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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Water Resources Division

PRELIMINARY EVALUATION OF HYDROLOGIC FACTORS RELATED TO RADIOACTIVE WASTE STORAGE IN BASALTIC ROCKS AT THE HANFORD RESERVATION, WASHINGTON

By A. M. La Sala, Jr., and G. C. Doty

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CONTENTS

ILLUSTRATIONS

TABLES

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ABSTRACT

A preliminary study of the hydrologic factors related to the feasibility of storing high-level radioactive wastes in deeply buried basaltic rocks of the Hanford Reservation was begun in 1969 with the drilling of test well ARH-DC-1. The factors of concern include the rate and direction of ground-water movement, the characteristics of ground-water discharge, and the geochemical nature of the waste-rock-water system that might affect the movement of radionuclides. The well was drilled to 5,661 feet. Hydraulic testing to determine the water-bearing properties of the rocks and to sample ground water was carried out to a depth of 4,280 feet. Testing was not completed because the well was lost following repairs to sections of the well that were caving.

Hydraulic testing consisted of (1) pumping tests which gave information mainly on the upper 1,200 feet of the section and (2) tests of zones, ranging from 80 to 200 feet in thickness, isolated with hydraulically inflatable packers, by injecting water or removing water with a swab. The intervals tested using the packers were distributed throughout the well from the 362-foot depth

of the casing bottom to 4,280 feet in depth. Samples of ground water were obtained during pumping tests and during swabbing of packer-isolated zones.

Analysis of the hydraulic data indicates that relatively permeable rocks are interbedded with the basalt from about 500 feet to 1,200 feet in depth, and that relatively permeable zones occur at depths of about 1,500 feet, 2,050 feet, 2,650 feet, 3,200 feet, and 4,000 feet. Values of hydraulic conductivity of the rock units penetrated by the well ranged from 1.6×10^{-3} to 6.7 feet per day, as computed from the injection test data.

The ground-water head in the upper basaltic rocks is about 165 feet below the surface and varies little for most water-bearing zones to a depth of about 3,700 feet. It then decreases within a short depth interval to about 206 feet below land surface in a permeable zone at about 4,000 feet in depth. This lowest head is 365 feet above mean sea level and therefore is above the level of the Columbia River to the east and south of the well. These facts suggest that the ground water may be part of a system discharging to the Columbia River.

Samples of ground water were obtained from discrete water-bearing zones after isolating them with inflatable packers. Analysis of the samples shows these ground waters to be (1) high in silica, (2) high in fluoride (20 mg/l), (3) high in bicarbonate, carbonate, and pH, and (4) to have low calcium to sodium and low calcium to magnesium ratios. The carbonate in the ground water from 900 to 1,200 feet in depth has δC^{13}_{PDB} values of about +15 o/oo (parts per thousand), unusually positive values which, along with other characteristics, serve to distinguish it from the ground water above and below it. The water from a zone at 540 to 620 feet has an adjusted carbon-14 age of about 13,000 years. It, and the waters below it, have stable oxygen and hydrogen isotope ratios that suggest that they entered the ground under colder climatic conditions than those at the Hanford Reservation.

Under the prevailing head relationships and assuming that the observed geohydrologic conditions are widespread, it may be feasible to store radioactive wastes that would decay to low levels in 600 to 1,000 years in mined cavities in thick impermeable rock layers below about 1,200 feet in depth. However, further studies will be necessary to define the characteristics of the ground-water system and to evaluate the conditions under which wastes could move through the system to the human environment. An appraisal of possible areas of ground-water discharge should be made from a study of hydrologic data available for the region of the Pasco Basin. Additional test wells should be drilled on the Reservation to define geohydrologic conditions; specifically the hydraulic gradients, head relationships, and the permeability distribution in the basaltic rocks.

INTRODUCTION

A large quantity of high-level liquid radioactive wastes is stored in below-ground tanks at the Hanford Reservation of the U.S. Atomic Energy Commission. These wastes were produced almost entirely by chemical processing of reactor fuels to extract plutonium and the bulk of the contained long-lived radionuclides will decay to a low level of activity in about 600 to 1,000 years.

The wastes are presently contained in 149 tanks, ranging in size from 50,000 to 1,000,000 gallons, buried beneath about 10 feet of earth (Isaacson, 1969). Several alternative means of storage are under consideration, one of which is the storage of the high-level wastes in a chamber that would be excavated at depth in the basaltic rocks. This scheme requires, among other things, (1) a body of competent rock thick enough to provide structural stability to the chamber, and (2) a slow rate of movement of long-lived radioisotopes through the chambered rock and surrounding rocks so that if they are carried away from the chamber by flowing ground water they will not reach the surface or sites of ground-water withdrawal before the radioactivity has been reduced to a level considered to be innocuous.

In 1969, the Richland Operations Office of the U.S. Atomic Energy Commission began a formal study of the feasibility of storing high-level wastes in a mined chamber in the basaltic rocks. The overall purposes of the study are to investigate (1) the engineering feasibility of mining a chamber at some depth between the surface and 4,500 feet, (2) the feasibility of different means of handling and emplacing wastes in the chamber, and (3) the long-term safety of the scheme. Included in the safety aspect are hydrologic factors such as the rate and direction of ground-water movement, the characteristics of ground-water discharge, and an appraisal of the geochemistry relevant to chemical changes that might affect the migration and concentration of particular radionuclides.

The initial stage of the study centered around the drilling of a deep test well, ARH-DC-1, in proximity to the waste-storage areas. (See fig. 1 for location.) The well was planned for a depth of 7,500 feet but was drilled only to a depth of 5,661 feet. Drilling began on April 27, 1969. Hydraulic test data and water samples were collected to a depth of 4,280 feet. The well was cased to a depth of 362 feet and was left open below this depth to allow hydraulic testing and sampling of ground water. It was drilled by the rotary method using air mist and aerated water with detergent for circulating mediums. Bit size was 9-7/8 inch throughout the uncased interval, but the bore of the well became considerably eroded during drilling. At a depth of 5,661 feet, drilling was stopped so cement repairs could be made to the interval of 824-1,220 feet. On attempting to drill out the cement, the bit deviated from the original hole. Considerable effort was made to recover the original hole, but without success, and drilling was suspended on September 23, 1969. The

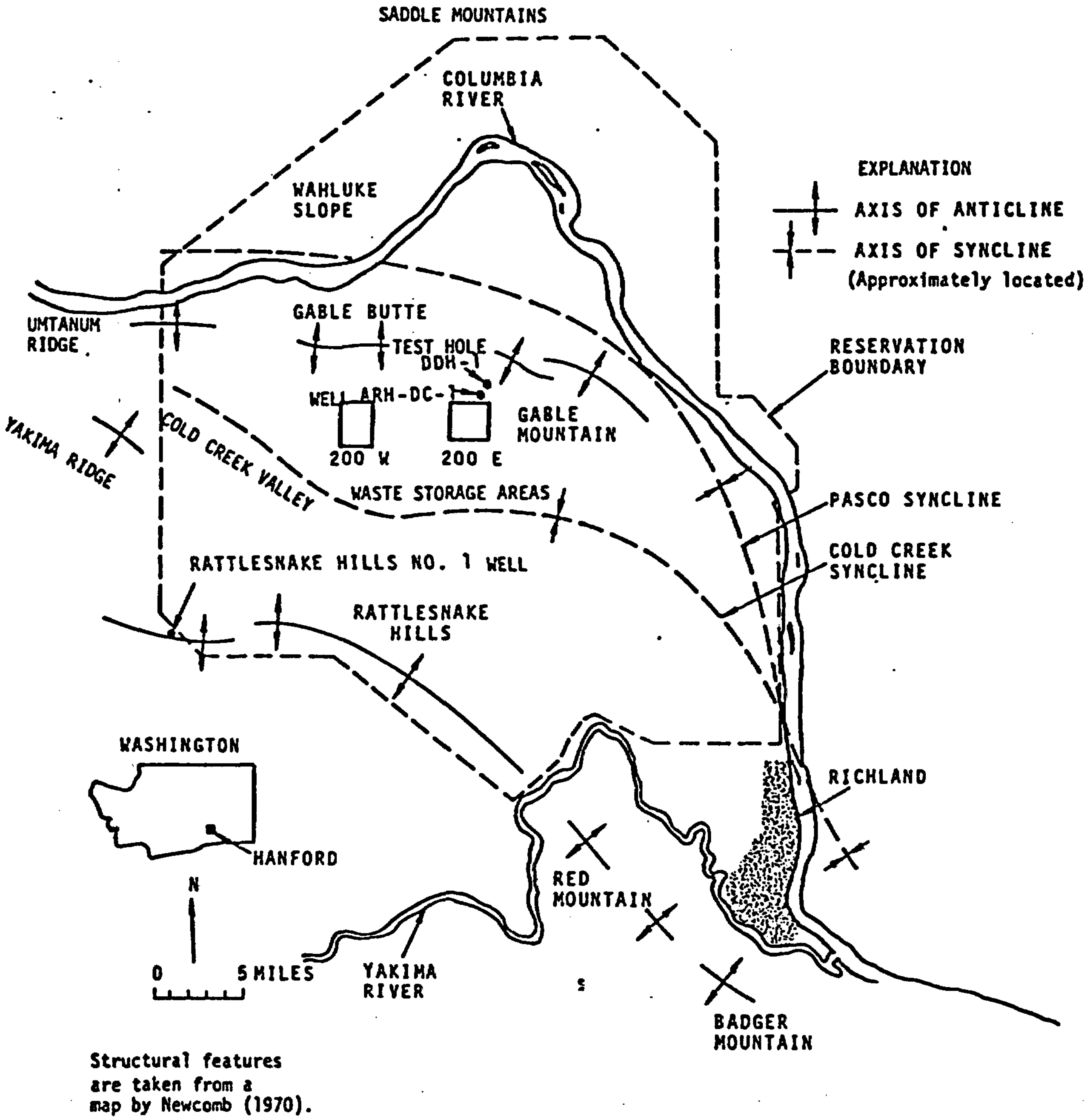


FIGURE 1. The Hanford Reservation and Generalized Geologic Structural Features

overall purposes of the investigation relating to this well are:

1. To define the distribution of the ground-water head with depth.
2. To define the ground-water transmission and storage characteristics of the basalt flows and interbedded rocks.
3. To estimate the age of the ground water.
4. To define the structural integrity of the rocks with respect to sinking a shaft and mining a chamber.
5. To define the geochemical characteristics of the rocks and ground water in order to predict chemical interactions with solutes containing radio-isotopes.
6. To define the subsurface geologic structure and stratigraphy.

The U.S. Geological Survey provided assistance to the Richland Operations Office in developing specifications for the well, in planning geophysical logging and hydraulic testing in the well, and in the evaluation of results. Geological Survey personnel collected hydraulic data by conducting pumping tests, injection tests, and swabbing tests, and by assisting in radioactive tracer logging. The Geological Survey also made physical analyses of rock cores, and collected and analyzed water samples from the well for chemical and isotopic constituents. This report describes the work done by the Geological Survey, presents summaries of the data collected along with appropriate analyses, and gives conclusions about the ground-water system pertaining to the deep storage of radioactive wastes. The work on the engineering aspects of rocks, the evaluation of the possible chemical interactions between soluble wastes and the rocks, and the definition of the stratigraphy and structure of the rocks is being carried on under the auspices of the Atlantic Richfield Hanford Company, which has overall technical direction of the project.

THE PHYSICAL ENVIRONMENT OF THE HANFORD RESERVATION

The Hanford Reservation lies in a structural and topographic basin through which the Columbia River flows generally southward. The basin is bounded on the west by the Rattlesnake Hills, Yakima Ridge, and Umtanum Ridge; on the north by the Wahluke Slope which rises to the east-trending Saddle Mountains; on the south by the Rattlesnake Hills and Red and Badger Mountains; and on the east by a plateau. (See fig. 1.) The region is underlain by a basaltic rock succession that exceeds 10,000 feet in thickness, consisting of younger basaltic rocks of the Yakima Basalt of the Columbia River Group which are exposed in the region and older basaltic rocks which are unexposed. Overlying the basalt are unconsolidated deposits consisting of gravel, sand, silt, and clay. The stratigraphic positions and descriptions of the geologic units are given in table 1.

The basaltic rocks are folded in a series of synclines and anticlines, forming valleys and hills, respectively (fig. 1). Most of the Reservation is underlain by the Pasco and Cold Creek synclines, which are the main parts of the structural basin. Gable Mountain anticline trends across the Reservation and separates these two synclines. Anticlinal structures form the hills bounding the basin. The unconsolidated deposits partly fill the synclines and form terraces overlapping the anticlines. Some deformation of the unconsolidated deposits probably occurred contemporaneously with folding of the basaltic rocks, but in general the unconsolidated deposits are undisturbed by tectonic forces.

The hydrology of the region is characteristic of a semiarid climate. The average annual precipitation is about 6.3 inches per year. Significant perennial surface-water flow occurs only in the Columbia and Yakima Rivers, which have average annual discharges at the Reservation of 120,000 and 2,000 cubic feet per second, respectively. Springs giving rise to some streamflow occur

Table 1.--Principal geologic units of the Hanford Reservation and their water-bearing properties

System	Series	Geologic unit	Lithology and origin	Water-bearing properties
Quaternary	Pleistocene	Glaciofluviatile and fluviatile deposits (0-200 ft thick).	Sand and gravel laid down by glacial streams. Generally coarse sand, pebbles, and cobbles.	The most permeable deposits on the Reservation. Hydraulic conductivity values of 50,000 gpd per square foot or higher have been determined. Porosity is intergranular. (Bierschenk, 1959)
	Pleistocene	Ringold Formation (200-1,200 ft thick).	Lacustrine silt and sand with local beds of clay and gravel. Clay at depth with considerable sand and gravel.	Permeability low because of the fine-grained character of the beds; hydraulic conductivity values range from 10 to 600 gpd per square foot. Porosity is intergranular. (Bierschenk, 1959)
Tertiary	Miocene and Pliocene	Yakima Basalt of Columbia River Group (about 4,500 ft thick).	Basaltic lava flows with interbedded sedimentary rocks, ash beds, and palagonite.	Basaltic rocks range from dense to extremely vesicular. However, even the most vesicular basalt is essentially impermeable with regard to intergranular porosity. Water moves through basalt in vertical shrinkage fractures and horizontal fracture zones. Permeabilities of most basaltic rocks are low but occasional horizontal fracture zones at same apparent flow contacts have high permeabilities. Some interbedded sedimentary rocks have intergranular porosity and have moderate permeabilities.
	Miocene	Lower part of Columbia River Group (greater than 5,000 ft thick).	Basaltic rocks and interbeds.	Water-bearing properties are probably similar to those of Yakima Basalt.

in the upper part of Cold Creek valley and on the flanks of the Rattlesnake Hills and Umtanum and Yakima Ridges. The flow from these springs generally sinks into the ground within one-half to one mile of the origin.

Ground water occurs under artesian conditions in the basaltic rocks and under water-table conditions in the unconsolidated deposits (table 1). Ground-water recharge to the unconsolidated deposits occurs by (1) infiltration of surface runoff from the ridges to the west and southwest, (2) discharge of waste water to the ground as part of processing operations on the Reservation, and (3) movement of water from the Yakima River year-round and, at high stages, from the Columbia River into the deposits along its banks. Because of the low precipitation, recharge through direct infiltration is probably insignificant. Ground-water discharge is to the Columbia River.

The unconsolidated deposits are the most permeable of the geologic units underlying the Reservation (table 1). These deposits contain the zone of most active ground-water circulation on the Reservation, that is the zone in which ground water moves comparatively rapidly and directly to the Columbia River. This zone of circulation possibly extends into the uppermost fractured or weathered rocks of the Yakima Basalt directly in contact with the unconsolidated deposits. The basaltic rocks of the Reservation are less permeable than the unconsolidated deposits. The direction and rate of movement of ground water through them are unknown.

RESULTS OF THE TESTING PROGRAM ON WELL ARH-DC-1

The data collected during investigations on well ARH-DC-1 were utilized in this report to (1) describe the lithology of the rocks penetrated by the well and classify them into rock units pertinent to hydrologic investigations, (2) describe the relationship of ground-water head to depth of the rocks, (3) estimate the hydraulic characteristics of the rock units, and (4) describe the ground water present in the rocks as to chemical and isotopic constituents that may be indicative of the source and flow pattern of the water.

Methods of hydraulic testing and water sampling are described briefly where appropriate to discussing the results of the program. The use of geophysical logs in planning and interpreting hydraulic testing and the methods of testing using inflatable packers are the same techniques used by the U.S. Geological Survey at the Nevada Test Site of the Atomic Energy Commission. These techniques are described in detail by Blankennagel (1967).

Lithology of the Rock Units

The lithology of the rocks in well ARH-DC-1 was described mainly from (1) geophysical logs made to depths of about 4,200 to 4,500 feet, (2) several rock cores cut in the well, and (3) rock cores continuous to a depth of 1,165 feet in test hole DDH-1 whose location is shown in figure 1.

Well ARH-DC-1 penetrated about 190 feet of unconsolidated deposits, consisting principally of sand and gravel, and then entered the underlying basaltic rock sequence, which persisted to the bottom of the well at 5,661 feet. A petroleum test well, Rattlesnake Hills Number 1 (fig. 1), drilled off the Reservation about 12 miles southwest of well ARH-DC-1, is 10,655 feet deep and did not completely penetrate the basaltic rock sequence (Raymond and Tillson, 1968). Therefore, a considerable thickness of basaltic rocks presumably lies below the bottom of well ARH-DC-1.

Well ARH-DC-1 and hole DDH-1 lie on the north flank of the Cold Creek syncline. The rock units dip southward in this area, but the rocks appear to be structurally uncomplicated and to exhibit a normal stratigraphic succession.

In interpreting the character of the rocks penetrated by the well, information contained in reports by Bingham and Grolier (1966), Brown (1968), Mackin (1961), and Schmincke (1967), which describe the lithology and relationship of the basaltic rocks and interbedded sediments exposed in the region, was found useful. Raymond and Tillson's (1968) evaluation of the geophysical logging characteristics of the rocks in the Rattlesnake Number 1 well provided background information on interpreting the geophysical logs from well ARH-DC-1.

A lithologic log of well ARH-DC-1 is given in figure 2. Also included in the figure to illustrate the geophysical logging characteristics that were considered in interpreting the lithology are density, electrical, caliper, and gamma-ray logs. Other geophysical logs made in well ARH-DC-1 were dual induction laterolog, sidewall neutron porosity, borehole compensated density, borehole compensated sonic, microlaterolog-microlog, single receiver-variable density sonic, borehole televiewer, temperature, radioactive tracer, casing collar locator, variable density 3-D sonic, and velocity. These logs were also studied in preparing the lithologic log, but are not presented here. They are, however, included in a report by Fenix and Scisson, Inc. (1969). Cuttings and drilling-rate logs prepared by contractors are also shown in figure 2. The cuttings are not always indicative of the material being drilled at a particular depth, because they may mix with cuttings or materials that slough from the walls of the well. Drilling rate is dependent on the resistance of the rock but also on such factors as sharpness of the drill bit, speed of rotation, and weight carried on the bit. The cuttings and drilling-rate logs do tend to indicate sections of resistant basalt and soft sediments.

