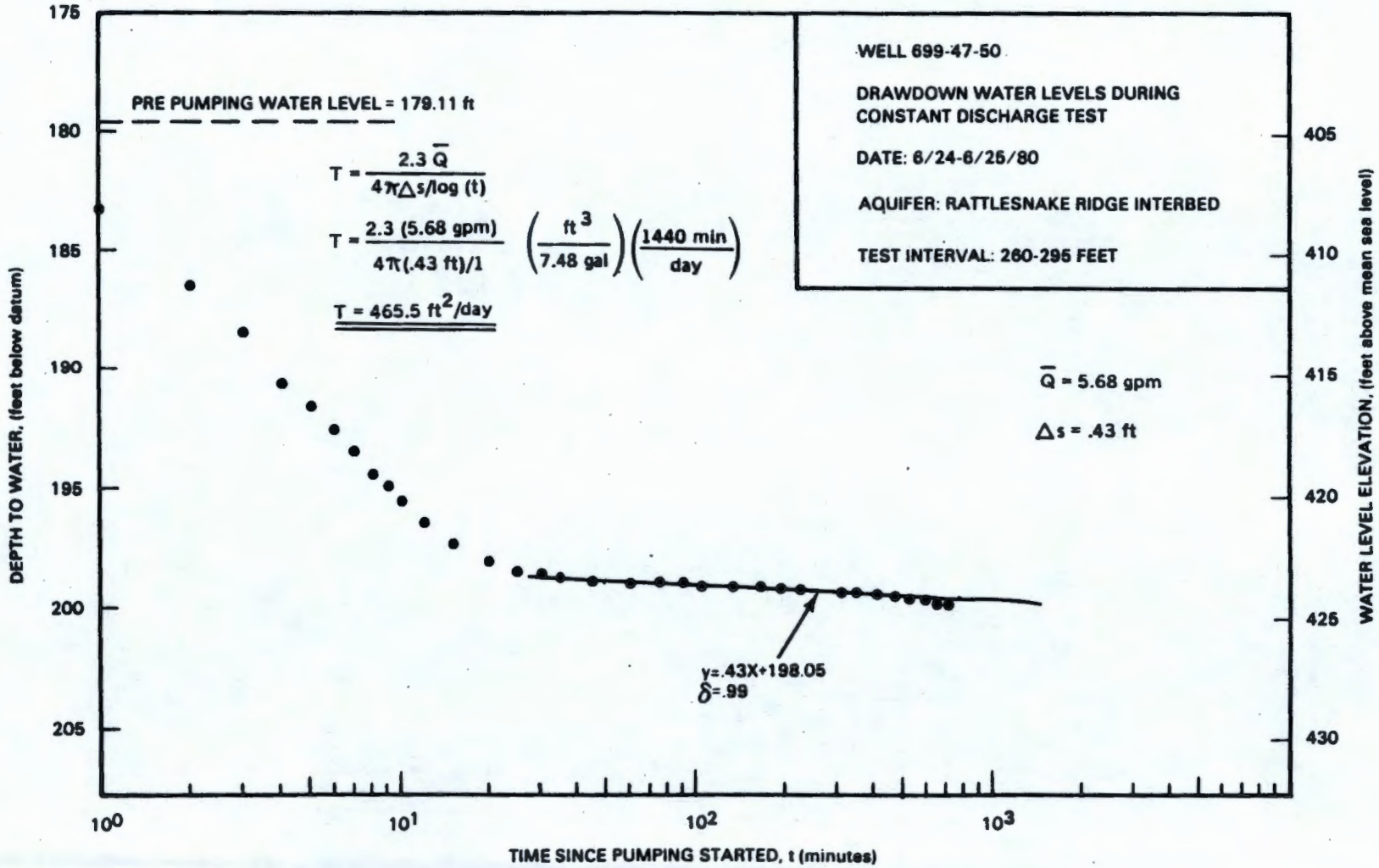


FIGURE C-1. Drawdown Water Levels from Well 699-47-50.

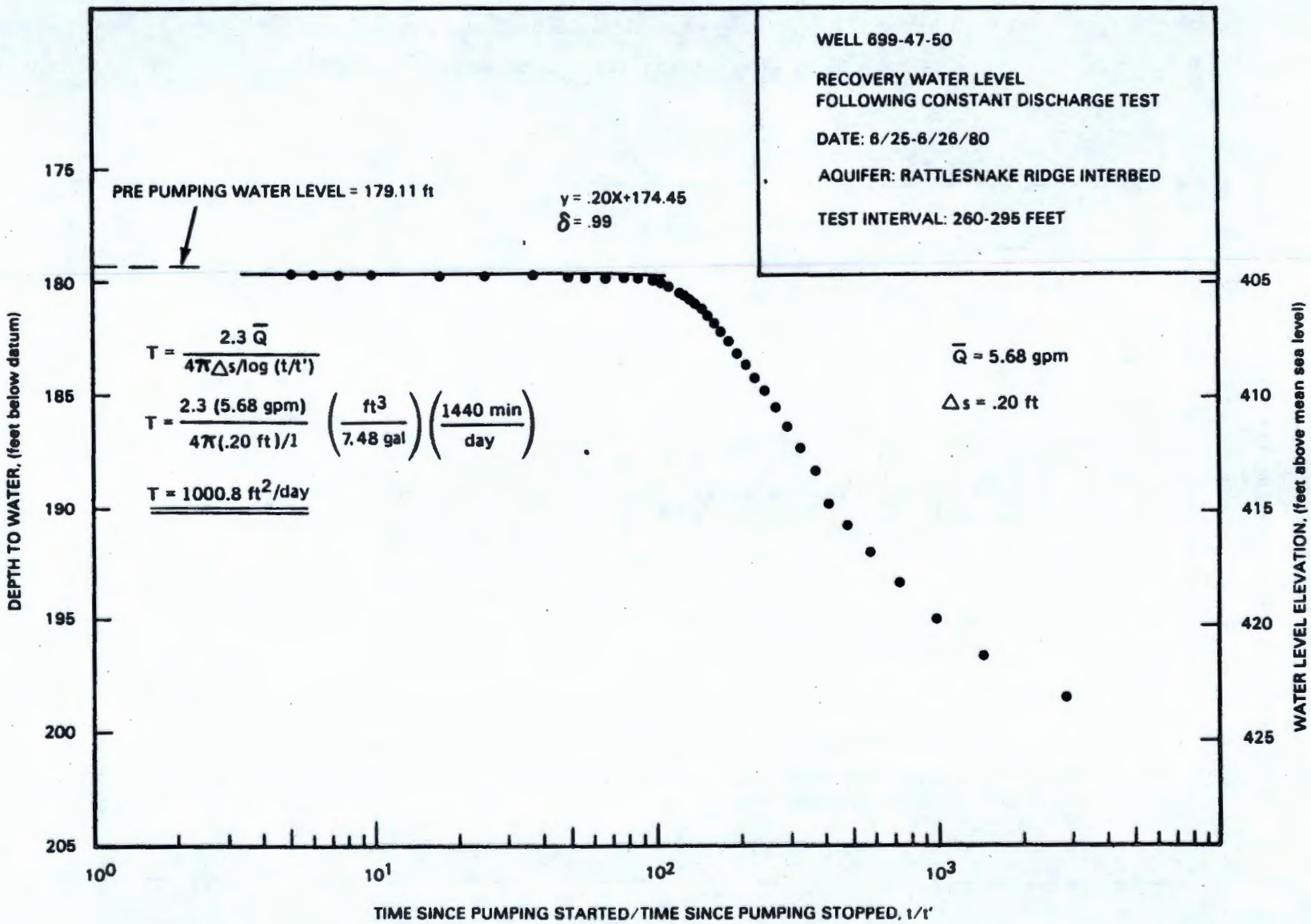


FIGURE C-2. Recovery Water Levels from Well 699-47-50.