The interpretations of lithology from the available logging information were keyed to descriptions of core samples from well ARH-DC-1 by R. E. Brown, Battelle Memorial Institute, Pacific Northwest Laboratory, and to descriptions of core samples from hole DDH-1 by A. G. Lassila, U.S. Atomic Energy Commission, Richland Operations Office. These descriptions are given in tables 2 and 3,

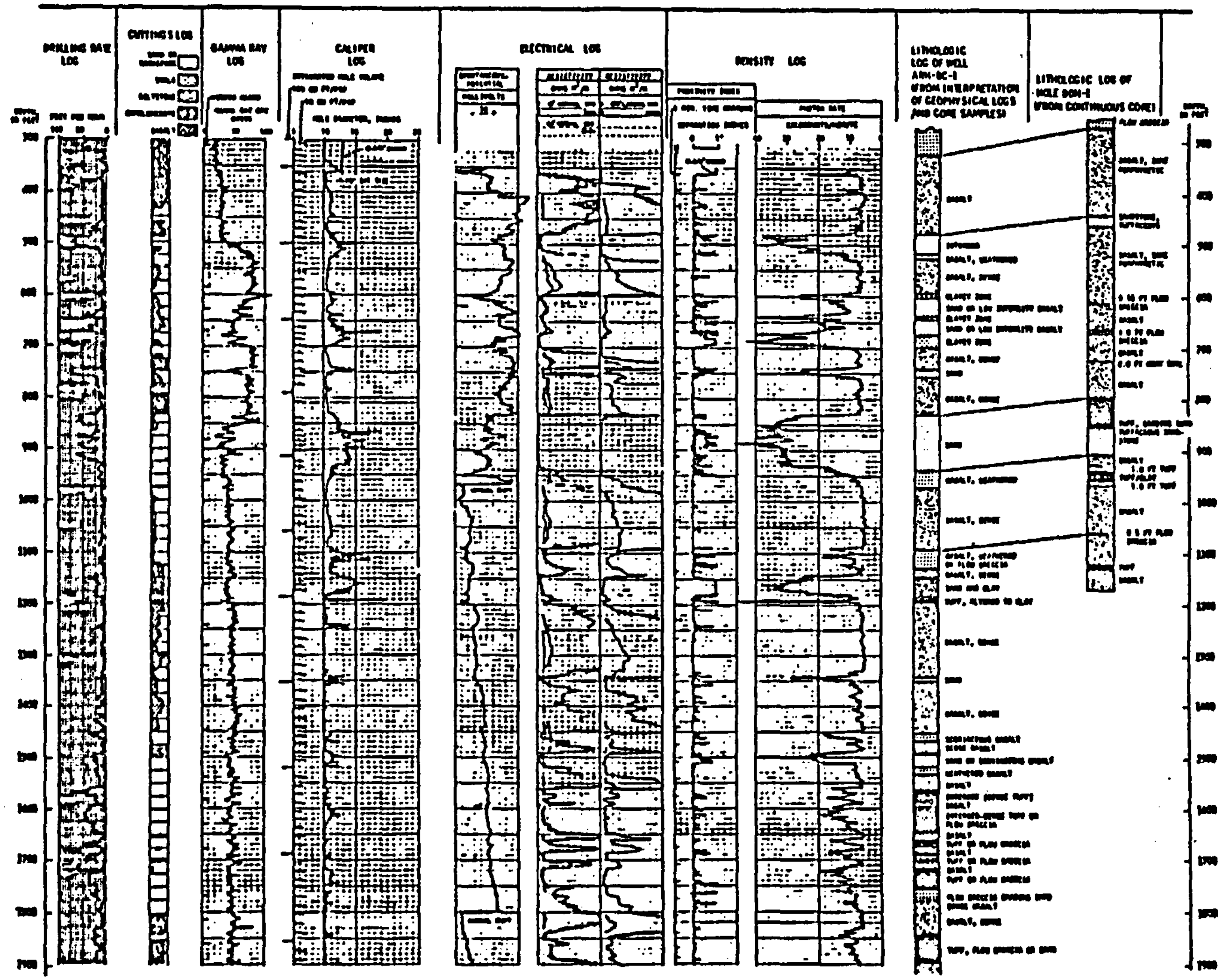


FIGURE 2. Lithology, Selected Geophysical Characteristics, and Drilling Rate for Well ARH-DC-1

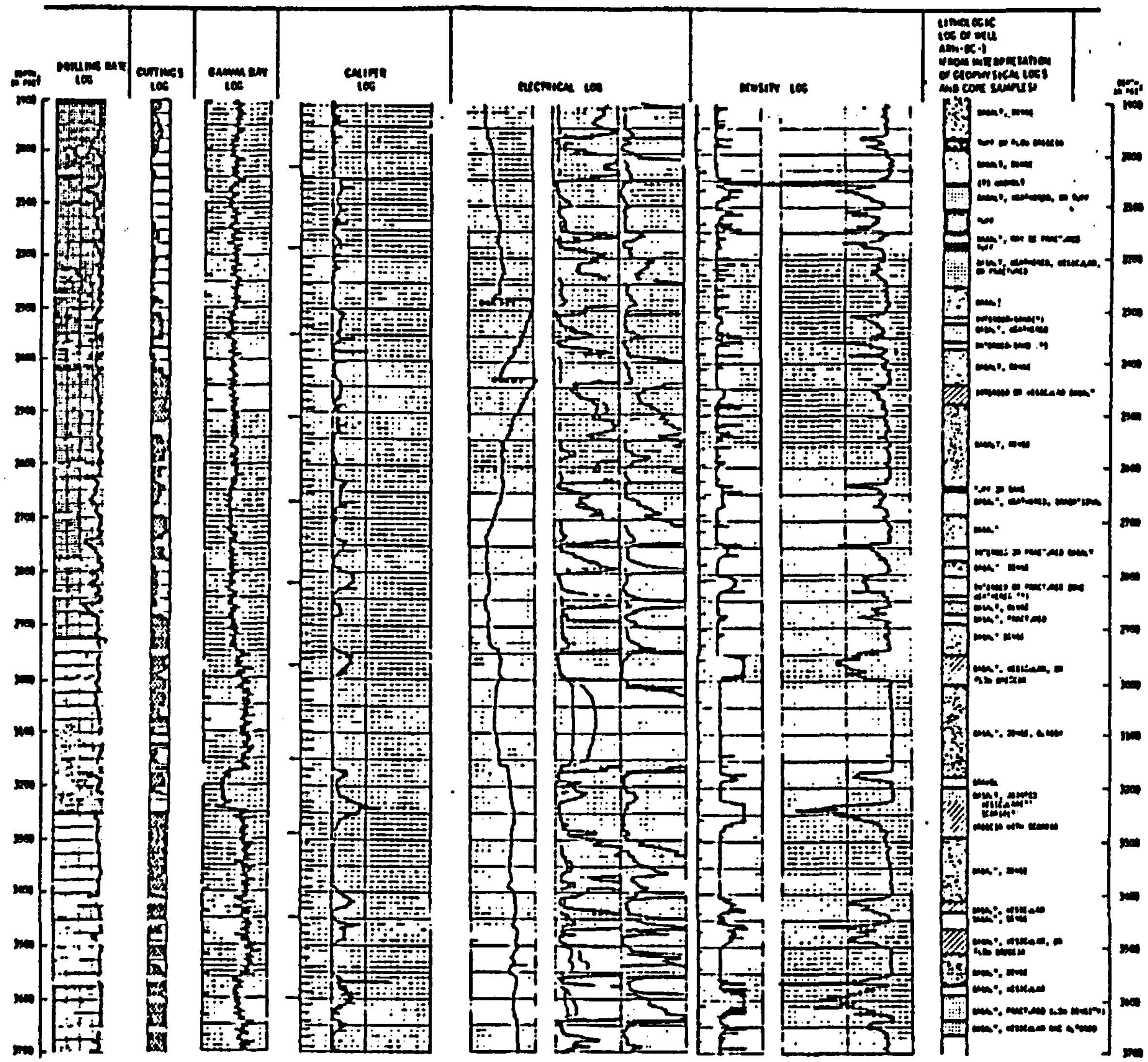


FIGURE 2. (contd)

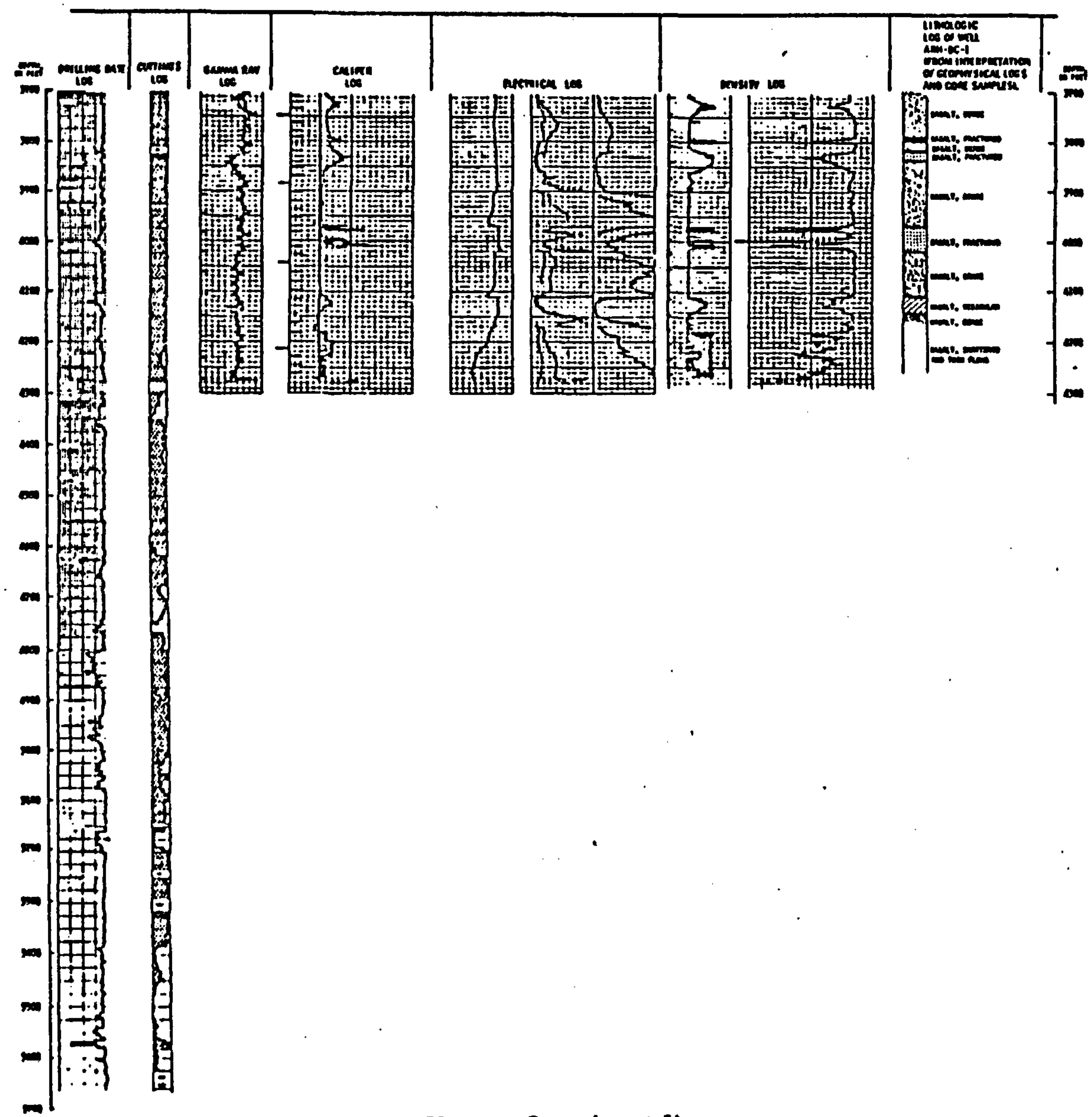


FIGURE 2. (contd)

Table 2.--Descriptions of core samples from well ARH-DC-1[1/]

[By R. E. Brown, Battelle Memorial Institute]

Core number	Description
1	Cored interval 706-712 feet. Recovered, 6 feet. A dense, fine-grained to glassy, black basalt. Highly jointed, with core segments averaging 4 inches in length. A trace of tuff at the upper end of the core probably represents cave-in either from the overlying Squaw Creek diatomite equivalent (at a depth of 675-685 ft) or from the higher Mabton bed (about 480-500 ft). Alteration is present on seams and joints, also occasional vesicle fillings occur. This flow appears to be the Sand Hollow flow of the Frenchman Springs Member. (See Mackin, J. H., 1961, A stratigraphic section in the Yakima Basalt and the Ellensburg Formation in south-central Washington: Washington Div. Mines and Geology Rept. of Inv. no. 19.)
2	No core recovered. Depth 781 feet.
3	Cored interval 783-784 feet. Recovered, 6 inches. A very fine-grained glassy, black basalt. The flow appears to be the Ginko flow of the Frenchman Springs Member.
4	Cored interval 1,188-1,190 feet. Recovered, 2 feet. Volcanic tuff, altered largely to a bentonitic clay. Hard, compact, tough and dense, indicating probably not a depositional clay but an in-place alteration. The sedimentary bed has not previously been described or recognized. It lies between what appears to be the overlying Rocky Coulee flow and the lower Dry Gulch flow of J. H. Mackin. (See above reference.)
5	Cored interval 1,709-1,711.5 feet. Recovered, 2-1/2 feet. A dense, dark gray, medium-grained basalt. The color, grain size, and the length of core segments (up to 8 in) indicate that the core came from near the base of the unnamed flow.
6	Cored interval 2,380-1/2-2,387 feet. Recovered, 5.5 feet. A medium-gray colored, holocrystalline, coarse-grained basalt. The color, crystallinity, and length of core segments (averaging about 6 in long and up to 16 in long) suggest a probably massive basalt flow. The geophysical logs suggest a break (flow top) at about 2,360 feet. Proximity of basalt of this type to a flow top suggests a thick, massive flow.
7	Cored interval 2,779-2,784-1/2 feet. Recovered, 5 feet. Identical in appearance to Core 6. More jointed, but core evidently followed one vertical joint.
8	Cored interval 2,943-2,954 feet. Recovered, 11 feet. A highly vesicular basalt and flow breccia containing a trace of carbonized wood. Vesicles are up to an inch in diameter, especially above 2,950 feet. Below 2,950 feet the core becomes more solid, less vesicular, and with contorted vesicle bands. Top of basalt flow.
9	Cored interval 3,087-3,089 feet. Recovered, 2 feet. A very fine-grained, glassy, black basalt. Core in segments up to 1-foot long, most 4-inches long. Core barrel twisted off.
10	Cored interval 3,103-3,103-1/2 feet. No recovery. Core barrel twisted off.
11	Cored interval 3,107-3,117 feet. No recovery.
12	Cored interval 3,126 feet. Did not cut. Ruined core head.
13	Cored interval 3,126-3,128-1/2 feet. Recovered, 2-1/2 feet. A fine-grained, glassy black basalt.
14	Cored interval 3,163-3,165 feet. Recovered, 1-1/4 feet.
15	Cored interval 3,171-3,173-1/2 feet. Recovered, 2 feet. A sandy granule gravel, with well rounded granules of basalt about 1/8 inch in diameter. Carbonized wood occurred in the sample, probably carbonized by heat of the flow overlying it. The sand has been baked by the overlying flow, also indurated by secondary quartz. The higher part of the core is a highly vesicular basalt (of the flow overrunning the interbed) in pieces up to 2 inches maximum length. Most of the core is in rounded fragments about 1 inch in diameter.
16	Cored interval 3,216-3,236 feet. Recovered, 9 feet. A dark gray, holocrystalline, coarse-grained basalt. Highly jointed with the average length of core about 2 inches. Joints commonly occur at angles to the core of about 30-40°, with some at right angles. One large vug was lined with quartz.
17	Cored interval 3,236-3,246 feet. Recovered, 2 feet. A vesicular flow breccia with scoria, forms the contact zone between Core 16 flow and the flow beneath Core 17. Many pieces of the core are 1 inch or less in diameter. One piece 3-inches long contains numerous yet unidentified zeolites and also some chalcedony.
18	Cored interval 3,411-3,421 feet. Recovered, 7-1/4 feet. A fine-grained, dense, black, vesicular basalt from near the top of the basalt flow. The core rapidly becomes less vesicular downward. Many vesicles are lined with zeolites. Only a few vesicles are drawn out or flattened. Vugs occur between 3,416 and 3,418 feet, then the core changes to a normal nonvesicular basalt.
19	Cored interval 3,451-3,453 feet. Recovered, 2 feet. A highly vesicular, fine-grained basalt. Core in many fragments. Some zeolites in some of the vesicles.
20	Cored interval 3,453-3,461 feet. Recovered--no core.
21	Cored interval 3,494-3,504 feet. Recovered, 4 feet. A basalt flow breccia from 3,495-3,497.2 feet with a tuffaceous matrix. Underlain by a fine-grained glassy, black, highly jointed basalt. The breccia may be either a flow breccia overlain by a thin tuff bed, or may be an altered pillow-palagonite or breccia-palagonite complex. Whether the breccia represents the base of the overlying flow or the top of the lower flow cannot be ascertained.
22	Cored interval 3,523-3,525 feet. Recovered, 2 feet. A fine-grained, dense, glassy, black, highly jointed basalt.
23	Cored interval 3,556-3,566 feet. Recovered, 5 feet. A highly vesicular basalt. Considerable opal, zeolites, and chalcedony in vesicles.
24	Cored interval 3,597-3,599 feet. Recovered--no core.
25	Cored interval 3,599-3,602 feet. Recovered, 2 inches. A very fine-grained, dense, black basalt. Occasional small feldspar phenocrysts. Vesicles constitute 10 to 30 percent of rock.
26	Cored interval 3,652-3,659 feet. Recovered, 4 feet. A dense, medium-grained, dark gray basalt. Locally greenish gray in color probably owing to chloritization. Occasional vugs and vesicles filled with chalcedony, some quartz. Higher cores have contained dominantly quartz and zeolites. Core occurs in segments 3-4 inches long with scattered vesicles.
27	Cored interval 3,935-3,938 feet. Recovered about 2 feet. A fine-grained, dark gray to nearly black basalt. Feldspars commonly about 1 mm long. A few vesicles lined with secondary minerals (chlorophaeite?) and quartz. Most of core 2-4 inches long, one piece 1-foot long.
28	Cored interval 4,285-4,292 feet. Recovered, 2 feet.
29	Cored interval 5,148-5,149 feet. Recovered--no core.
30	Cored interval 2,828-2,836 feet. Recovered, 8 feet. Vesicular basalt. This core was cut in a deviated, not the original, bore hole.

1/ Stratigraphic nomenclature does not conform to U.S. Geological Survey usage.

Table 3.--Description of core samples from test hole DDH-1

[By A. G. Lassila, U.S. Atomic Energy Commission. Wording of some descriptions modified slightly for uniformity of presentation]

Material	Depth (feet) From	Depth (feet) To
Previously drilled well	0	171
Basalt, dark gray; phenocrysts 1 mm long by 1/4 mm wide comprise 20 to 30 percent of rocks. Fresh matrix. Core lengths averaging about 0.5 foot long. High angle fractures predominate; fractures have been healed by secondary mineralization--possibly chlorite	171	201
Tuff to tuff breccia, light gray	201	204
Sandstone, tuffaceous, light gray, friable. Faint indication of cross bedding--probably water deposited	204	236
Sandstone, olive gray, medium-grained, well sorted, subrounded, friable, massive. Sixty percent quartz, 30 percent basalt, 10 percent ash. Mica present	236	252
Basalt, scoriaceous to vesicular; some vesicles filled with secondary mineralization. Develops flow breccia appearance about depth 260	252	269
Flow breccia, greenish gray, fractured; fractures rehealed with chlorite	269	275
Basalt, dark gray to black, finely crystalline to porphyritic with phenocrysts 1/8-inch long by 1/32-inch wide. High angle to vertical fractures rehealed with as much as 1/8-inch of chlorite material	275	441.5
Tuff, dark gray, massive; partially decomposed	441.5	450
Sandstone, tuffaceous, light gray, fine-grained, well sorted, friable; interval 450 to 454 feet not recovered	450	460
Tuff, dark gray, partially decomposed	460	462
Basalt, dark gray to black, aphanitic to porphyritic with phenocrysts as much as 3/16 inch. Interval 462 to 473 appears to be decomposed flow breccia; interval 473 to 490 vesicular grading to massive	462	608.5
Basalt, black, aphanitic to porphyritic. Fractures rehealed by secondary mineralization; 0.5 foot of flow breccia from 608.5 to 609	608.5	663.5
Basalt, dark gray to black, finely crystalline. Flow breccia in the zone 663.5 to 667	663.5	716
Soil, gray	716	718
Basalt, black to gray, vesicular 718 to 735 and 787 to 794. Hairline fractures are filled with a black mineral	718	794
Tuff, or tuffaceous sandstone, dark gray to tan, with many engulfed particles. Some silt and clay intermixed with sand-size particles	794	903
Basalt, black, fine crystalline, fresh	903	925
Clay--no core recovery	925	955
Basalt	955	959
Tuff, or tuffaceous sandstone	959	960
Basalt, gray; percentage of phenocrysts ranges from 20 to 50 percent of the rock. Abundant fractures are healed by chlorite	960	1,059
Basalt, black, vesicular. The vesicles contain secondary mineral assemblages of at least two zeolites: one amorphous and the other is gray crystalline (scapolite?) calcite (crystals up to 2 mm across). Secondary pyrite crystals are 1/4 mm, but still show striations. Very little fracturing	1,059	1,115.5
Tuff, lapilla, gray	1,115.5	1,122.5
Basalt, vesicular, gray. Vesicles filled with zeolites similar to interval 1,059 to 1,115.5. Last few feet of interval is highly weathered	1,122.5	1,165 (TD)

respectively. The tentative stratigraphic correlation of the rocks in well ARH-DC-1 and hole DDH-1 are indicated in figure 2 and reflect the southward dip of the rocks off the flank of Gable Mountain anticline.

On the geophysical logs, competent dense basalt shows high electrical resistivity, high density, and high sonic velocity. Sedimentary rocks show different characteristics arising from their low electrical resistivity, low density, and low sonic velocity. Gamma-ray activity of rocks is a function of their radioisotope concentration and density. Cemented or compacted sediments, vesicular basalt, flow breccia, and palagonite may show various intermediate characteristics. Thick zones of basalt, such as those from 325 to 480 feet and from 2,966 to 3,166 feet are readily identified on the geophysical logs, as are the sedimentary sections at depths of about 500 and 900 feet. Zones in which one or more geophysical characteristics are different from those for competent basalt or soft sediments are more difficult and less certain of interpretation. In such instances, the authors made a judgment about the types of rocks likely to have such logging characteristics. For instance, the rocks in the zone from 1,090 to 1,120 feet have a low resistivity, a density and sonic velocity somewhat less than dense basalt, and a gamma-ray activity similar to the overlying competent basalt. The caliper log shows a rough, eroded well bore, which indicates that the rock is not competent. The gamma log is interpreted as indicating the rock is basaltic, but the low resistivity indicates that it contains water-filled openings. The rock may, therefore, be a weathered basalt or a flow breccia.

It can be expected that the authors' lithologic log will be revised as more information is developed on the geophysical properties of the rocks underlying the Reservation. For purposes of this report, the lithologic log is significant for identifying units that have distinctive physical and hydraulic properties.

Ground-Water Head

The water level in an unpumped well is a composite of the heads in the various water-bearing openings penetrated by the well. The position of the water level is, in part, affected by movement of water through the well from zones with higher head to zones with lower head. The water level approaches an equilibrium that depends on the relative heads and the transmissivity of the various water-bearing zones. Direct measurements can be made of the head in discrete water-bearing zones penetrated by the well by isolating hydraulically the zone of interest in the well. This is done with packers operated by a tool carried on a string of tubing that extends to the surface. The tubing can be connected hydraulically to the isolated zone after setting the packers, and the head in the zone can be measured as a depth to water in the tubing.

The measurements of ground-water head in well ARH-DC-1 through use of such a packer tool are shown in figure 3. These data are not precise representations of the undisturbed heads in the rocks, because of several factors. Drilling the well had considerable influence on the heads. Circulation of air mist and, during subsequent stage of drilling, aerated water removed ground water from the rocks and in some cases caused the rocks to be invaded by air. Pumping or blowing the well to clean out drilling fluid and facilitate collecting water samples caused a lowering of head, particularly in the more permeable zones. Other effects were caused by circulation of water between zones through the well during geophysical logging and hydraulic testing. This caused a reduction of head in zones contributing water and an increase in head in zones receiving water. Recovery of water levels from these various effects doubtless was occurring to some degree at the times most zones would be isolated by packers.

The method of hydraulic testing also produced an effect on the head in the isolated zone. To both conduct injection tests and check functioning of

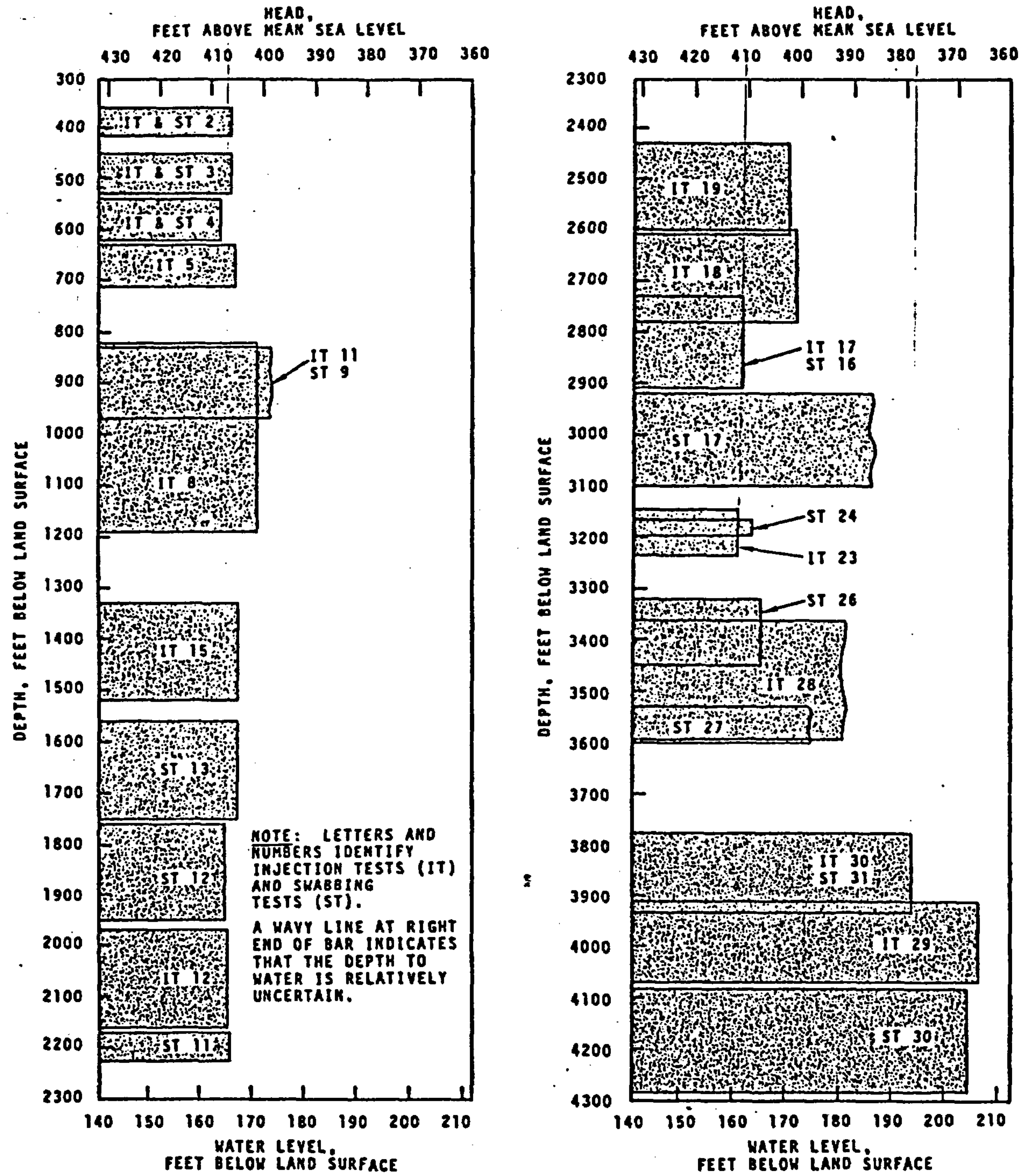


FIGURE 3. Approximate Undisturbed Ground-Water Head for Isolated Water-Bearing Zones in Well ARH-DC-1

the packer tool, it was necessary to begin a test with the tubing filled with water, so that a decline in water level signaled that the tool had opened to the test zone. The water in the tubing created an increase in head in the test zone, and measurements of the rate at which this head decayed provided information on the hydraulic properties of the rock. However, to obtain a measurement of the undisturbed head it would be necessary to wait for complete decay of the additonal head imposed by the water in the tubing. In general, this was impractical because of the time involved, and measurements were continued only until the rate of change of water levels was small. Most zones were tested also by swabbing, a technique which withdraws water from the tubing and lowers the head on the test zone. Recovery of water level was measured until the rate of change was small. In general, then, it was assumed that the undisturbed head would be between the lowest water level measured following injection and the highest water level following swabbing. A value for undisturbed head was picked by extending the trends of graphs of the water-level recoveries, or, where the rate of change was very slow, by taking the median value between the lowest recovery level following injection and the highest recovery level following swabbing. In general, these values were within 3 feet of one another. These values for undisturbed heads were satisfactory for computing hydraulic constants of the rocks as will be explained later. However, there was no definite method by which antecedent effects on undisturbed head due to influences from drilling or circulation through the well could be evaluated. The original plan was to complete the well with several piezometers finished in representative water-bearing zones. Measurements of water level or pressure over several months would then have shown if the heads in these zones were recovering from such disturbances and eventually would have provided true values of undisturbed heads for comparison with the data obtained from hydraulic tests. The well bore at depth, unfortunately, was lost following a cementing operation and could not be relocated within the limitations of the funds that were available.

The differences among the heads in different zones shown in figure 3 are probably significant only with regard to major characteristics of the head distribution. Small differences between adjacent zones may be due only to effects of particular antecedent conditions or measuring errors. The distribution of head with depth does show some significant characteristics, however, in different parts of the well. From 362 feet (the depth of casing during the hydraulic testing) to about 2,700 feet, the water level generally ranges from 165 to 170 feet below land surface. Zones from 540-620 feet and 1,760-1,950 feet in this depth interval have slightly higher measured heads, and zones from 820-1,190 and 2,600-2,780 feet have slightly lower heads. In the depth interval from about 2,800 to 4,280 feet, the heads in the zones tested range widely. The relatively high heads measured in the zones, 2,730-2,910 feet, 3,146-3,236 feet, and 3,166-3,196 feet are at variance with the lower heads in adjacent zones. The heads in the depth interval from 2,800 to 3,450 feet may well be relatively high and between 160 and 165 feet below land surface. It should be noted that the higher heads measured were unlikely to be caused by any factor other than entrapment of drilling air. However, the hydraulic-test data did not indicate the presence of air in the rocks. The relatively low heads in the test zones in the depth interval 2,800 to 3,600 feet may be indicating drawdowns resulting from the production of water during drilling. The rocks in these zones have very low permeability, and because they were tested for the most part within one day after drilling was suspended, the heads may not have recovered from production of water during drilling. Winograd (1970, p. 20-21) points out that in low-permeability rocks at the Nevada Test Site, recovery of water levels in wells usually requires a few days.

The relatively low water levels measured in the interval from 3,800 to 4,280 feet represent a real difference in head with respect to the heads higher up the hole. Temperature logs and radioactive tracer logs of the well both indicated downward movement of water from upper zones with higher heads to about the depth of 4,000 feet. The head measured in the zone 3,910 to 4,070 feet may be higher than the undisturbed head because of the recharge the zone received by the downward flow of water through the well.

Hydraulic Properties of the Basaltic Rock Sequence

The capacity of rocks to transmit and store water is described by the magnitudes of hydraulic conductivity and storage coefficient, respectively. The hydraulic conductivity is a measure of the rate at which a rock will transmit water under field conditions and can be given with the dimensions of (1) units of length per unit of time for a unit head loss or, equivalently, (2) as a volume rate of flow per unit cross-sectional area at a right angle to the direction of flow under a unit hydraulic gradient. The storage coefficient describes the characteristics of a rock in storing and releasing water. It is a dimensionless number representing the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head. In confined aquifers, such as occur in the basaltic rocks, the storage coefficient is determined principally by the elastic properties of the aquifer and the confining beds and by the compressibility of water. In making field tests in wells, the hydraulic conductivity cannot be determined directly. Instead, the parameter "transmissivity" is determined. Transmissivity is equal to the average hydraulic conductivity multiplied by the thickness of the water-bearing zone. It is defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

In well ARH-DC-1, tests were made to determine values of transmissivity of the rocks by (1) isolating zones between packers, using the tool mentioned previously in the section on ground-water head, and injecting water from the filled tubing or withdrawing water from the tubing with a swab; and (2) by pumping from the well itself using a submersible pump. The most reliable data on transmissivities of isolated water-bearing zones were provided by the injection tests on zones isolated by packers. Swabbing of isolated zones and pumping from the section open to the well were done primarily to obtain water samples, and the hydraulic effects produced by these operations could, in most tests, be used only for order-of-magnitude estimates of transmissivity. Measurements of hydraulic conductivity also were made in the laboratory on samples of basalt obtained from cores cut in well ARH-DC-1.

Values of Transmissivity and Storage Coefficient from Tests of Isolated Zones

The transmissivity values of test zones computed from the water-level data obtained during injection and swabbing tests are summarized in table 4. These computations were done by the method of Cooper, Bredehoeft, and Papadopulos (1967), who present a solution for the change in water level in a well of finite diameter after a known quantity of water is instantaneously injected or withdrawn. These authors present a set of type curves computed from this solution, which permits a determination of the transmissivity of an artesian aquifer through a curve-matching technique. The aquifer is homogeneous, of uniform thickness, and bounded top and bottom by impermeable rocks. This solution is developed for a model in which a nonflowing well is cased to the top of the artesian aquifer and is screened or open throughout the entire thickness of the aquifer. When a well is instantaneously charged with a quantity of water (as was done in the injection tests on well ARH-DC-1) or a

Table 4.--Summary of results for analysis of hydraulic data collected for zones isolated by packers in well ARH-DC-1

Interval (depth in feet)	Test number1/	Apparent undisturbed water level (feet below land surface)	Computed transmissivity2/ (gpd/ft)	Computed transmissivity2/ (ft^2/day)
362-416	IT2	3/169.9	3/12.0	3/1.6
	IT2	-----	13.2	1.8
	ST2	165.0	-----	----
450-530	IT3	-----	~500	~67
	ST3	4/165.4	-----	----
540-620	IT4	163.2	High	
630-712	IT5	166.2	-----	----
820-1,190	IT8	170.5	-----	----
830-970	IT11	>173	High	
1,130-1,190	IT9	4/163.3	High	
	ST7			
1,330-1,520	IT15	3/168.1	3/52.6	3/7.0
	IT15	167.1	65	8.7
1,560-1,750	IT14	-----	Low	
	ST13	166.8	Low	
1,760-1,950	IT13	-----	Low	
	ST12	164.7	Low	
1,970-2,160	IT12	3/165.4	3/285.7	3/38.2
	IT12	-----	264	35.3
	ST10	4/165.3	-----	----
2,100-2,280	IT21	----	Low	
	ST21			
2,170-2,225	ST11	166.0	Low	
2,240-2,420	IT20	-----	Low	
	ST20			
2,430-2,610	IT19	169.2	-----	----
	ST19	-----	Low	
2,600-2,780	IT18	170.16	170	13.4
2,730-2,910	IT17	3/224.8	3/0.8	3/0.1
	IT17	-----	2.2	0.29
	ST16	160.7	-----	-----
2,920-3,103	ST17	>185.1	Low	
3,144-3,236	IT23	3/162.0	3/515.4	3/68.9
	IT23	159.8	583	77.9
3,166-3,196	IT24	3/353.05	3/1.3	3/0.17
	IT24	------	4.8	0.64
	ST24	162.9	-----	-----
3,206-3,246	ST25	168.6	-----	-----
3,320-3,451	IT26	-----	4.3	0.58
	ST26	164.5	-----	-----
3,360-3,597	IT28	>180.6	Low	
3,516-3,676	ST32	------	Low	
3,530-3,597	ST27	>173.9	Low	
3,774-3,934	IT30	------	3.3	0.44
	ST31	4/193.4	4.1	0.55
3,910-4,070	IT29	206.3	~500	~67
4,080-4,283	ST30	204.2	-----	-----

1/ The prefix IT indicates an injection test; ST a swabbing test.

2/ Values of transmissivity given as "high" or "low" indicate that the water-level data could not be used to obtain a numerical value. For those test results indicated as "low," the transmissivity probably is less than 10 gpd/ft (1.3 ft^2/day). For those indicated as "high," the transmissivity probably exceeds 500 gpd/ft (67 ft^2/day). 2.3x10-4

3/ These values are obtained by digital computer program.

4/ The value of water level given is the average obtained from recovery during injection and swabbing tests.

quantity of water is withdrawn instantaneously (a procedure approximated by a single-pass swab test), the water level in the well instantaneously moves to a new level and then begins to return to its original level. The solution ignores only inertial forces on the column of water in the well, which are small, and therefore is virtually exact.

In these authors' method for computing transmissivity, a semi-log plot of the quotient of the head, H, divided by the initial head, H_o, versus the time, t, at which H occurs, is matched to a family of type curves of H/H_o versus the expression $\frac{Tt}{r_c^2}$, in which T is transmissivity and r_c is the radius of the casing or pipe to which the slug of water is added or removed. Each curve of the family corresponds to a value of $\alpha = \frac{r_s^2}{r_c^2} S$, in which r_s is the radius of the open well bore and S is the storage coefficient. The transmissivity can then be computed by substituting the values for any match point in the relationship

$$T = \frac{xr_c^2}{y}$$

where

x = the value of $\frac{Tt}{r_c^2}$ at the match point,

y = the value of t at the match point.

This method of computation is illustrated using the data for injection test 2, which are shown in figure 4[1/]. These data are used to prepare the plot of H/H_o versus t, which is then matched to the family of type curves as illustrated in figure 5. A match point is then selected and the appropriate values are used to compute the transmissivity as is done in figure 5. As can

1/ Water-level measuring instruments used in field studies were calibrated in meters. Actual field measurements are given in meters throughout this report.