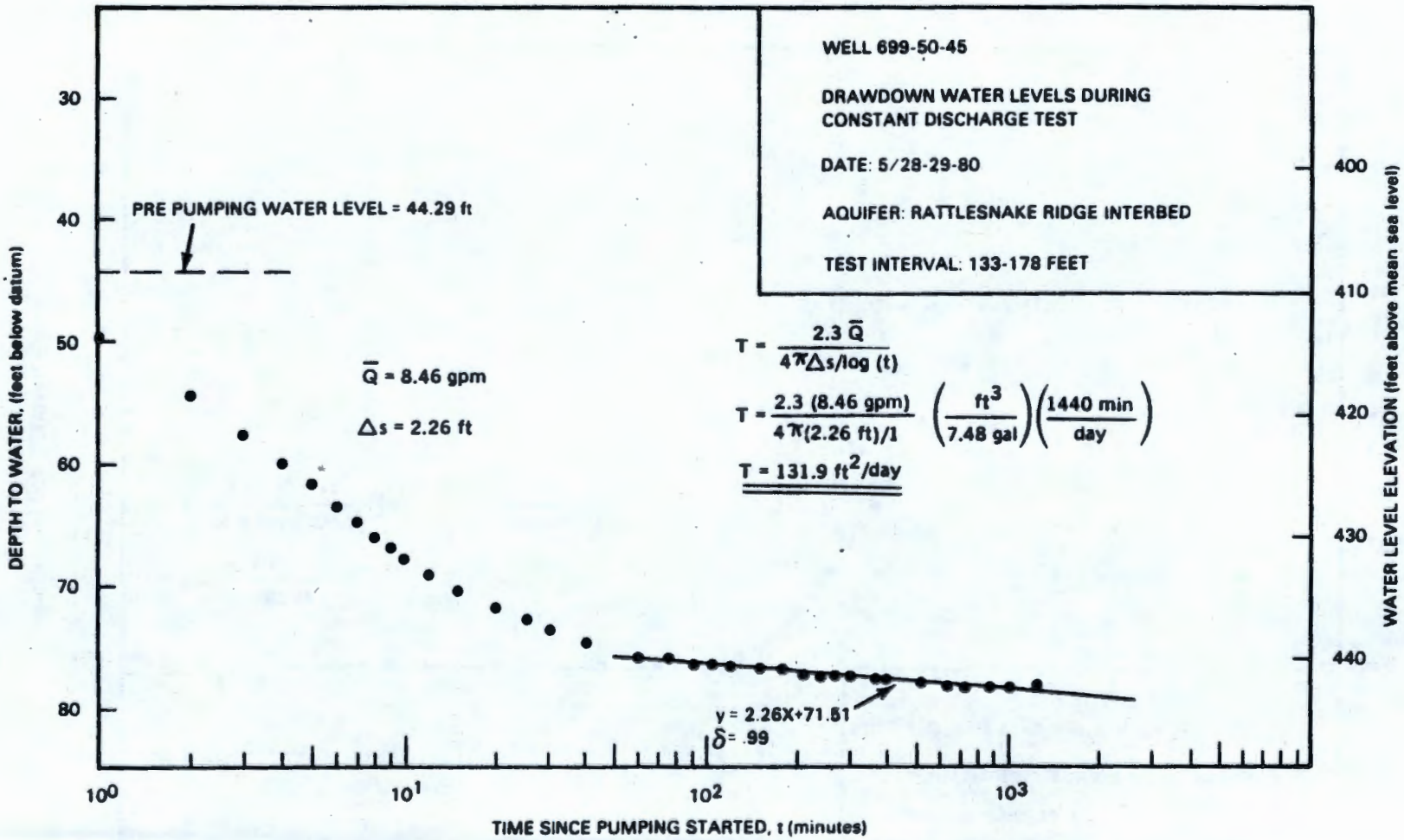


FIGURE C-3. Drawdown Water Levels from Well 699-50-45.