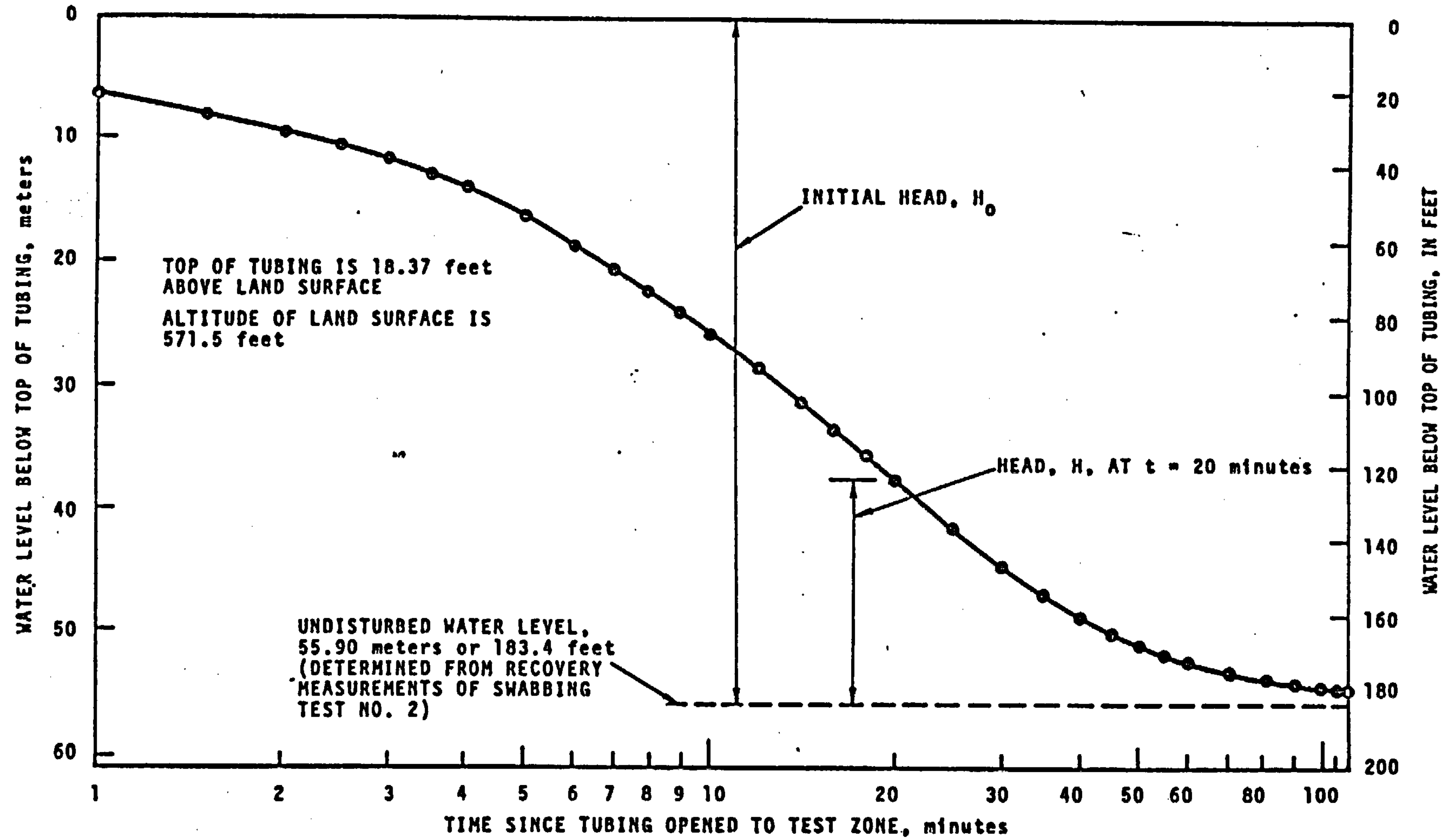


FIGURE 4. Water-Level Change with Respect to Time for Injection Test No. 2, After Instantaneous Injection of Water in Test Zone at Depth of 362 to 416 feet in Well ARH-DC-1

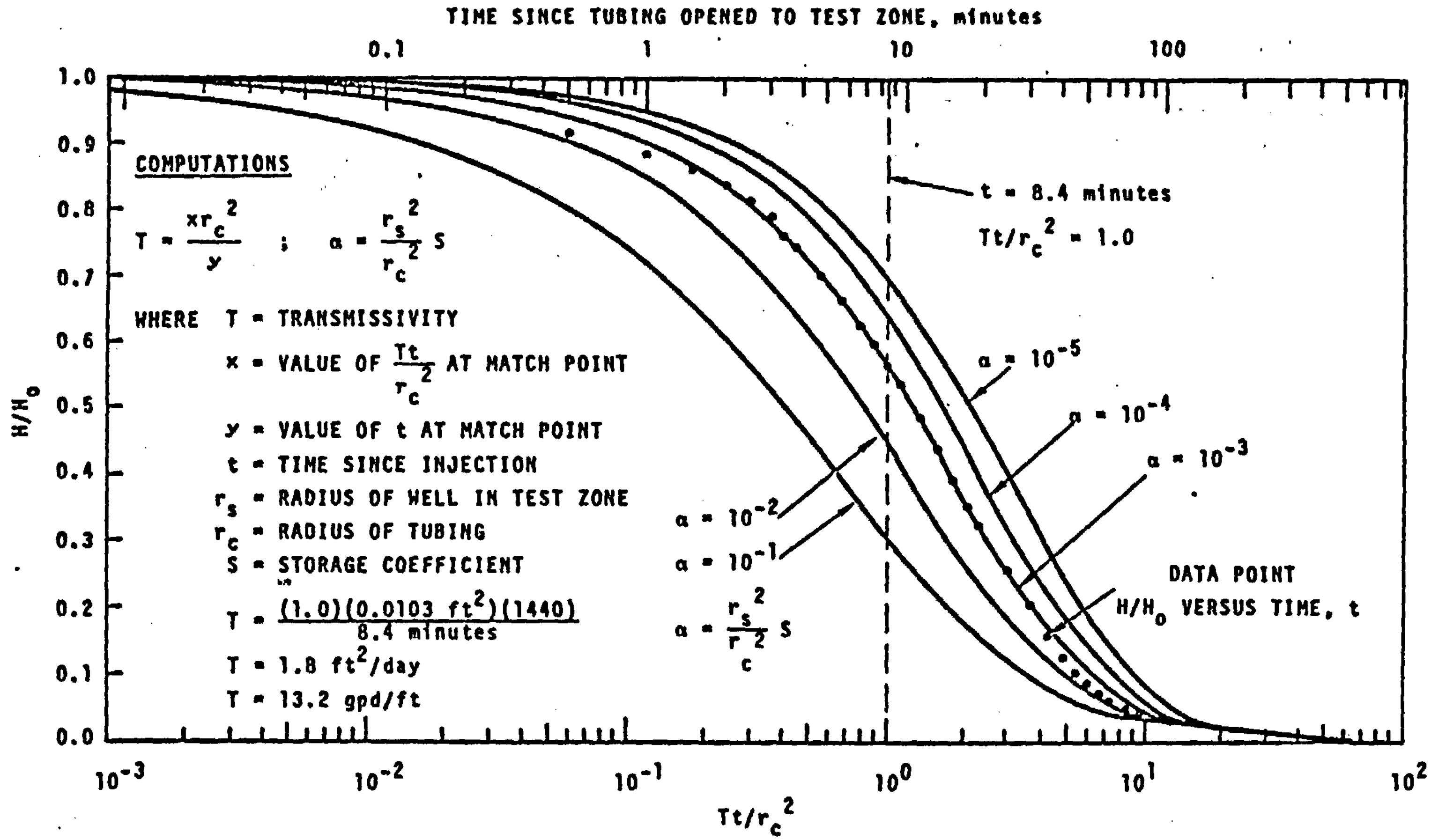


FIGURE 5. Plot of H/H_o Versus Time for Injection Test No. 2, matched to Type Curves of Cooper and others (1967), and Computation of Transmissivity

be seen in figure 4, it is necessary to determine the heads required for plotting H/H_0 in figure 5 from the water levels measured in the tubing and the undisturbed water level in the test zone. For an injection test, the initial head is the difference in height between the water level in the completely filled tubing and the undisturbed water level in the test zone. At time, t, after the tool was opened, the corresponding head, H, is the difference in height between the water level in the tubing and the undisturbed water level.

The data curve in figure 5 matches the type curve only in the central region. This observation is generally true for the injection test data on the well and may be explained as resulting from (1) antecedent effects on the water level from drilling or within-hole circulation, as was explained in the section on ground-water head; (2) lack of precision in determining the undisturbed head because recovery measurements following injection and swabbing could not be continued long enough; (3) significant departure of the physical situation during a test from the model of Cooper and others (1967); or (4) malfunction of the packer tool. With respect to these four explanations, only malfunction of the packer tool could be directly investigated by means of pressure charts provided by the contractor operating the tool. The physical situation existing during a test could be controlled only to the extent of setting the packers against apparently dense rock, in zones of high electrical resistivity which were presumed to be of low permeability, so that vertical movement of water out of the test zone would be at a minimum. Recovery of water levels from antecedent conditions could in some tests be recognized from a plot of the water levels during injection versus time, but the magnitude of the effect could not be determined. If water levels were recovering from some antecedent conditions during an injection test, then the actual heads existing during an injection test would be greater than the heads indicated from the water level measured several hours later at the end of recovery following a swabbing test. This condition is shown diagrammatically in figure 6.

Because of the uncertainty as to the exact heads existing during the hydraulic tests, a computer program was developed to optimize the field data and to obtain an optimal fit to the type curves of Cooper and others (1967). Programming was done by Computer Sciences Corporation, and computations were made on that firm's computer at the Richland Federal Building, under a contract with the Atomic Energy Commission. Cooper and others (1967) give a table of values for particular solutions of the theoretical equation, which were used to plot the type curves. These values were used to generate a surface to which it was attempted to fit the injection-test data, through an iterative procedure by allowing transmissivity, alpha, and initial head to vary freely. Varying initial head in the program also had the effect of varying each measured head by the same increment. Thus, the optimum solution for an injection test gave an H_o (numerically equivalent to the undisturbed water level in the test zone) that was arrived at by a procedure that averaged the effect of any change in head in the test zone that occurred as a result of conditions antecedent to the test. A graduated correction to account for a water-level trend could have been applied to the heads measured during a test but would have been impracticable from the standpoint of the computing time required. As the program was written, solutions generally required about 20 seconds of machine time. To facilitate computations, values of transmissivity, alpha, and initial head are estimated from a data plot and are used in the initial iteration. In running the program, iterations usually produced values that were beyond the bounds of the type surface. However, solutions could be obtained by changing the initial values of the three parameters.

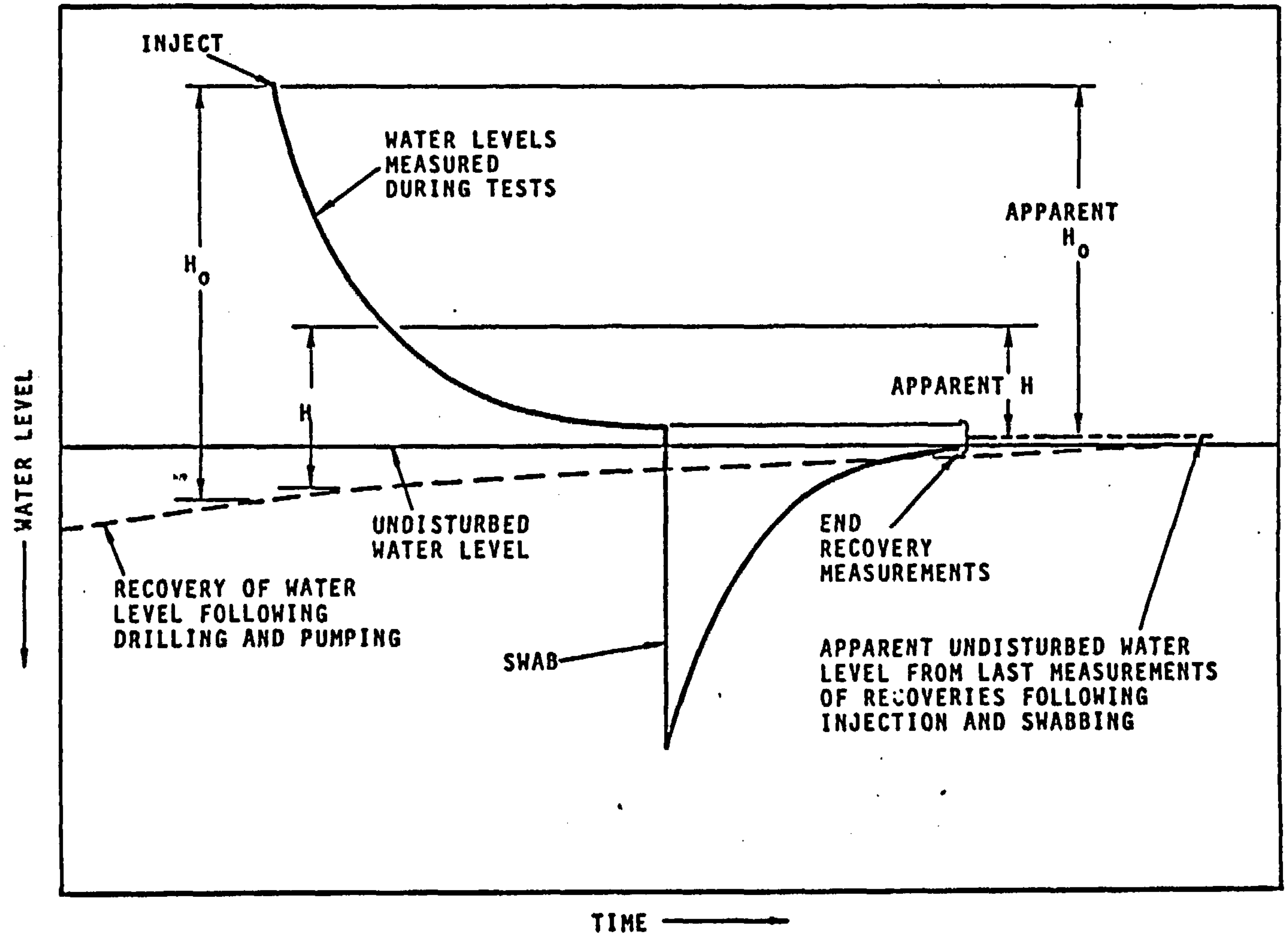


FIGURE 6. Possible Relationship of Water-Level Trends Occurring During Injection and Swabbing Tests

The results of the computer analysis of injection test data are given in table 4 and figure 7. In order to test the solutions obtained, the optimum values of transmissivity, alpha, and H_o were used to compute theoretical water levels. The measured water levels and computed water levels agree closely, as shown in figure 7. The optimum values of initial head computed from the data also agree closely with the undisturbed water levels determined from recovery following injection and swabbing, with the exception of injection tests 17 and 24. It can also be seen that the transmissivity obtained by graphic analysis of injection test 2 in figure 5 is of the same order of magnitude as that obtained from the digital computer analysis as shown in figure 7. Graphic analysis and computer analysis did, in all six tests of figure 7, give transmissivity values that were in reasonable agreement (table 4). The computed optimum water levels are somewhat lower than the measured levels and may indicate that (1) there was generally an upward trend in water level in the test zones due to recovery from an antecedent drawdown, or (2) the test situations deviated somewhat from the model of Cooper and others (1967). Vertical leakage, for example, would have caused the test zones to take in water at a somewhat faster rate than if flow were entirely lateral and it would appear that the heads were somewhat greater than those actually existing. In injection tests 17 and 24 in which the computed initial head is much greater than that indicated by the field data, vertical leakage may have been considerable. It is also possible that the computer program provided a local fit in these two cases.

Storage coefficients for the tests solved with the computer program are given in table 5 from the optimum values of alpha. Hydraulic tests utilizing only one well, as did these, generally are not considered suitable for determining the storage coefficient. Cooper and others (1967) state that their

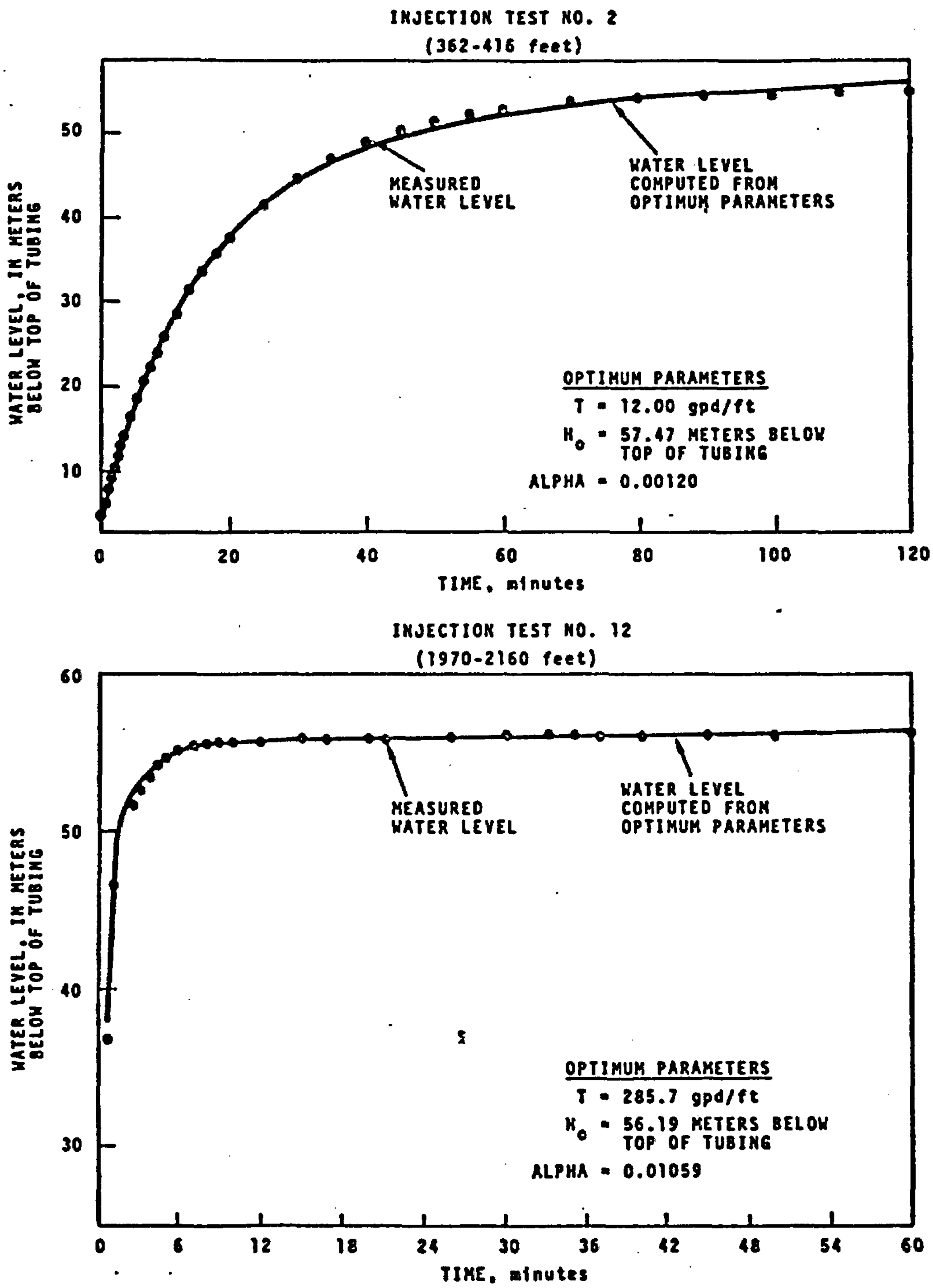
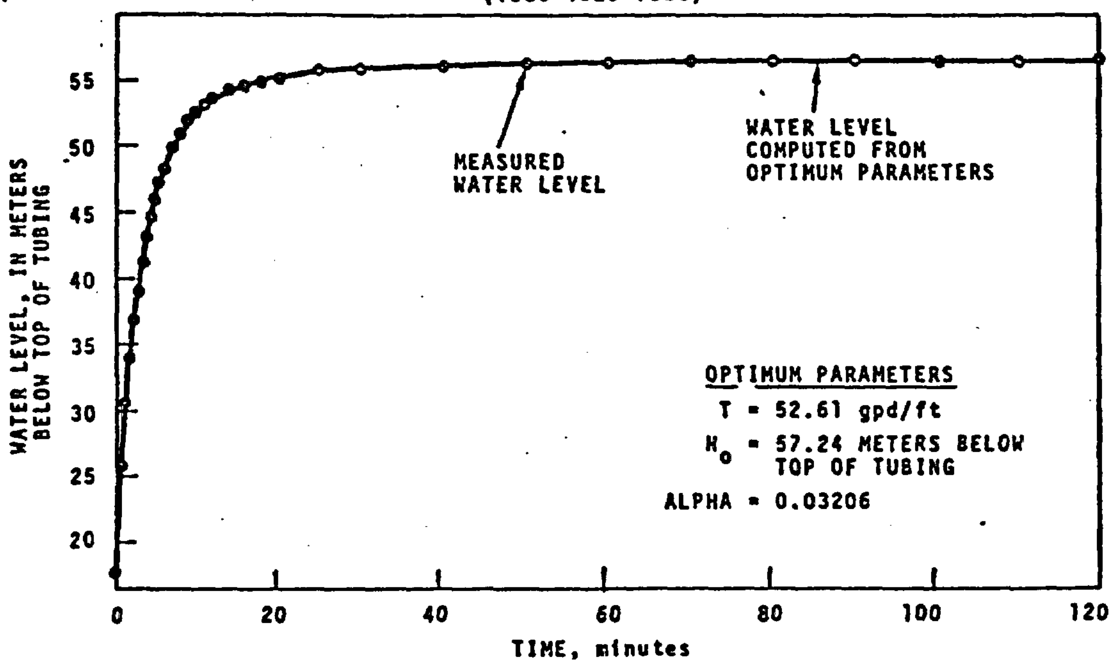


FIGURE 7. Graphic Comparison of Measured Water Levels and Water Levels Computed from Optimum Solutions for Injection Tests

INJECTION TEST NO. 15
(1330-1520 feet)



INJECTION TEST NO. 17
(2730-2910 feet)

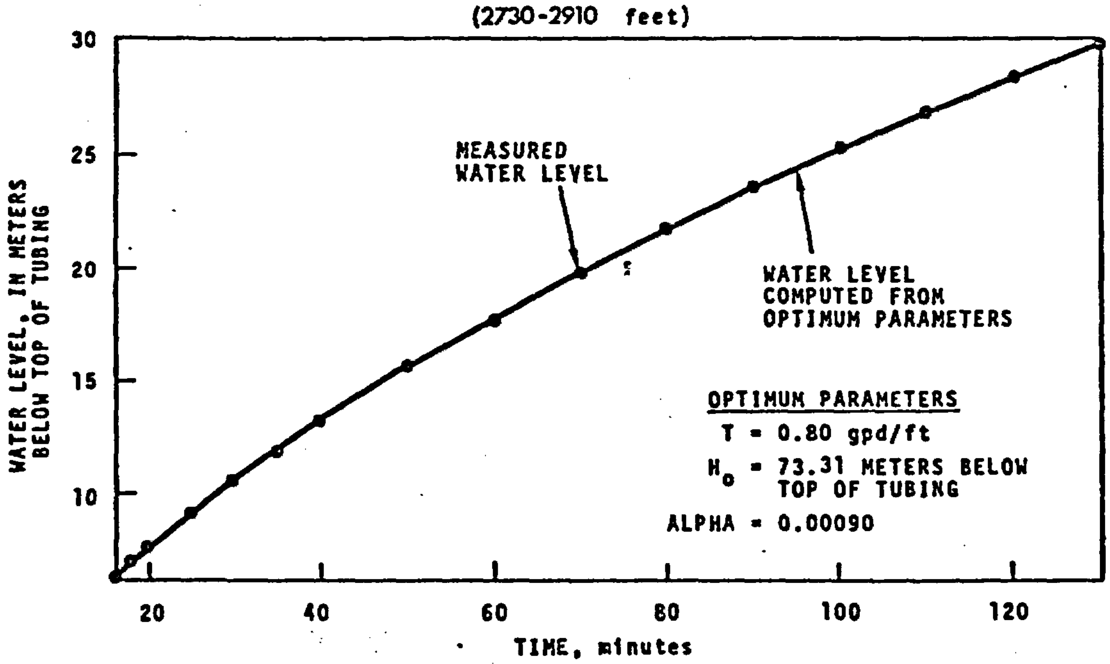
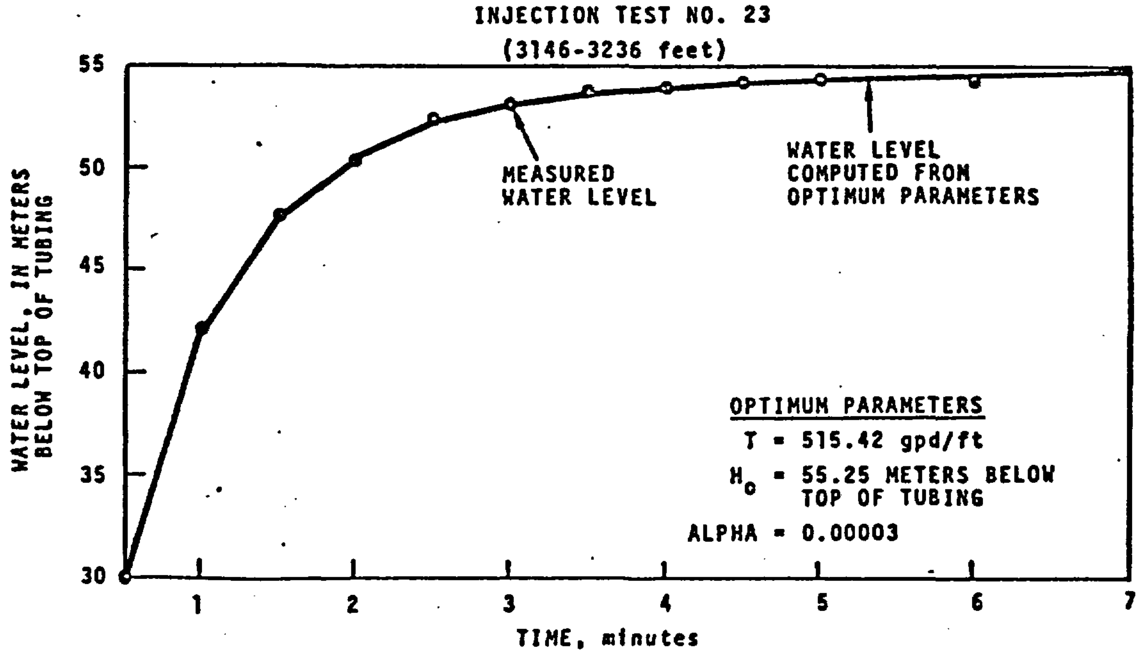
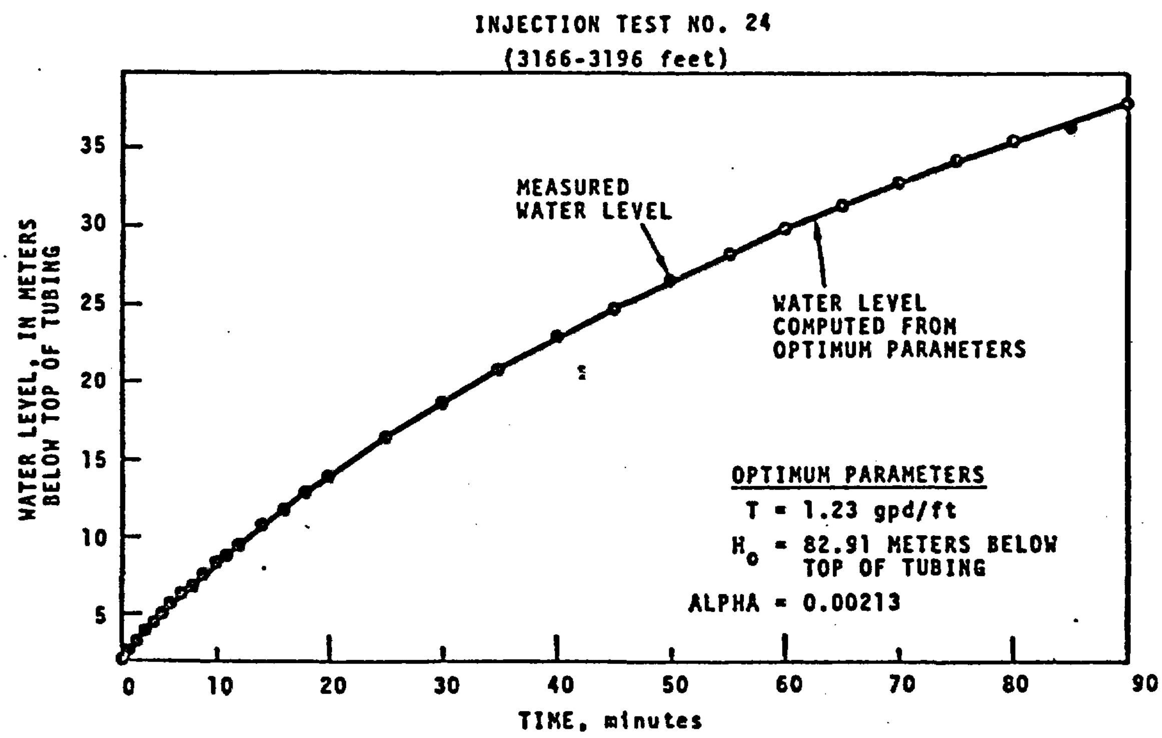


FIGURE 7. (contd)





<u>FIGURE 7.</u> (contd)

Table 5.--Storage coefficients computed from hydraulic test data

[Radius of tubing, r_c = 1.22 inches]

Depth interval (feet)	Injection test	Optimum alpha	Radius of well, r_s (inches)	Storage coefficient, S
362-416	IT 2	0.001198	5.2	0.000066
1,330-1,520	IT 15	.03206	5.1	1/ .0018
1,760-1,950	IT 12	.01059	5.1	.00063
3,146-3,236	IT 23	.000029	5.5	.0000014

1/ This comparatively high-storage coefficient may reflect largely the characteristics of two sections of sand interlayered with the basaltic rocks in this zone. The storage coefficients of basaltic rocks generally should be smaller and, for the most dense, most competent rocks, should approach the value for the compressibility of water.

graphical method of solution is relatively insensitive to variations in the value of the storage coefficient. However, because a high degree of mathematical precision was obtained with the digital computer, the sensitivity with respect to the storage coefficient was improved somewhat over the graphical-solution methods. The storage coefficients are, therefore, presented as order of magnitude values, which would certainly be revised if suitable pumping-test data were available.

Swabbing tests in which only one swab run was made can be analyzed in the same manner as an injection test, except that the initial head is the initial drawdown created by the swab. This initial head is computed indirectly, and with low precision, from the quantity of water withdrawn by the swab and from the undisturbed water level. The quantity of water withdrawn by the swab could not be measured exactly because some water was always spilled and because the calibrated tank in which the water was collected and measured was large and had a low sensitivity. Swabbing also produced some uncertain effects by (1) creating a suction head on the test zone as the swab was lifted clear of the water, and (2) creating an extraneous head by water leaking around the swab and back down the tubing. It was possible then for the water-bearing zone to receive three pulses, consisting of (1) the intended negative pulse from withdrawing water from the tubing, (2) a positive pulse due to suction, and (3) a later positive pulse from leakage. For the foregoing reasons, the swabbing-test data were analyzed only to determine if they gave results of the same order of magnitude as those obtained for corresponding injection tests.

Swabbing tests in which multiple swabbing runs were made could be analyzed to determine transmissivity only by the method of Skibitzke (Ferris and others, 1962, p. 103-104). The assumption on which Skibitzke's model is based, that a well is a line sink, does not allow an exact solution. If the number of swab runs is very great, and the time between runs and the quantity withdrawn on each run vary, the computations are long and tedious. Therefore, computations were simplified by treating blocks of swab runs as being uniformly spaced in time and as producing a uniform quantity of water. The values of transmissivity obtained were considered only from the standpoint of their orders-of-magnitude and to investigate the possibility that swabbing caused significant increase in the transmissivity of the test zone by removal of cuttings or entrapped air.

Values of Transmissivity from Pumping Tests

Four pumping tests were run during testing sequences when well ARH-DC-1 was variously at depths of 712, 1,190, and 2,242 feet. As no nearby wells were available, measurements of drawdown and recovery could be made only in well ARH-DC-1. These tests were run in connection with pumping to clean the well of drilling fluid, to sample the ground water, and to develop the water-bearing zones, and not primarily to obtain hydraulic data. Because of this, and because some difficulties were encountered in maintaining constant pumping rates, the pumping-test data do not lend themselves well to analysis. Furthermore, in each time interval between pumping tests, cementing repairs were made to the well. The cement did not stop the flow of water from the cemented zones into the well during drilling or pumping, but undoubtedly had some effect in reducing the flow. Despite the obvious difficulties with the pumping tests, the data were analyzed so that some approximate values of transmissivity could be obtained for permeable zones above 1,200 feet that could not be adequately tested by injection.

During the pumping tests when drawdowns became relatively stable, a radioactive tracer log was made of the well. In this procedure, a small quantity of iodine-131 is ejected from a logging tool into the water in the well, and its movement is followed by means of a detector in the tool. Approximate flow rates of the water in the well can be computed from the data obtained, and the relative contributions of different zones of rock can be estimated. The results of the tracer-ejector surveys obtained during pumping tests are summarized in figure 8. Because the flow rates measured in the tracer-ejector surveys are not precise, only large percentage differences in flow are significant. The zones that were repaired by cementing are also shown, and it is obvious from the data that cementing did not entirely stop the flow of water from the permeable zones.

The transmissivity values obtained from the pumping tests apply mainly to relatively permeable zones at depths of about 480-515, 596-700, 740-754, 830-936, and 1,100-1,200 feet. Logarithmic plots of water level during pumping versus time of pumping most closely match type curves developed for leaky artesian conditions, as described by Hantush (1956). As an example, the determination of transmissivity for pumping test 4 by a graphical method given by Walton (1962) and based on Hantush's solution (1956) is shown in figure 9. Data of a lesser quality are available for pumping tests 1, 2, and 3. The curve fits obtained may be fortuitous. As is recommended later in the report, more closely controlled pumping tests using two or more observation wells would be necessary to evaluate the hydraulic conditions of the aquifers in this rock section. The estimated values of transmissivity from the pumping-test data are summarized below and also are given in figure 8.

Pumping test number	Depth of well (feet)	Estimated transmissivity (gpd/ft)
1	712	1,600
2	1/ 1,190	3,100
3	1,190	5,200
4	2,242	3,700

1/ Hole filled by caving material from 890-1,190.

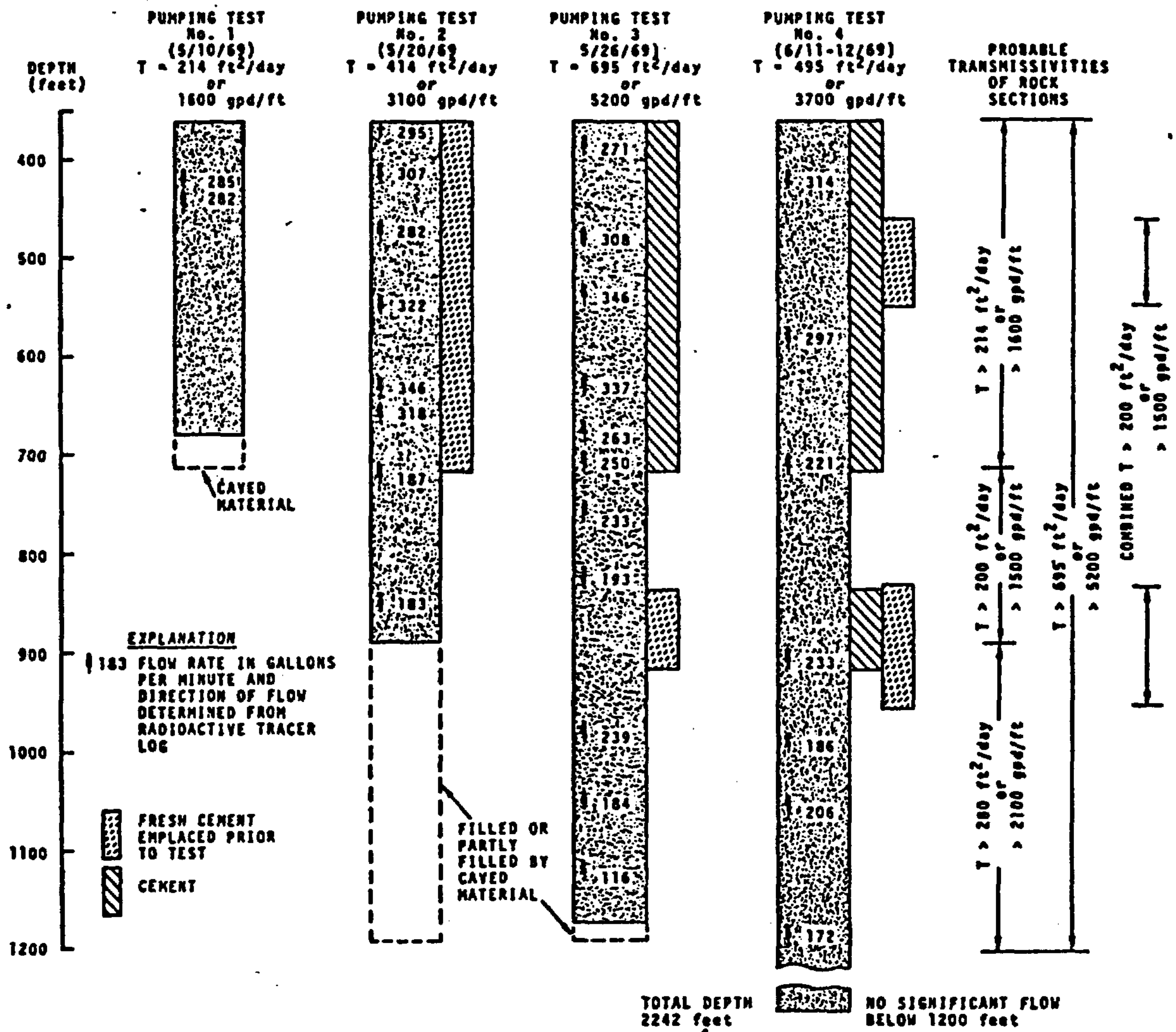


FIGURE 8. Flow Rates in the Bore of Well ARH-DC-1 During Pumping Tests, Intervals Repaired by Cementing, and Probable Values of Transmissivity of Rock Zones