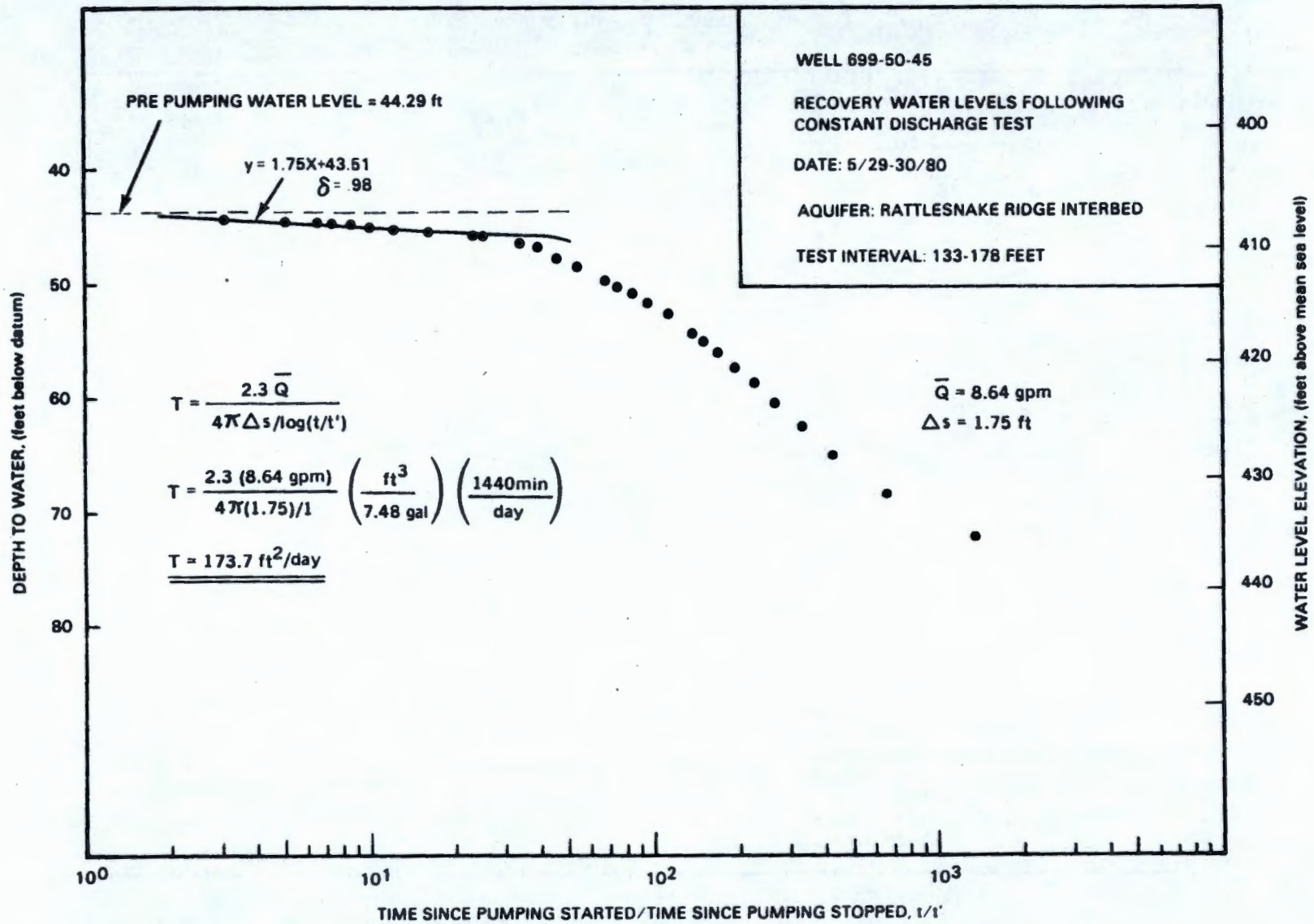


FIGURE C-4. Recovery Water Levels from Well 699-50-45.

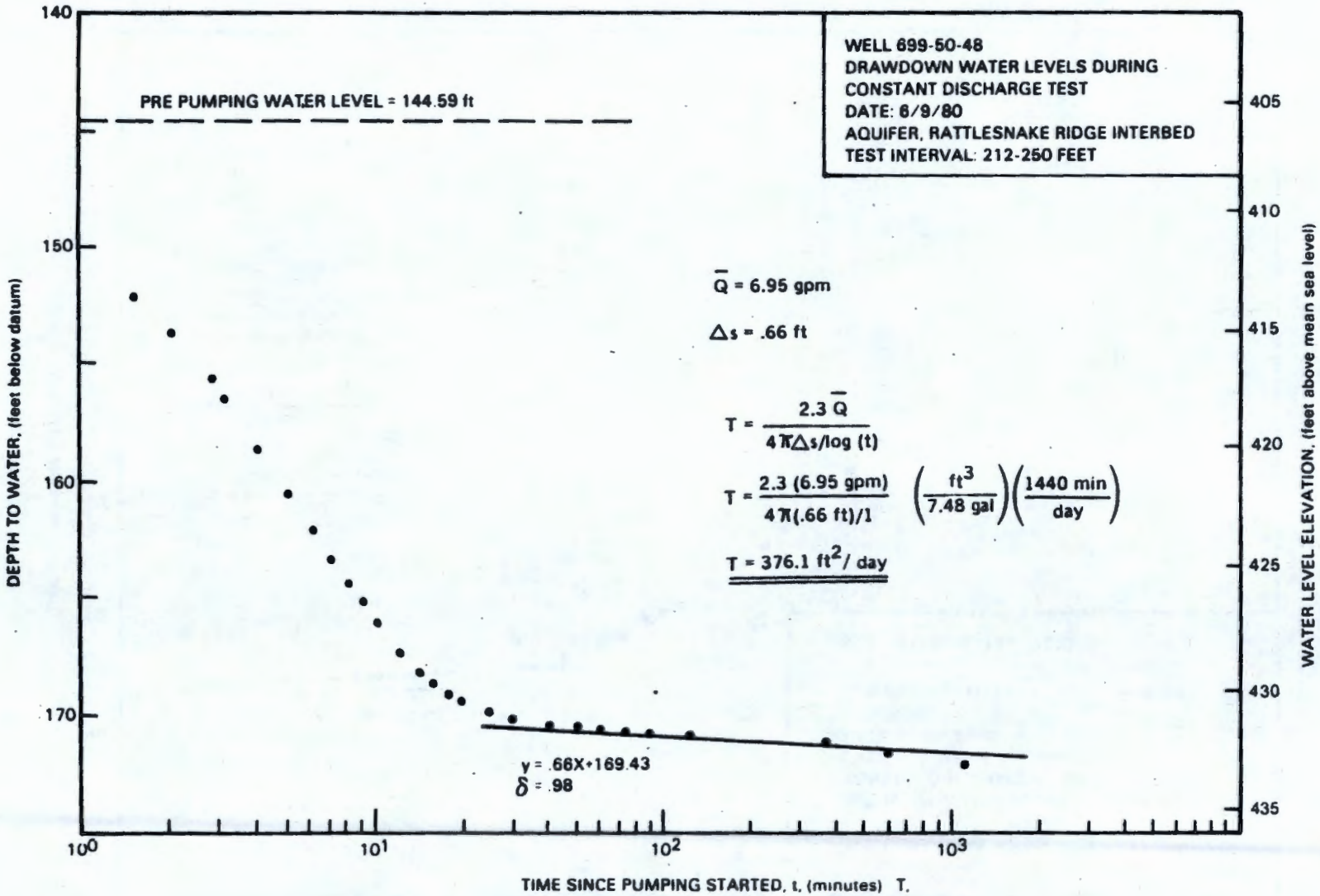


FIGURE C-5. Drawdown Water Levels from Well 699-50-48.

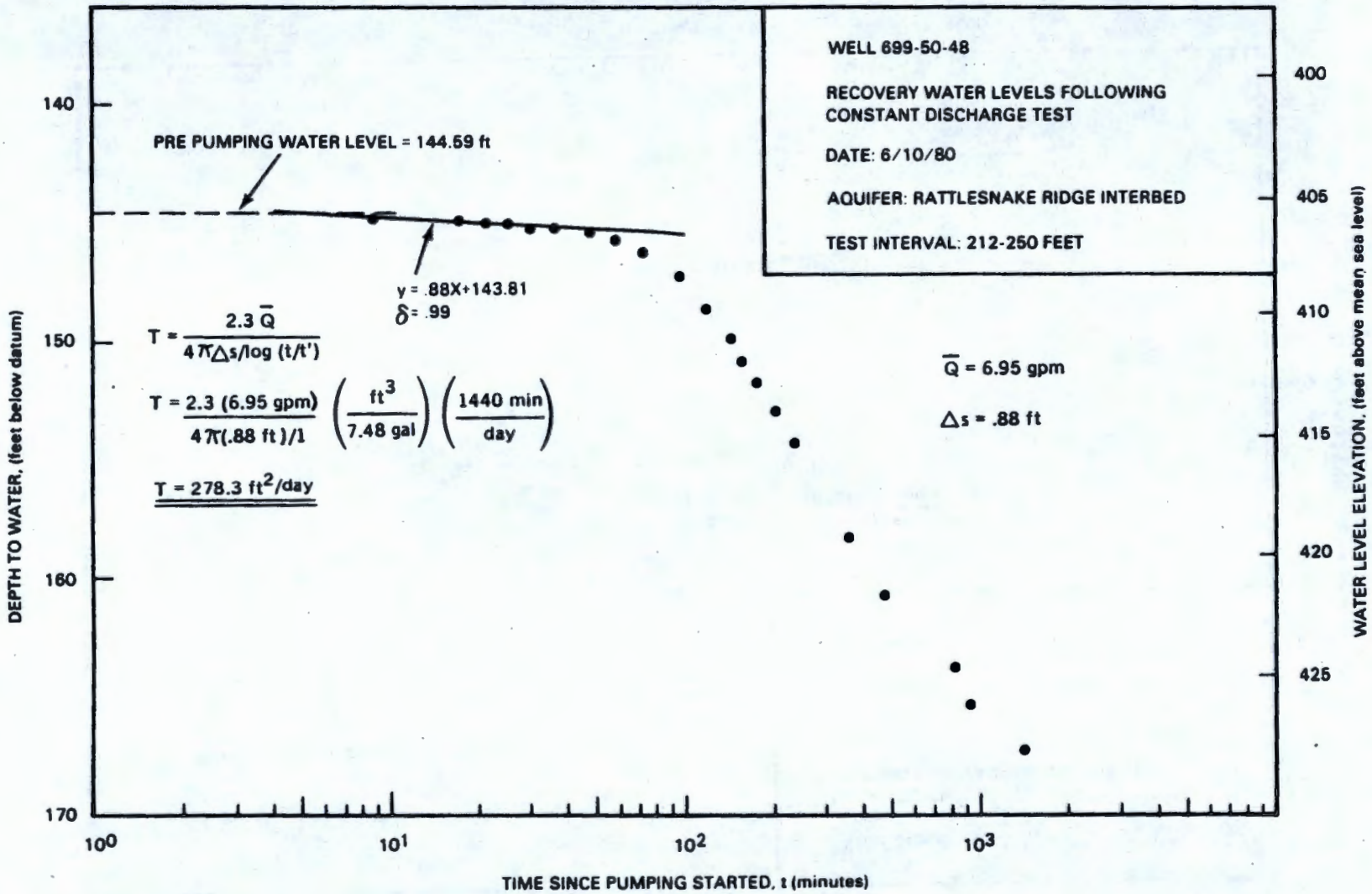


FIGURE C-6. Recovery Water Levels from Well 699-50-48.

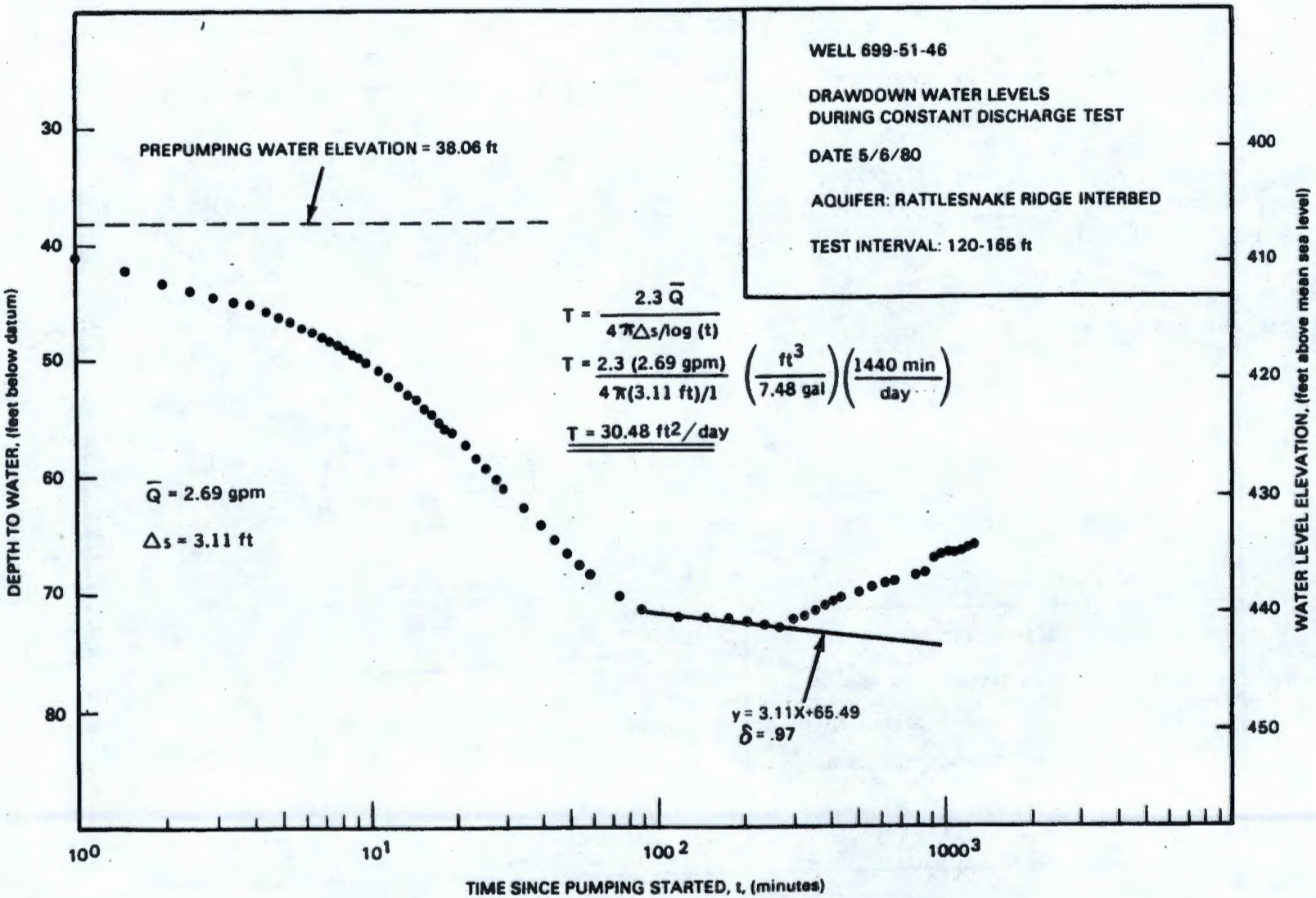


FIGURE C-7. Drawdown Water Levels from Well 699-51-46.