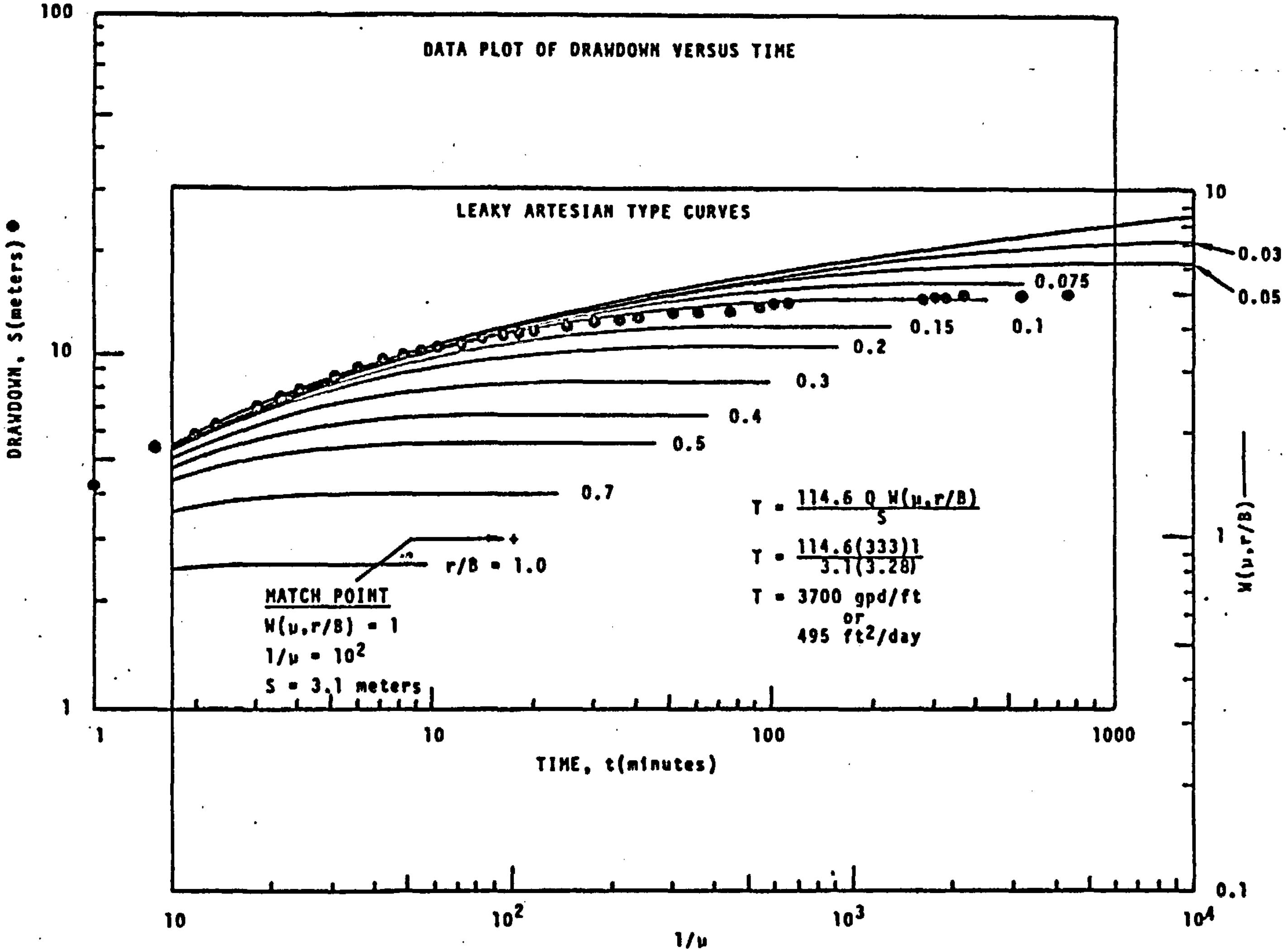


FIGURE 9. Logarithmic Plot of Drawdown Versus Time for Pumping Test No. 4 and Method of Computing Transmissivity for Leaky Artesian Conditions

It can be seen from figure 8 that the permeable zones centering at 500 and 900 feet were recemented between the running of pumping tests 3 and 4. This recementing caused a decline of 1,500 gpd/ft (gallons per day per foot) in transmissivity for the nearly identical sections to which the transmissivity values apply. It should be noted from the trace-ejector survey that during pumping test 4 the section of the well below 1,200 feet contributed little water to the discharge from the well. By appropriately summing or subtracting the transmissivity values determined from the pumping tests, the transmissivities of different zones of rock open to the well can be determined, as is shown in figure 8.

Hydraulic Conductivity of the Rock Units

The values of transmissivity determined from injection tests on isolated zones and from pumping tests were used to estimate the average values of hydraulic conductivity of the rocks in the units identified in the lithologic log of figure 3. The estimated values of hydraulic conductivity are shown in figure 10 for the rocks to a depth of 4,280 feet, for which hydraulic tests and geophysical logs are available.

The analysis by which the hydraulic conductivity values were estimated is based on the following considerations. For a section of rock composed of multiple units, the transmissivity can be defined as

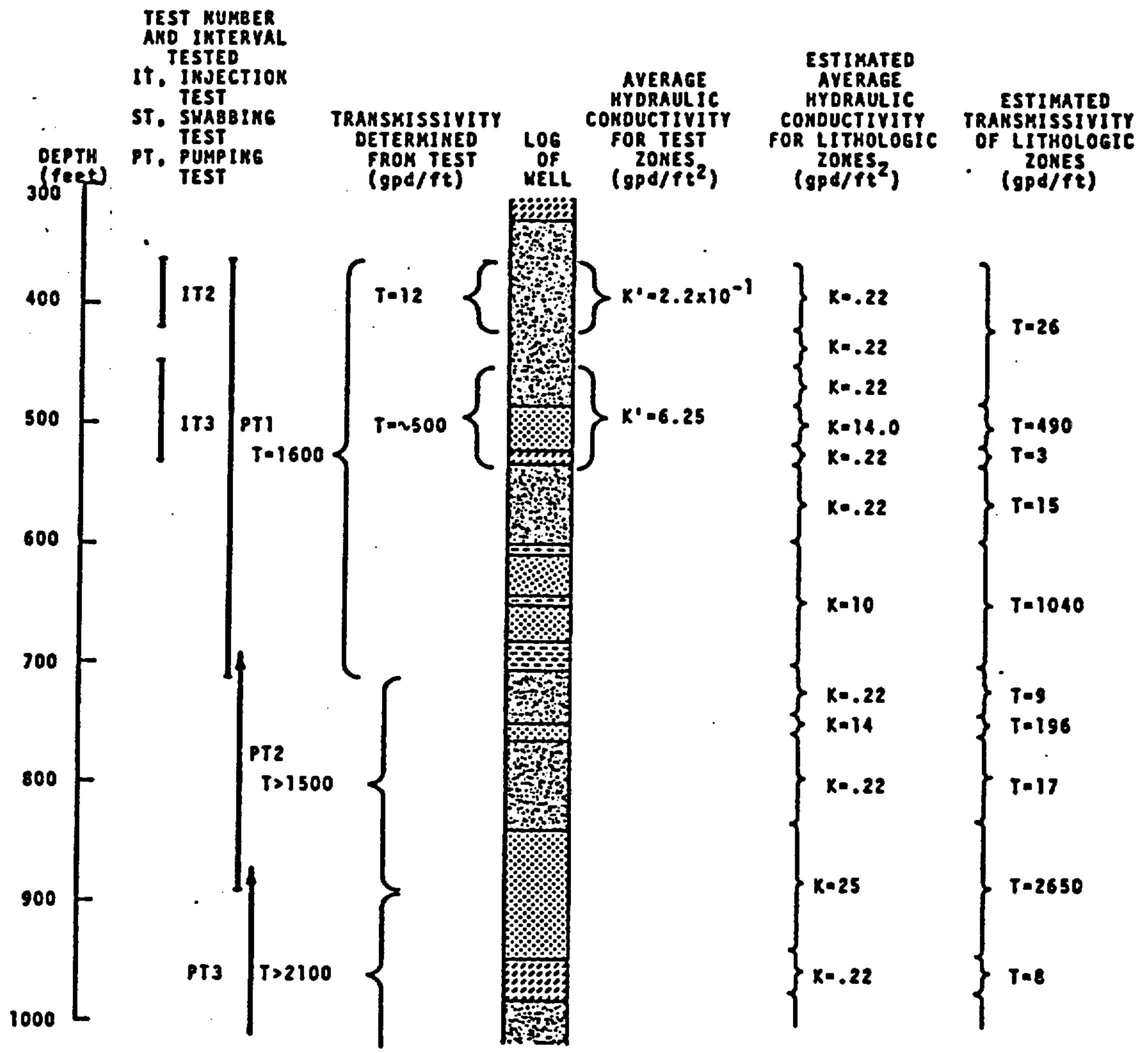
$$K_1m_1 + K_2m_2 + K_3m_3 + \text{---} + K_nm_n = T$$

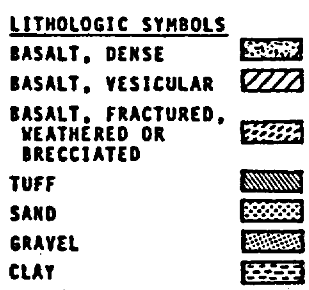
where

K_1, K_2, K_3, --- K_n are the hydraulic conductivity values of the rock units,

m_1, m_2, m_3, --- m_n are the thicknesses corresponding to K_1, K_2, K_3, --- K_n, and

T is the transmissivity.





CONVERSION FACTORS

HYDRAULIC CONDUCTIVITY, K

$1.0\ gpd/ft^2 = 0.134\ ft/day$

$1.0\ ft/day = 7.48\ gpd/ft^2$

TRANSMISSIVITY, T

$1.0\ gpd/ft = 0.134\ ft^2/day$

$1.0\ ft^2/day = 7.48\ gpd/ft$

FIGURE 10. Values of Transmissivity and Hydraulic Conductivity of Lithologic Zones in Well ARH-DC-1

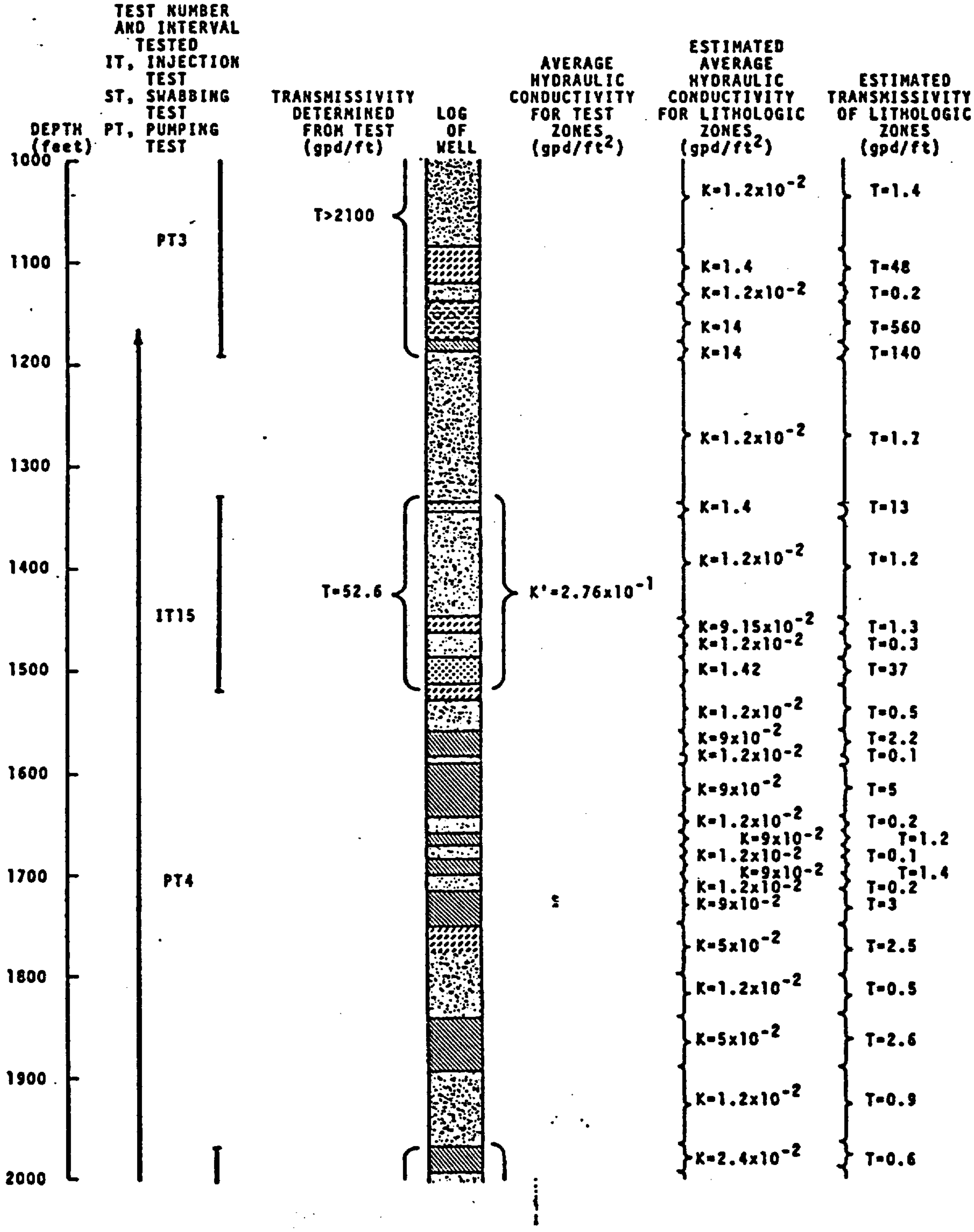


FIGURE 10. (contd)

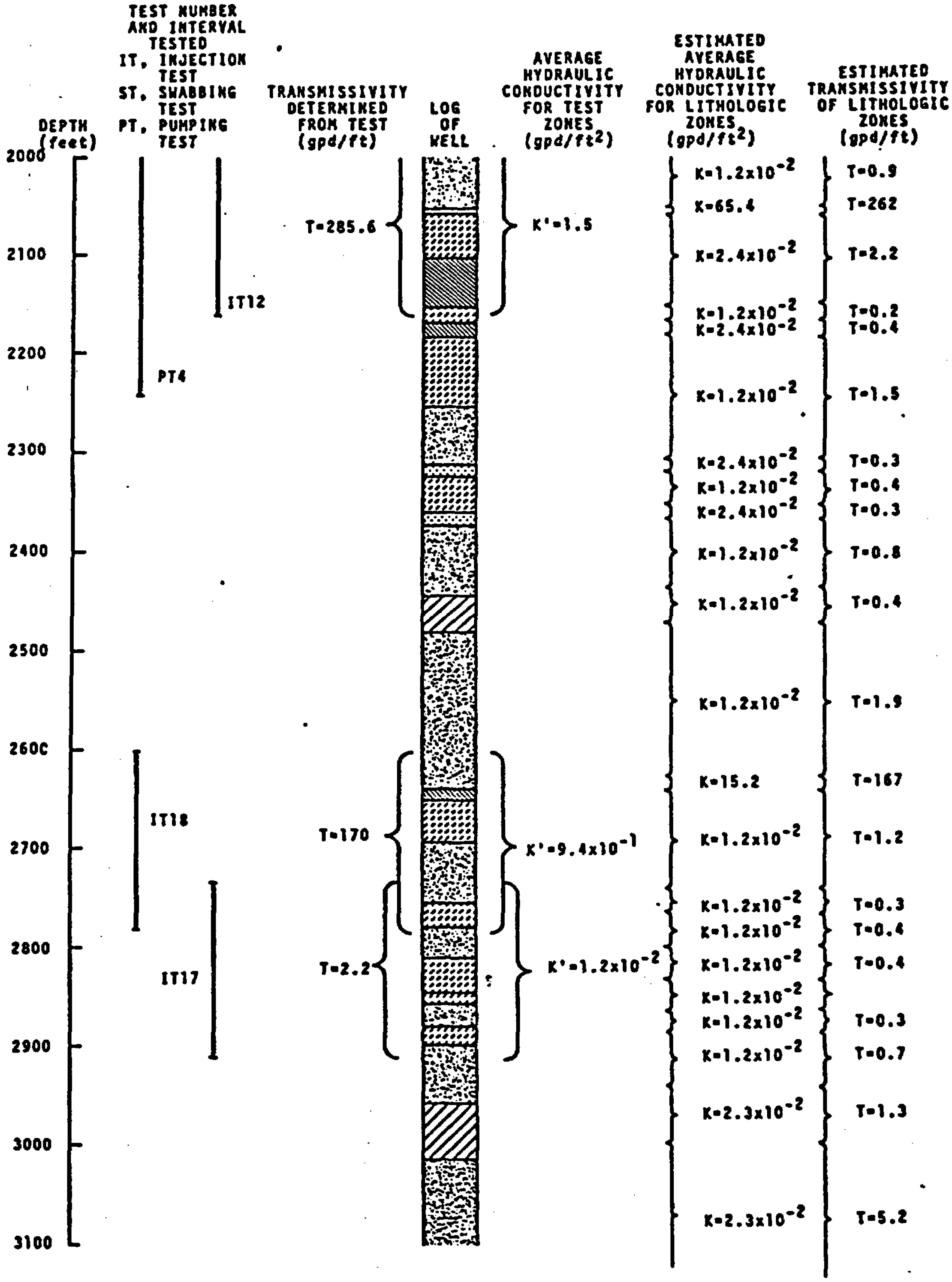


FIGURE 10. (contd)

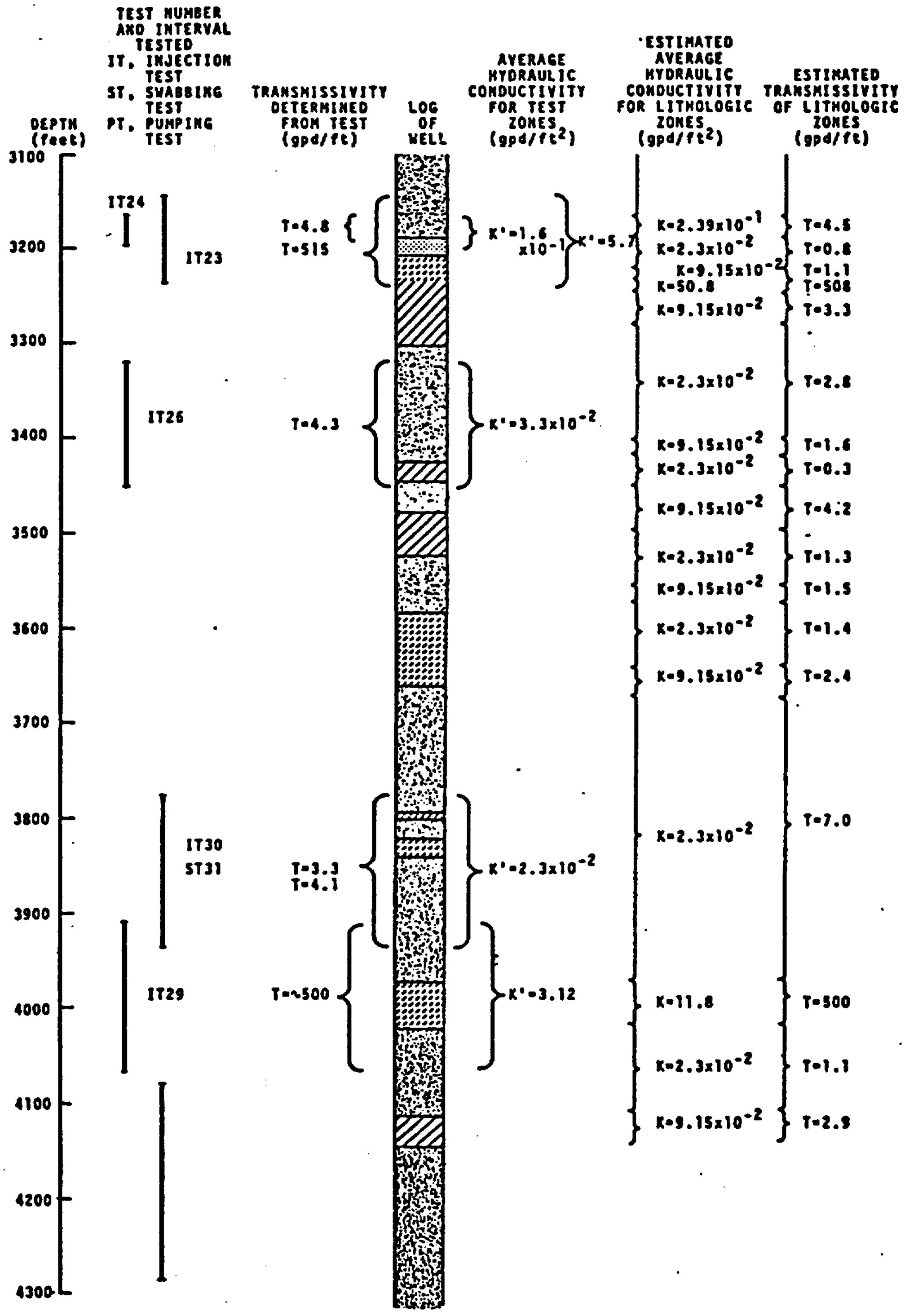


FIGURE 10. (contd)

In the equation stated above, the terms K_1m_1, K_2m_1, --- K_nm_n each refer to a discrete unit of rock. If in a well, geophysical logs and core samples allow classification of the individual rock units into lithologic types having similar permeabilities, class terms can be substituted for K_1m_1, K_2m_2, --- K_nm_n. In well ARH-DC-1 the following classes of rock could be identified:

Dense basalt

Basalt having healed fractures and joints

Vesicular basalt

Flow breccia

Basalt with open fractures

Gravel

Sedimentary interbeds

For each hydraulic test, an equation could be written in the form of the equation above but containing class terms. As multiple tests were performed, a family of simultaneous equations results, which can be solved for the values of hydraulic conductivity of the commonly occurring individual rock units. Data were insufficient for computing the hydraulic conductivity of each rock unit. Where the hydraulic conductivity could not be computed, it was estimated by comparing the geophysical logging characteristics of that unit with the characteristics of units for which the hydraulic conductivity values were computed. In using the values of hydraulic conductivity in figure 10, it should be recalled that all these values are based on interpretive relationships developed between the geophysical logging characteristics of the rocks and the transmissivity values determined in hydraulic tests. When more information is obtained on the geophysical properties and transmissivity of the rocks, the hydraulic conductivity values given in figure 10 will probably be changed through reinterpretation.