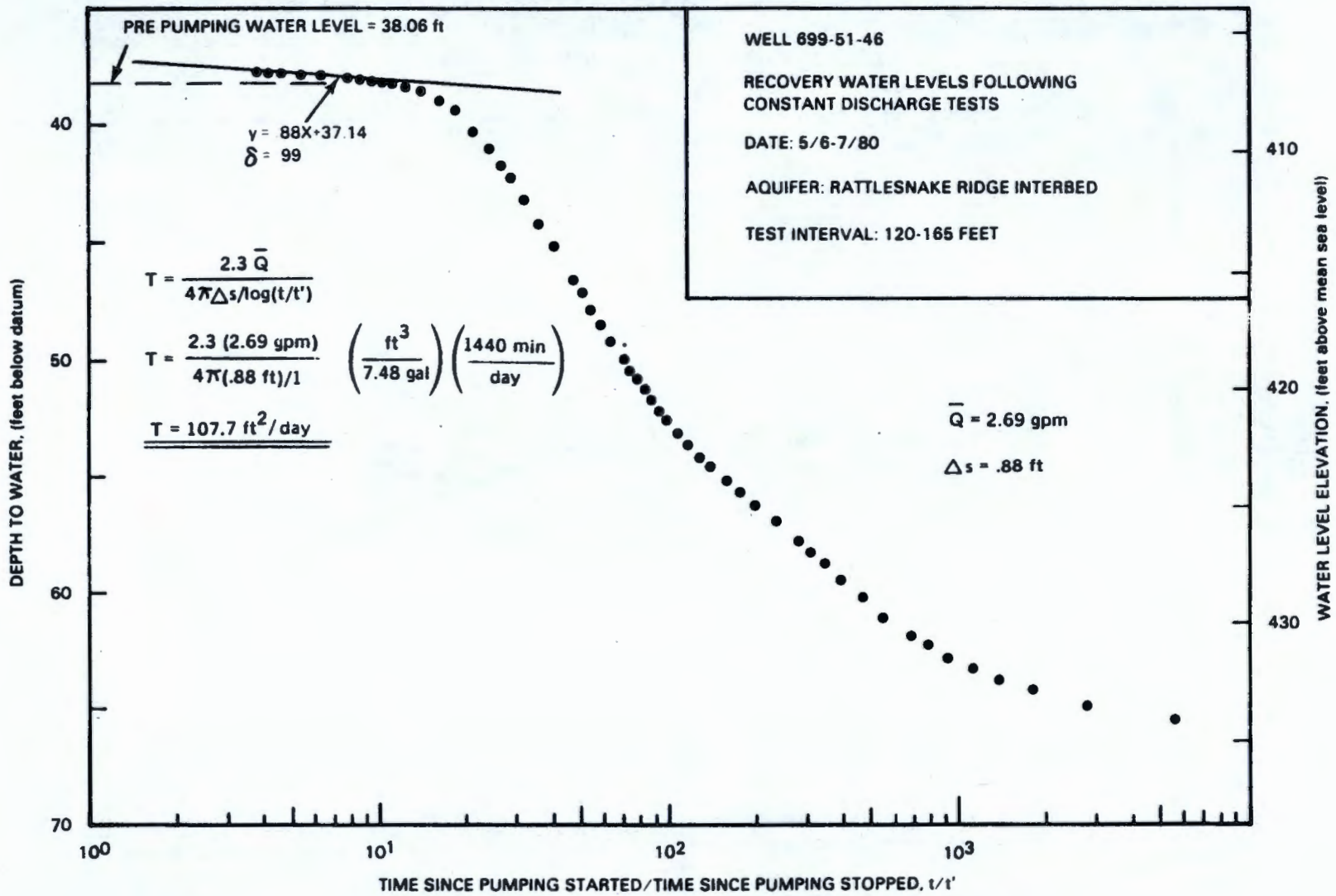


FIGURE C-8. Recovery Water Levels from Well 699-51-46.

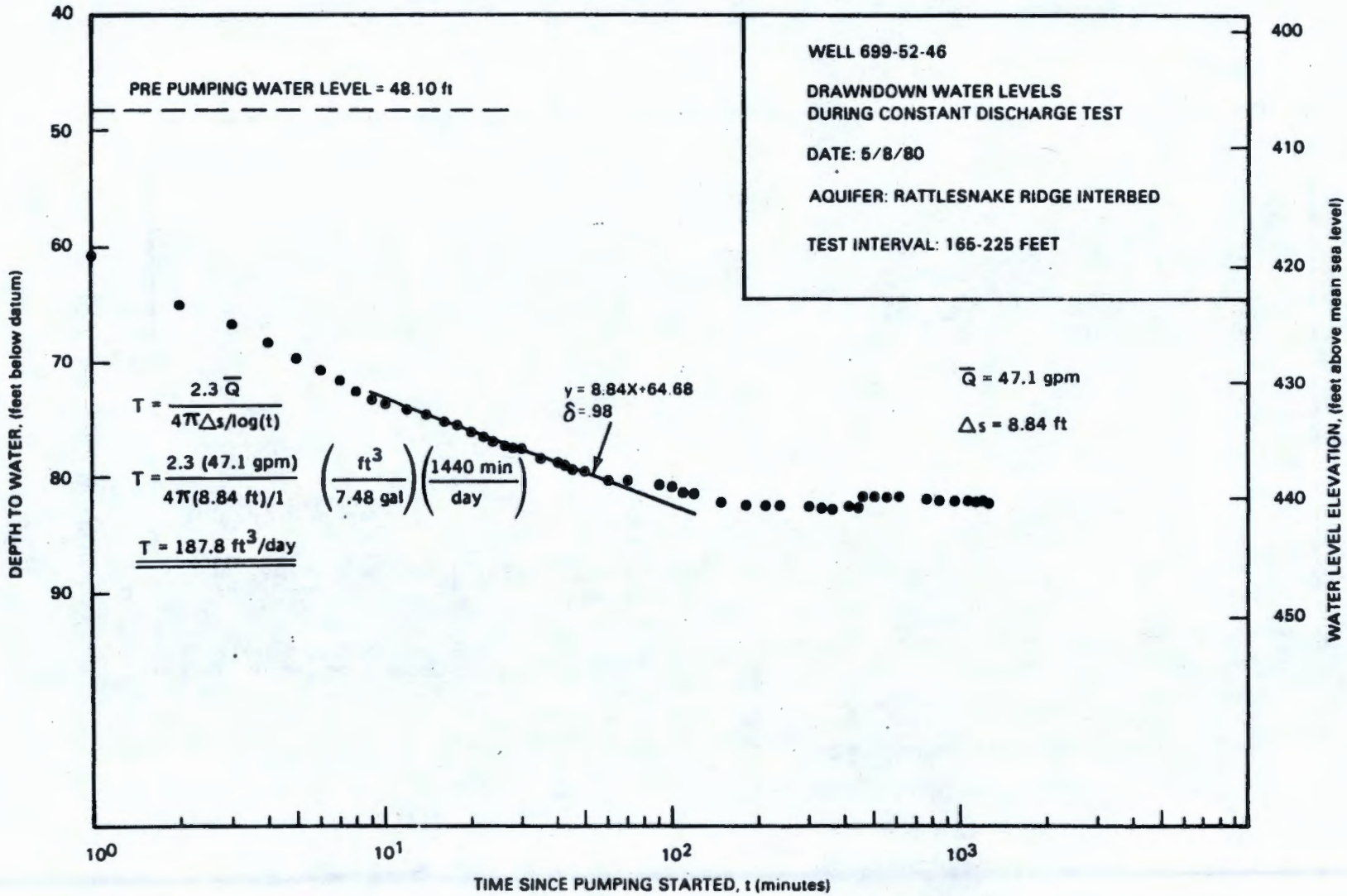


FIGURE C-9. Drawdown Water Levels from Well 699-52-46.

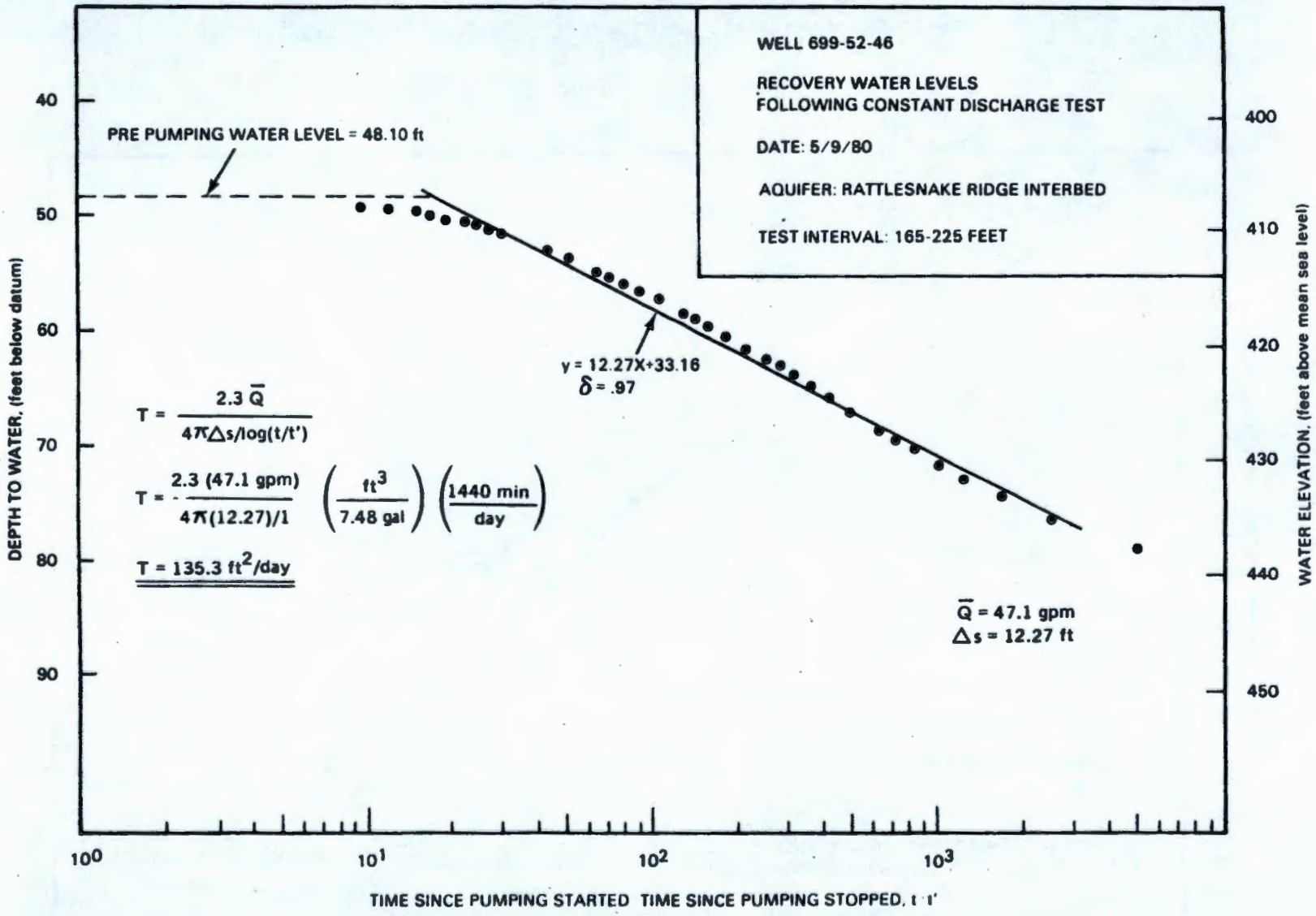


FIGURE C-10. Recovery Water Levels from Well 699-52-46.