Physical Tests on Core Samples

Laboratory tests were made by the Hydrologic Laboratory, U.S. Geological Survey, on five cores of basalt obtained from well ARH-DC-1. The numbers of the cores are 6, 7, 8, 13, and 28, and their descriptions are given in table 2. The characteristics measured are hydraulic conductivity, porosity, compressive strength, and tensile strength, which are reported in table 6. Measurements of sonic velocity, not reported here, were also made and were used in computing Poisson's ratio, Young's modulus, shear modulus, and bulk modulus of the core specimens.

Values of hydraulic conductivity of the core specimens were small, ranging from about 1.4×10^{-4} gpd/ft^2 (1.9×10^{-5} ft/day) to 4.5×10^{-4} gpd/ft^2 (6.0×10^{-5} ft/day). The very vesicular basalt of core 8 has a hydraulic conductivity about the same as less vesicular samples from cores 6 and 28 and only about 60 percent greater than the dense specimen from core 13 (table 6). Apparently, vesicles in the basalt samples were not interconnected to an extent that would cause a significant increase in hydraulic conductivity with increasing vesicularity.

The cores have hydraulic conductivity values about two orders of magnitude smaller than the average values determined from injection tests on basalt, which range from 1.2×10^{-2} gpd/ft^2 (1.6×10^{-3} ft/day) to 2.3×10^{-2} gpd/ft^2 (3.1×10^{-3} ft/day). These differences in values of hydraulic conductivity result, because these two types of tests measure different characteristics of the rocks. The field values of hydraulic conductivity were determined on a large volume of in-place rocks. The basalt, as can be seen in outcrops, is cut by shrinkage cracks and other fractures which are capable of transmitting water. The field hydraulic conductivities therefore, apply not only to the ability of the basalt flows to transmit water through intergranular pore spaces, but also through

Table 6.--Summary of laboratory analyses of rock cores from test well ARH-DC-1

Core number	Depth (feet) From	Depth (feet) To	Hydraulic conductivity	Porosity (percent)	Compressive strength (unconfined) Kgm cm^{-2}	Compressive strength Moisture content (vol. percent)	Compressive strength Sample diameter (cm)	Tensile strength (Reichmuth test) Kgm cm^{-2}	Tensile strength Moisture content (vol. percent)	Tensile strength Sample diameter (cm)
6------	2,381.4	2,384.6	1.3×10^{-8} cm/sec	9.8	1/ 738	6.2	5.38	28	6.2	5.38
			3.68×10^{-5} ft/day							
			2.76×10^{-4} gpd/ft^2					2/ 816	2.7	2.52
7------	2,779.0	2,779.8	2.1×10^{-8} cm/sec	10.5	1892	3.8	2.52	300	3.6	2.53
			5.96×10^{-5} ft/day							
			4.46×10^{-4} gpd/ft^2		2425	4.0	2.52	339		2.53
8-------	2,946.8	2,950.1	1.1×10^{-8} cm/sec	3/ 25.4	240	28.6	5.37	60	28.5	5.38
			3.12×10^{-5} ft/day							
			2.34×10^{-4} gpd/ft^2							
13------	3,127.1	3,128.0	6.7×10^{-9} cm/sec	2.1	1006	2.0	2.52	150	1.9	2.52
			1.9×10^{-5} ft/day							
			1.42×10^{-4} gpd/ft^2		3219	1.9	2.53	229	1.5	2.53
28------	4,285.0	4,285.5	1.4×10^{-8} cm/sec	10.9	----	----	----	---	----	----
			3.97×10^{-5} ft/day							
			2.98×10^{-4} gpd/ft^2							

1/ Sample failed along a partially penetrating fracture surface not visible in the original specimen.

2/ Value undoubtedly too high as the result of using value of compressive strength from first specimen in calculation of tensile strength for second specimen.

3/ Porosity determined on small specimen apparently more dense than those used for other physical tests on Core 8.

fractures. The laboratory tests were made on small cylinders of rock that were selected to be free of open fractures and, therefore, indicate the hydraulic conductivity dependent on movement through intergranular pore spaces. The results of the tests indicate that the hydraulic conductivity of basalt flows results mainly from fractures.

Chemical and Isotopic Characteristics of the Ground Water

Ground-water samples were collected from well ARH-DC-1 both by pumping from the entire well bore using a submersible pump and by swabbing from selected isolated zones. The samples were analyzed for dissolved chemical constituents, tritium content, deuterium-hydrogen ratio, and oxygen-18-oxygen-16 ratio. A carbon-14 age determination was also made on one sample. The data obtained from analyses are given in table 7. The interpretations of the analytical results given in the following sections were made mainly by F. J. Pearson, U.S. Geological Survey.

Reliability of Samples

Tritium is useful in this investigation as an indicator of the quantity of drilling water present in a sample. Meteoric and surface waters are high in tritium. The Columbia River, for instance, during 1969 had a tritium content that generally ranged from 300 to 600 TU (tritium units; 1 TU = 10^{-18} tritium atoms per hydrogen atom). Ground water of recent origin is also high in tritium. However, as ground-water movement generally is very slow and tritium decays rapidly, having a half-life of about 12.3 years, and there are no natural sources of tritium underground, ground water is ordinarily low in tritium. Considering these facts, the ground-water samples obtained from well ARH-DC-1 were analyzed for tritium to determine if they were representative of the formation water.

Table 7.--Chemical and isotopic analyses of water samples from well ARM-DC-1[1/]

[Concentrations in milligrams per liter, mg/l]

Depth interval (feet)	Date of collection	Silica (SiO_2)	Iron (Fe)	Aluminum (Al)	Boron (B)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Orthophosphate (as PO_4)	Phosphate, total (PO_4)	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Calculated	Hardness: As $CaCO_3$	Hardness: Noncarbonate	Detergents as linear alkyl sulfonate	Specific conductance (micromhos at 25°C)	pH, Laboratory	pH, Field	Tritium: Tritium units±1σ	$\delta^{13}C_{PDB}$ (o/oo)	δD_{SMOW} (o/oo)	$\delta^{18}O_{SMOW}$ (o/oo)
Collected from discharge of submersible pump																													
362-712	5/10/69	53	0.05	0.7	0.06	2.2	0.3	79	8.0	205	7	0.4	3.9	1.0	0.2	0.25	0.25	259	257	7	0	0.01	351	8.5	-----	---------	-14.0	---	----
362-890	5/20/69	73	.05	.5	.56	2.0	.4	124	9.6	133	35	.0	68	10	.2	.14	.14	389	389	7	0	.03	580	9.2	9.62	1.1± .2	-2.9	---	----
362-1190	5/26/69	79	.00	.0	.74	2.4	.1	142	10	98	54	1.8	85	13	.0	.06	.07	451	436	7	0	.00	664	9.4	9.58	1.0± .3	+2.0	---	----
362-2242	6/12/69	81	.00	.8	.58	2.5	.1	141	11	72	67	5.6	83	15	.1	.06	.08	438	441	7	0	.00	707	9.5	9.61	---------	----	---	----
Collected by swabbing from zones isolated by packers																													
2/ 362-416	5/8/69	23	0.25	0.1	0.06	4.7	1.2	60	8.8	148	0	19	11	0.5	0.5	0.01	0.03	208	202	17	0	0.16	314	8.1	-----	23 ±1	-13.3	-145	-17.2
450-530	5/8/69	37	.05	.1	.05	2.2	.3	77	8.4	167	14	12	7.7	.8	.2	.08	.07	240	242	7	0	.12	353	8.9	-----	5.3±0.4	-14.2	---	----
540-620	5/8/69	46	.10	.1	.06	2.1	.3	79	7.8	199	10	.0	4.2	1.0	.1	.11	.12	252	249	6	0	.05	344	8.6	8.6	2.2± .3	-14.3	-154	-18.3
636-726	5/19/69	55	1.4	.1	.10	1.7	.4	90	9.9	205	14	.0	13	1.7	.2	.17	.16	293	289	6	0	.04	402	8.9	-----	2.2± .3	-10.5	-150	-17.7
720-810	5/19/69	57	.57	.4	.45	1.7	.4	114	14	134	43	1.6	49	7.5	.3	.21	.21	366	356	6	0	.18	552	9.3	-----	2.3± .3	-4.0	-142	-16.9
980-1120	5/27/69	89	.03	.0	.94	.9	.4	164	10	55	67	2.0	120	16	.1	.05	.08	518	496	4	0	.00	773	9.5	9.70	6.2± .4	+15.4	-138	-15.5
3/ 1090-1280	6/11/69	90	.00	1.1	.73	5.8	.1	177	12	---	92	10	120	20	.2	.01	.03	554	538	15	0	.02	904	10.2	10.48	1.3± .3	+13.2	-136	-15.6
4/ 1330-1520	6/10/69	81	.20	1.1	----	5.0	.1	163	15	32	86	12	110	20	.3	.01	.05	516	508	13	0	.11	839	9.7	9.94	108 ±6	+1.4	-139	-15.9
5/ 2600-2780	6/22/69	48	1.0	.1	.00	1.2	.2	87	8.0	181	18	3.6	13	2.0	.3	.07	.09	274	270	4	0	.92	408	8.9	9.10	9.6± .6	-12.6	-151	-17.8
3146-3236	6/28/69	116	.10	1.1	.72	.8	.0	182	3.3	49	101	13	98	21	.2	.01	.04	565	559	2	0	.03	867	9.6	10.12	0 ± .3	-7.0	-138	-16.0
6/ 3166-3196	6/29/69	120	.15	1.1	.65	.7	.1	181	3.9	---	125	12	94	20	.2	.00	.04	566	558	2	0	.10	860	9.9	9.78	2.0± .3	-7.6	-148	-15.9
3206-3246	6/29/69	105	.65	1.1	.17	.6	.1	176	5.9	2	120	10	98	20	.2	.01	.02	542	537	2	0	.35	852	9.9	9.72	4.4± .4	-7.3	-138	-15.9
4/ 3320-3451	7/2/69	63	1.8	.9	.66	.2	.1	166	4.7	68	75	14	90	18	.3	.01	.01	476	464	1	0	.39	800	9.7	9.70	17.8± .4	-7.0	-138	----
5/ 4080-4283	7/14/69	67	2.1	1.3	.38	.2	.0	134	3.0	164	16	21	68	11	.4	.03	.03	410	402	1	0	.32	630	8.9	9.10	---------	----	---	----

1/ Manganese (Mn) and chromium (Cr) were determined for all samples and were absent.
2/ Sample is contaminated with drilling fluid.
3/ Hydroxide (OH) is 11 mg/l.
4/ Sample is contaminated with water and drilling fluid that leaked around upper inflatable packer.
5/ Sample is contaminated with drilling fluid and water originating in shallower rocks that invaded the test zone through the bore of the well.
6/ Hydroxide (OH) is 1 mg/l.

The water used to make up the drilling fluid was obtained from the Reservation water supply, the source of which is the Columbia River. One analysis made on the drilling fluid showed a tritium content of 418 TU. The analyses for the ground-water samples from the intervals 362-890, 362-1,190, 1,090-1,280, and 3,146-3,236 indicate that normally the tritium content of the ground water is at no more than about the level of detection, 1 TU. The tritium determinations, therefore, indicate the extent of contamination of the samples with drilling fluid left in the well when drilling was stopped. In general, based on a mass balance, the samples contain 0.25 to 1 percent drilling fluid. Those samples that are high in tritium were collected (1) presumably before the test zone was swabbed sufficiently, as with the samples from 362-416 feet, 450-530 feet, and 3,206-3,246 feet; or (2) during a test when leakage is suspected to have occurred around the packer tool, as inferred from hydraulic data or pressure records, as with the samples from 980-1,120, 1,330-1,520, and 2,600-2,780 feet. The samples from 1,330-1,520, and 2,600-2,780 feet are grossly contaminated with nonformation water and should not be used for geochemical interpretations. The chemical constituents in the sample from 2,600-2,780 feet indicate that the zone probably was invaded by water moving through the well from shallow depth. This zone has a lower hydraulic head than the zone at shallow depth.

Detergents, which were added to the drilling fluid in large concentrations, are useful in determining the extent of contamination of the samples with drilling fluid, but to a lesser extent than tritium. The amount of detergent added to the fluid varied, and the detergent analysis is less sensitive than that for tritium.

The portland cement used in emplacing the casing and repairing the well is another possible source for contaminating the ground-water samples.

Hydrolysis of portland cement produces a solution with a high pH and a high carbonate content, and the ground-water samples do exhibit both of these chemical characteristics. A possibility is that all water samples from the well are contaminated with the hydrolysis products of portland cement. However, this is unlikely because the cement was in place only above depths of 1,000 feet in the well during the periods of sample collection and the waters were sampled from tubing that was isolated from the upper parts of the well by a packer. A summary of cement repairs to the well is shown in figure 8 and the dates of sample collection are given in table 7. Cement was also emplaced around the casing, whose bottom is at 362 feet, prior to the collection of any samples. The pH and carbonate content of the samples generally increased with depth. Furthermore, the samples collected below 2,200 feet in depth were from rocks not yet penetrated by the well when the last of the cement was emplaced.

Source of the Water

Stable isotope variations are reported in delta units (δ), defined as follows: if R_{sm} is the isotopic ratio (D/H, 0-18/0-16, C-13/C-12, etc.) in a sample and R_{std} is the ratio in some standard material, then

$$\delta = \left(\frac{R_{sm}}{R_{std}} - 1\right) \times 1000.$$

The δ values are expressed in parts per thousand, or per mil (o/oo). The standard used for hydrogen and oxygen in natural waters is a standard mean ocean water, SMOW (Craig, 1961a). The carbon standard is a Cretaceous belemnite, PDB, with isotopic composition close to that of normal marine limestone (Craig, 1953). Samples with the same isotopic compositions as the standard have δ values of 0; those depleted in the heavier isotope have negative δ values. The analyses reported here were made in the U.S. Geological Survey.

Chemical and Carbon Isotope Characteristics

Ground waters from basalt typically are characterized by (1) high ratios of calcium to sodium and of magnesium to calcium, (2) relatively high silica content, and (3) relatively low fluoride content (White, Hem, and Waring, 1963). The samples from well ARH-DC-1 are abnormal for ground water from basalt in that they are characterized by low ratios of calcium to sodium and of magnesium to calcium, and high fluoride. The deeper waters from the well are also high in carbonate and chloride.

The ground water is of the sodium bicarbonate type at shallow depth and of the sodium-bicarbonate-chloride type below 980 feet. The samples from the zones of 636-726 and 720-810 feet are the result of simple mixing between the upper sodium bicarbonate water and the lower sodium-bicarbonate-chloride water. This is demonstrated by mass balances based on the change in chloride and the C-13/C-12 ratios through these zones to determine the mixing ratios. Both balances give about the same mixing ratios; the zone 636-726 feet contains 10-15 percent and the zone 720-810 feet contains 30-40 percent of the sodium-bicarbonate-chloride water.

Waters from the zones between 980 and 1,280 feet are different from the deeper waters of the sodium-bicarbonate-chloride type in some characteristics. Mainly, they are highly enriched in C-13 but also have a lower total carbonate content (about 70 percent of the deeper water) and a slightly higher chloride content.

The data from the chemical analyses were analyzed by means of a computer program being developed by Blair F. Jones and A. Truesdell of the U.S. Geological Survey. This program compares the activity products of the ions in solution with the equilibrium constants of rock-forming minerals in order to investigate the mineralogic controls of the water chemistry. Conclusions drawn from the results of this analysis are included in the discussion which follows.

Silica.--The silica content indicates near equilibrium with a silica phase having properties similar to those of chalcedony or cristobalite. If only uncontaminated samples are considered, the silica content can be seen to increase with depth. This increase is an effect of the increasing temperature of the rock with depth. (See Fenix and Scisson, 1969, for temperature logs.) The silica probably comes into solution from feldspars and other silicate minerals but at a concentration higher than that which would be in equilibrium with quartz. Because the silica goes out of solution slowly and forms, at first, chalcedony rather than quartz, the solution appears to be in equilibrium with this phase. Chalcedony is present in some of the core samples (table 2).

Cations.--Sodium is the predominant cation in the samples and presumably is derived from the solution of sodic feldspars in the basalt. Aluminum is present in low concentrations only but is significant from the standpoint of determining chemical equilibrium between the water and feldspars. It is, however, an extremely difficult constituent to measure in low concentrations. The accuracy of the measurements is not sufficient to determine the equilibrium involving aluminum in the upper part of the well. In the three samples from 3,146-3,246 feet the water appears to be in equilibrium with a feldspar of about equal calcium and sodium content. However, despite the abundance of calcium feldspar in the basalt, the calcium in solution is low, and roughly what it should be when in equilibrium with the mineral calcite. This doubtless occurs because the high bicarbonate content of the water drives calcite out of solution and lowers the calcium content of the water.

The potassium content is somewhat higher than expected for equilibrium with a potassium feldspar or potassium mica. Magnesium is low or absent, though magnesium is present in the dark minerals of the basalt. The concentrations of potassium and magnesium may, as supposed for calcium, be affected by their relative solubilities in the presence of bicarbonate and carbonate.