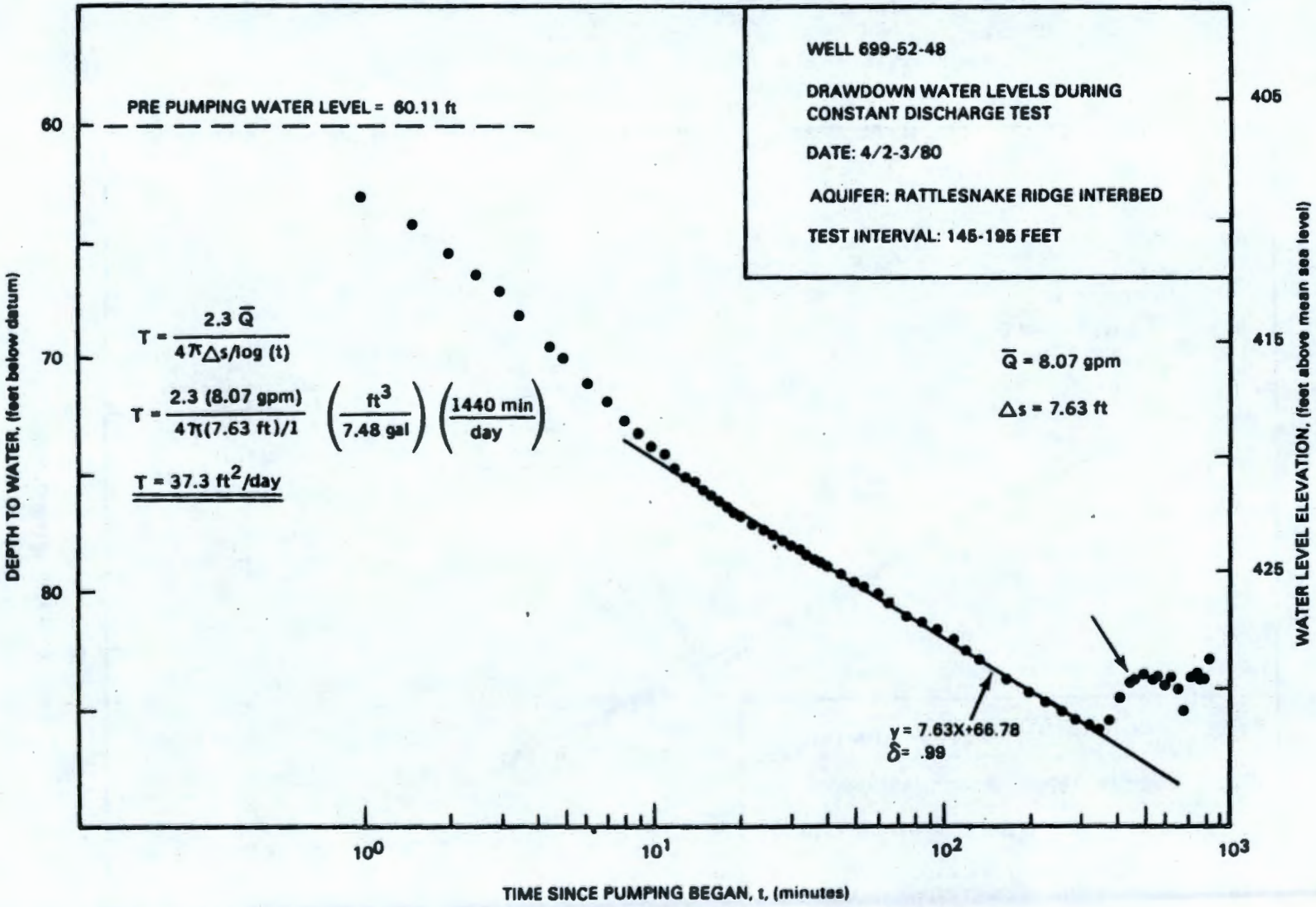


FIGURE C-11. Drawdown Water Levels from Well 699-52-48.

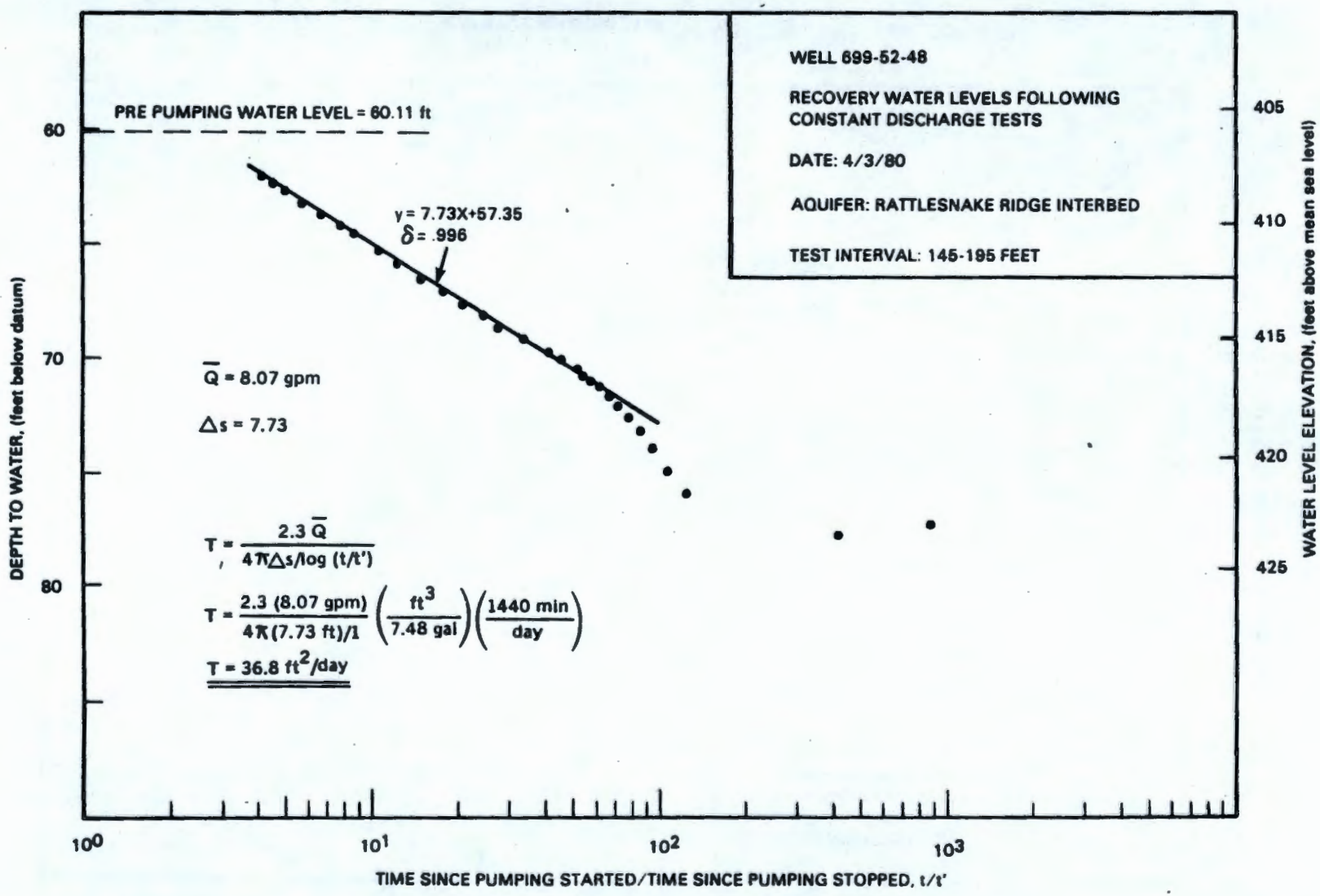


FIGURE C-12. Recovery Water Levels from Well 699-52-48.

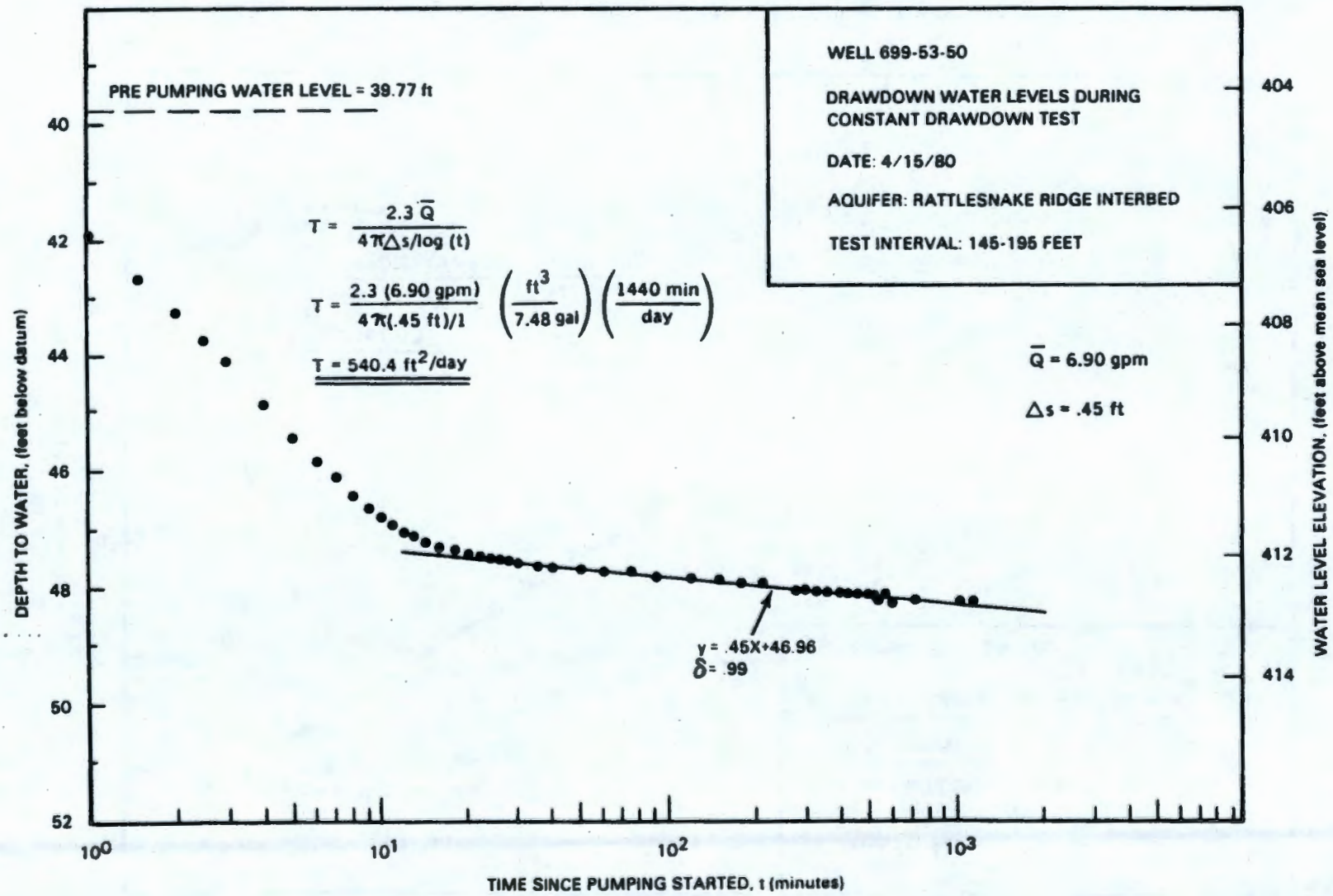


FIGURE C-13. Drawdown Water Levels from Well 699-53-50.

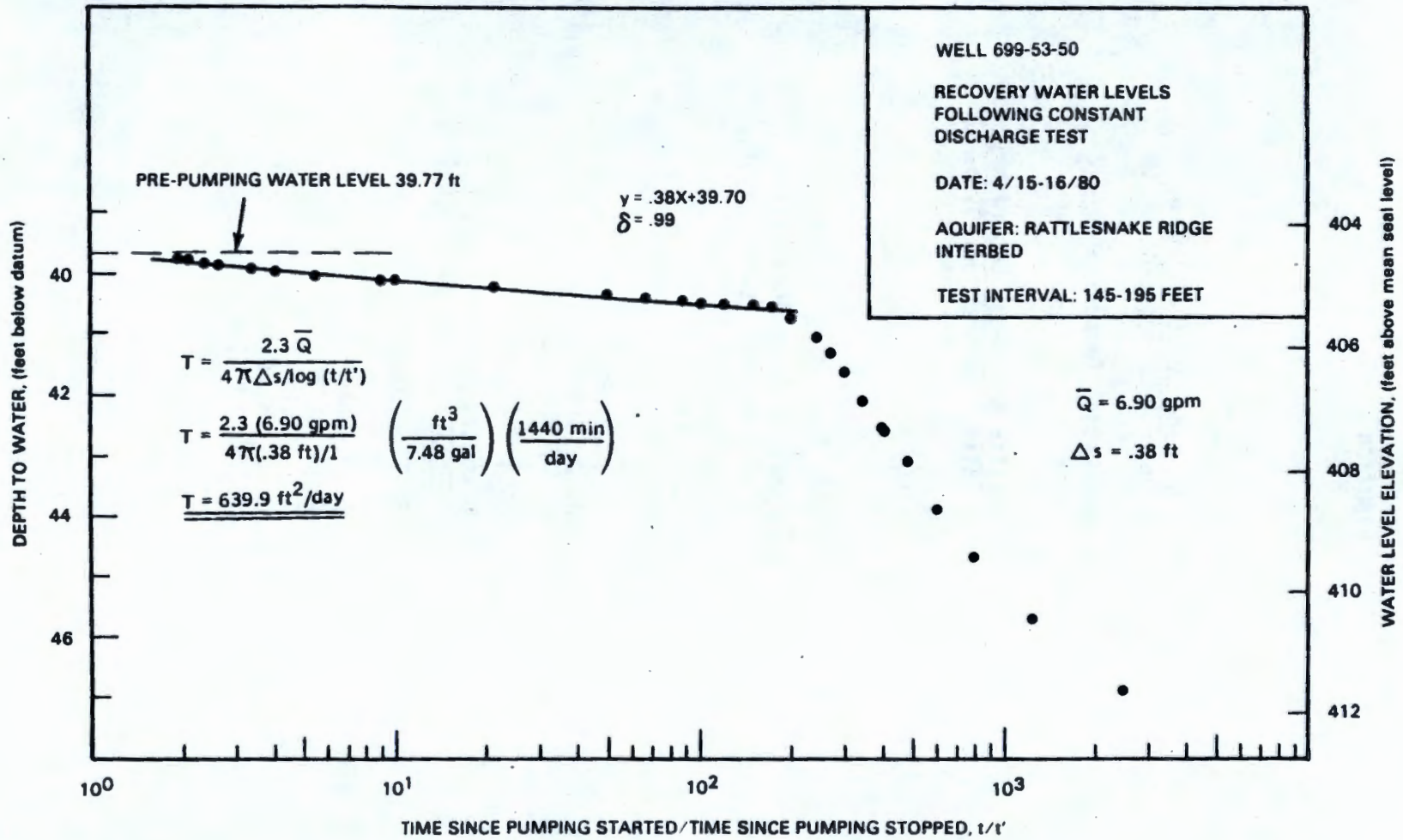


FIGURE C-14. Recovery Water Levels from Well 699-53-50.

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