Chloride.--The uppermost ground water contains chloride in the concentrations generally present in meteoric waters. The ground water in the zones from 980-1,280 feet contains 120 mg/l (milligrams per liter) and below this to 3,246 feet the water contains less than 100 mg/l. These chloride concentrations are rather high for a basaltic terrane. No explanation can be offered at this time either as to a source or a possible mechanism for concentrating the chloride.

Fluoride.--Fluoride increases in concentration in the ground water with depth in the hole from about 1 mg/l to 20 mg/l in the 1,090-1,280-foot zone and then is more or less constant to 3,246 feet. These fluoride concentrations are high for ground water and particularly so for waters from basaltic rock. The source of the fluoride is unknown. The samples are undersaturated in fluoride with respect to the mineral fluorite, so that if a considerable amount of fluorite is present in the rocks it would be actively dissolving.

Sulfate.--Sulfate occurs in low concentrations in the samples. Its concentration generally is less than 13 mg/l, but shows a tendency to increase with depth. The sample from the zone at 4,080-4,283 feet is not entirely representative of water from that zone because of invasion by water that moved down the hole from shallower zones. However, the relatively high concentration of 21 mg/l in that sample indicates that the zone contains water of higher sulfate concentration than the upper zones.

In the interval between 540 and 1,120 feet, sulfate is extremely low or absent. Hydrogen sulfide gas was present when these samples were collected. The lack of sulfate probably is explained by the reduction of sulfate to produce hydrogen sulfide. Reducing conditions less severe than needed to reduce sulfate commonly give rise to relatively high dissolved iron concentrations, such as were measured in the samples from 636-810 feet.

Carbonate.--Bicarbonate and carbonate occur in unusually high concentrations for waters from basaltic rocks. The occurrence of these two species are dependent on pH. The proportion of carbonate to bicarbonate increases as the pH increases, until at a pH of about 10, essentially only carbonate is present. The pH of these waters is also exceptionally high, so that much carbonate is present. In the sample from the zone at 1,090-1,280 feet, the pH is 10.2 and carbonate is present to the exclusion of bicarbonate.

δC-13 values for carbonate in ground waters are commonly in the range of -7 to -15 per mil, because dissolved carbonate tends to be roughly a 1:1 mixture of plant-derived carbon from the soil zone (δC-13 $\simeq$ -25 o/oo) and of mineral carbonate (δC-13 $\simeq$ 0 o/oo) from the aquifer (Pearson and Hanshaw, 1970).

The samples from the well show that the ground water to a depth of 620 feet has δC-13 of about -14 o/oo, about normal for ground water. The lowermost zones contain water with a less negative δC-13 of about -7 o/oo. However, the zones from 980 to 1,280 feet contain water with the extraordinary δC-13 value of about +15 o/oo.

The C-13 enrichment in the zones from 980-1,280 is not explained adequately. Methane production under reducing conditions can, in some circumstances, selectively remove C-12 and in effect concentrate C-13 as bicarbonate ions are reduced to methane. As the waters in the zones 980-1,280 are otherwise chemically similar to deeper waters in the well, it may be assumed that they originally had δC-13 of about -7 o/oo. Then, if C-13 were concentrated through methane production, about 25 to 30 percent of their carbonate would have been lost. The zone from 980-1,120 is lower in total carbonate than deeper zones by 25 to 30 percent. However, for methane production to proceed, sulfate must first be entirely reduced. Sulfate has concentrations of 10 mg/l in the sample from 1,090-1,280 feet and 2.0 mg/l from 980-1,120 feet. Methane production and concentration of the C-13 could have taken place outside these zones and the water later migrated into them, picking up sulfate on the way. This is not consistent with the general character of the water in the well. Where reducing conditions exist from 540-726 feet, the δC-13 values are negative. Three samples of rock core obtained from core hole DDH-1 were analyzed by the U.S. Geological Survey for carbon isotope ratios to investigate the rocks themselves as a source of the heavy carbon. These cores are from depths of 457, 825, and 1,060.5 feet and are equivalent to rocks at about depths of 497, 865, and 1,100 feet in well ARH-DC-1. Relatively heavy carbon occurs in the 825-foot core, but the 1,060.5-foot core contained too little carbonate for analysis, as is shown in the table following. The small amount of carbonate in these cores suggest the carbonate present was deposited from the water itself. The results of the analyses are given in the following table.

Results of analyses for stable carbon-isotope ratios on core samples from hole DDH-1

Interval	Sample weight (grams)	Volume CO_2 evolved	δC^{13}_{PDB} (o/oo)
457 - 458.5	10.8025	2.7 cc (2.86×10^{-4} moles)	-11.61
825 - 826.5	10.4281	6.4 cc (1.21×10^{-4} moles)	+ 0.13
1,060.5 - 1,062	10.7155	0.09 cc (4.0×10^{-6} moles)	Not analyzed

CONCLUSIONS AND DISCUSSION

The hydraulic and water-quality data collected from well ARH-DC-1 allow some general conclusions to be drawn about the hydrologic system, though they are tenuous, particularly because the well was lost before hydraulic testing and water sampling were completed. The data reasonably support the thesis that thick sections of basaltic rocks of high density and low permeability occur at depths below the zone of active ground-water circulation; that is, the zone, including the glacial deposits, through which ground water moves comparatively rapidly and directly toward the Columbia River. Values of hydraulic conductivity of the rock section are small below about 1,200 feet in depth, except for fracture or interbed zones at about 1,500, 2,050, 2,600, 3,200, and 4,000 feet. The hydraulic conductivity of the rocks below 4,280 feet was not determined. The data on hydraulic heads indicate that there is little or no significant upward movement of water toward the permeable section above 1,200 feet. The heads measured at depths of 2,730-2,910 feet, 3,146-3,236 feet, and 3,166-3,196 feet are somewhat higher, by less than 5 feet, than the heads measured in shallower zones. However, these zones are interspersed with other zones in the section from 2,800-3,450 feet having apparent lower heads. Retesting of the heads in these zones and the installation of piezometers in two zones in this section probably could have shown if these data are valid. The lower head in the zones between 2,800 and 3,450 feet may be spurious, and the higher heads may prevail generally through this interval. If so, ground-water flow may have an upward component in this interval. Any upward component of flow could be expected to be extremely small, however, because of the thick sections of dense basalt that occur between the permeable rocks above 1,200 feet and the permeable zone at 3,200 feet. The chemical and isotopic characteristics of the ground water show a strong horizontal zonation of the deeper water in the well, the water from 980 to 1,280 feet, and the shallower water. This zonation indicates that little, if any, vertical movement of water has occurred at the site of the well.

The carbon-14 age of the water in the zone from 540 to 620 feet is about 13,000 years. The relationship of the stable hydrogen and oxygen ratios in this and other samples from greater depth suggest the water may have entered the ground under relatively cool climatic conditions. These data suggest that the deeper ground-water samples in the well may have entered the ground at least no later than the close of the last glaciation. Presumably, these rocks have continued to receive ground-water recharge and the water is moving towards points of discharge. The location and characteristics of the recharge and discharge areas for ground water in the basaltic rocks of the Hanford Reservation can only be surmised. The nature of the flow system in the basaltic rocks is not known from work done on the Reservation. If the flow system is in approximate balance, recharge and discharge being equal as classical hydrologic theory assumes, then the water in the basaltic rocks possibly moves from where it enters the rocks on the ridges and plateaus fringing the Pasco Basin to the Columbia River or the low ground south of the Reservation near Wallula Gap, where structural features of the rock may assist its discharge. Even the lowest ground-water head measured in well ARH-DC-1 (365 feet above mean sea level in the zone 4,000 feet deep) is above the stage of the Columbia River, suggesting that the ground water is part of a hydrologic system discharging to the river. However, in view of the meagerness of the data, the possibility exists that the head relationship with the river is fortuitous.

The actual rate of water-particle movement through the rocks depends on the hydraulic conductivity and the effective porosity of the rocks and the hydraulic gradient. These are related by an expression which is a form of Darcy's Law

$$v = \frac{K}{\theta} \cdot \frac{dh}{dl}$$

where

v is the average velocity of ground-water flow,

K is the hydraulic conductivity of the rock,

θ is the effective porosity of the rock,

$\frac{dh}{dl}$ is the hydraulic gradient.

Rock type	Hydraulic conductivity (ft/day)	Estimated effective porosity	Relative velocity of ground water (ft/day)
Interbed, sand	3.3	0.2	$16.5 \frac{dh}{dl}$
Fracture zone in basalt	6.7	0.1	$67 \frac{dh}{dl}$
Vesicular basalt	3.1×10^{-3}	0.05	$6.2 \times 10^{-2} \frac{dh}{dl}$
Dense basalt	1.6×10^{-3}	0.01	$1.6 \times 10^{-1} \frac{dh}{dl}$

The above tabulation shows that for a given hydraulic gradient $\left(\frac{dh}{dl}\right)$, ground water will travel fastest through the fracture zone. The zone has a hydraulic conductivity twice that of the interbed, but its porosity is only half that of the interbed. As a result, water will travel four times faster through it than through the interbed. The dense basalt, though the least permeable rock penetrated by the well, does not necessarily transmit water at the lowest velocity as can be seen by comparing the values given for it with those for vesicular basalt. The only importance to be attached to the effective porosity values, and relative velocities given is that they illustrate the relationship of effective porosity to ground-water velocity computations and the likelihood that the highest ground-water velocities are obtained in the thin fracture zones of high hydraulic conductivity.

RECOMMENDATIONS

In well ARH-DC-1, dense basalt zones 100 to 150 feet thick occur within a predominantly basaltic rock section of low permeability lying between 1,200 and 4,000 feet in depth. The hydraulic heads and the chemical and isotopic characteristics of the water indicate that there is little if any significant upward movement of water at the well site. Assuming that these conditions are widespread, deep cavern storage of radioactive wastes may be feasible from a hydrologic standpoint for those radionuclides that decay to innocuous levels in 600 to 1,000 years. However, the feasibility can ultimately be determined only if it can be shown with a high level of confidence that no possibility exists for the wastes to reach man's environment by movement through the hydrologic system in this period of time.

In order to assess the possible movement of wastes, hydrologic investigations should provide enough information such that (1) the hydraulic conductivities, ground-water flow patterns, and rates of flow are known within reasonable limits in the geologic framework of the Pasco Basin; and (2) the geochemistry of the ground-water system is known so that interactions among the rocks, water, and radioactive waste can be predicted with some confidence.

To obtain this information, the following studies should be conducted:

1. Study the regional ground-water system, mainly using available data from Federal and State agencies, to attempt to identify the discharge areas of deeply circulating ground water and to anticipate the direction in which wastes escaping from storage could move.
2. Drill and test additional deep wells. Sites should be chosen with regard to determining the geologic controls on hydraulic conductivity and to obtaining head measurements to define hydraulic gradients. Ground-water samples and any contained gas should be collected to define the age of the ground water and the geochemical environment. Wells should be completed with piezometers open to several different depths.
3. Recover well ARH-DC-1 and complete with one or more piezometers. In its present condition, the well probably is an avenue of vertical circulation. This is undesirable, because the circulation will disturb the natural head relationship which must be determined and because it provides a means by which wastes may accidentally enter the ground-water system.

4. Drill test wells to the permeable interbeds above 1,200 feet and conduct pumping tests. The tests using well ARH-DC-1 indicate that leaky artesian conditions prevail in these rocks. Therefore, two or more observation wells should be used for each test in order to assess leakage factors and the possibility of vertical movement through these beds in areas where wastes might be stored in subsurface chambers.

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from ST-5,

(Figure III-7). Chapter I and the section entitled Future Studies in this chapter give an outline of ongoing efforts to gain additional head measurements within the Grande Ronde Basalt. Outside of the Hanford Site, no other wells are known to penetrate the Grande Ronde Basalt in the Pasco Basin from which head data may be obtained.

Borehole RSH-1. In June 1967, Cook Testing Company completed DST tests and head measurements in RSH-1. The results were documented by Raymond and Tillson (1968). Table III-24 lists the heads recorded along with the investigator's comments on the validity of each test. Head measurement accuracy is considered ± 20 feet under excellent test conditions. These data are plotted on Figure III-25. Question marks are adjacent to those points considered of poor quality by Raymond and Tillson (1968). RSH-1 had been open to groundwater cross-flow within the borehole for 10 years following its completion in 1958; this most likely created non-static heads in some test intervals which were later reflected, to some extent, during the short testing period.

Figure III-25 shows a steep, downward hydraulic gradient of 0.6 percent over the 2,600- to 4,200-foot depth. This depth extends through most of the lower Grande Ronde Basalt. The highest pressure of 1,954 feet was recorded at a depth of 2,614 to 2,690 feet which lies within the Umtanum unit. Between 4,200 and 4,900 feet, the head increases 42 feet to +999 feet before again decreasing 144 feet upon reaching a depth of 6,000 feet; however, these head differences are most likely within the error of measurement, since the borehole was open to groundwater cross flow for several years and the shut-in period for the tool was only a few hours per measurement. Thus, the head data available between the depths of 4,100 and 6,000 feet are perhaps best interpreted as having little or no head change. This rock zone would characterize an interval of essentially horizontal groundwater movement. The only measurement below 6,000 feet is one highly questionable head measurement of -4,691 feet recorded between the depths of 8,275 and 8,351 feet. No hydrologic significance can be assigned to this value.

TABLE III-24. Hydraulic Heads within Basalts Penetrated by Borehole RSH-1.

Test Interval* (feet below ground level)	Head** (feet above mean sea level)	Test*** Comment
1,929 - 2,005	+1,829	Poor
2,614 - 2,690	+1,954	Fair
3,213 - 3,289	+1,360	Good
4,119 - 4,195	+957	Excellent
4,832 - 4,908	+999	Excellent
5,921 - 5,997	+855	Good
8,275 - 8,351	-4,691	Order of Magnitude Estimate

*Data from Raymond and Tillson (1968).
**Ground level elevation 2,889 feet.
***Measurement accuracy ± 20 feet under excellent test conditions.

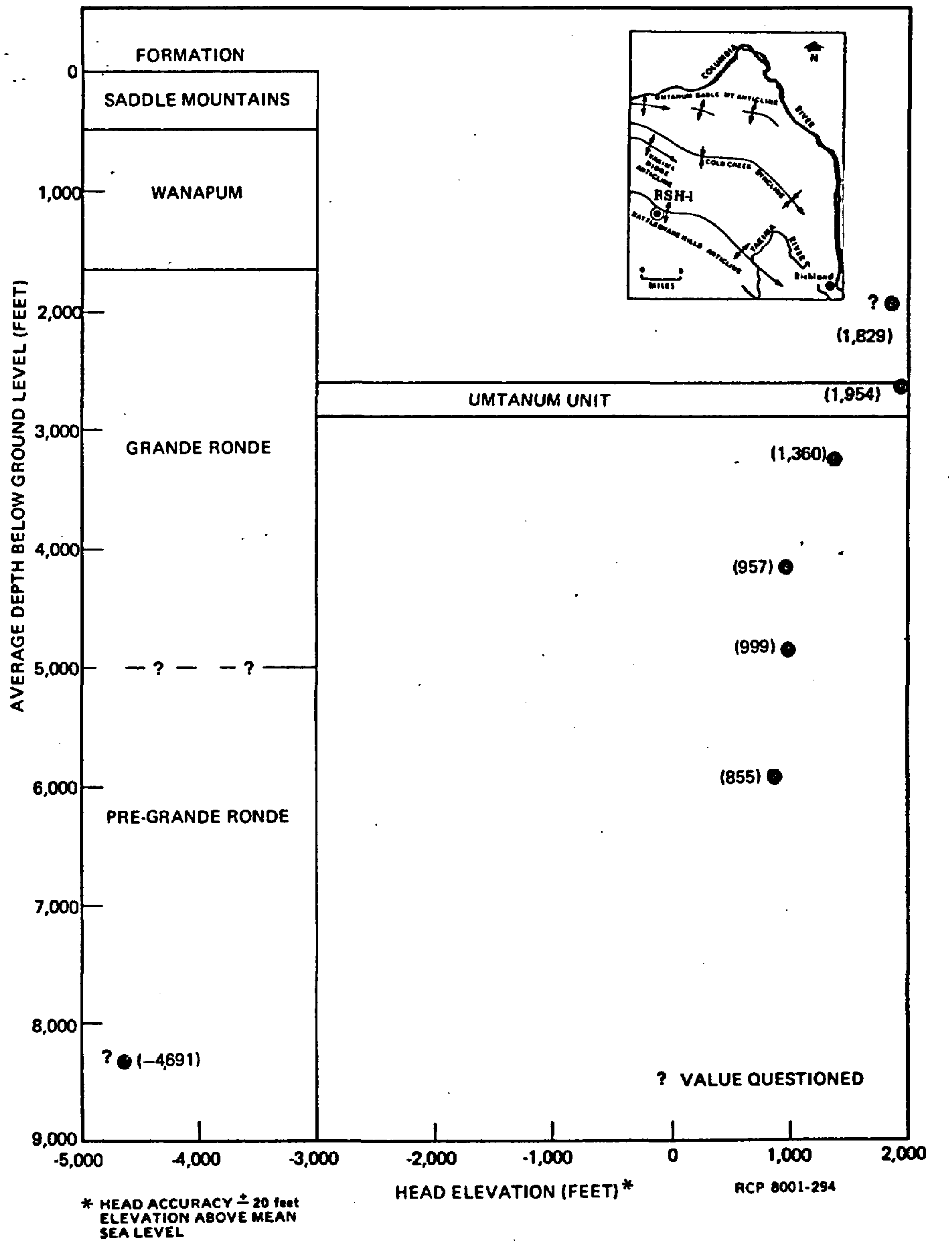


FIGURE III-25. Hydraulic Heads within the Basalts Penetrated by Borehole RSH-1.

It is important to note that each of the heads within the Grande Ronde Basalt of RSH-1 is 500 to 1,600 feet higher than those in DC-1, DC-2, and DC-6 located 20 to 25 miles to the east (heads in these boreholes are addressed in the following text). For example, the head in the interflow of the Umtanum unit of RSH-1 is at an elevation of 1,954 feet. This compares to 395 to 460 feet for the same horizon in DC-1, DC-2, and DC-6. The difference may be accounted for by either: (a) a uniformly steep hydraulic gradient (20 to 80 feet per mile) separating RSH-1 and the other boreholes; or (b) a major interruption in the regional hydraulic gradient created by the Rattlesnake Hills anticline and associated faulting. The second interpretation is believed to be the most plausible.

Borehole DC-1. Table III-25 lists those heads reported by LaSala and Doty (1971) across the Grande Ronde Basalt in borehole DC-1. The straddled intervals varied between about 30 and 200 feet although most packers were separated by 90 or 180 feet. Because of these long spacings, more than one interflow was normally straddled during each measurement. As previously mentioned, these heads were taken during permeability testing and groundwater sampling. LaSala and Doty (1971) acknowledged that these activities disturbed static heads, thus, the reported values must be used cautiously; however, the general hydraulic gradient is probably realistic. Head measurements were made using down-hole mechanical pressure gages.

I'm getting this

Two features are revealed by plotting Table III-25 data onto Figure III-26. These are:

a. The highest heads (402 to 411 feet) are recorded above the depth of 3,451 feet--This suggests an interval of essentially vertical equipotential;

b. Below the Umtanum unit, head decreases reaching a low of 366 feet at a depth of 4,000 feet--This suggests a zone of apparent downward hydrologic gradient.

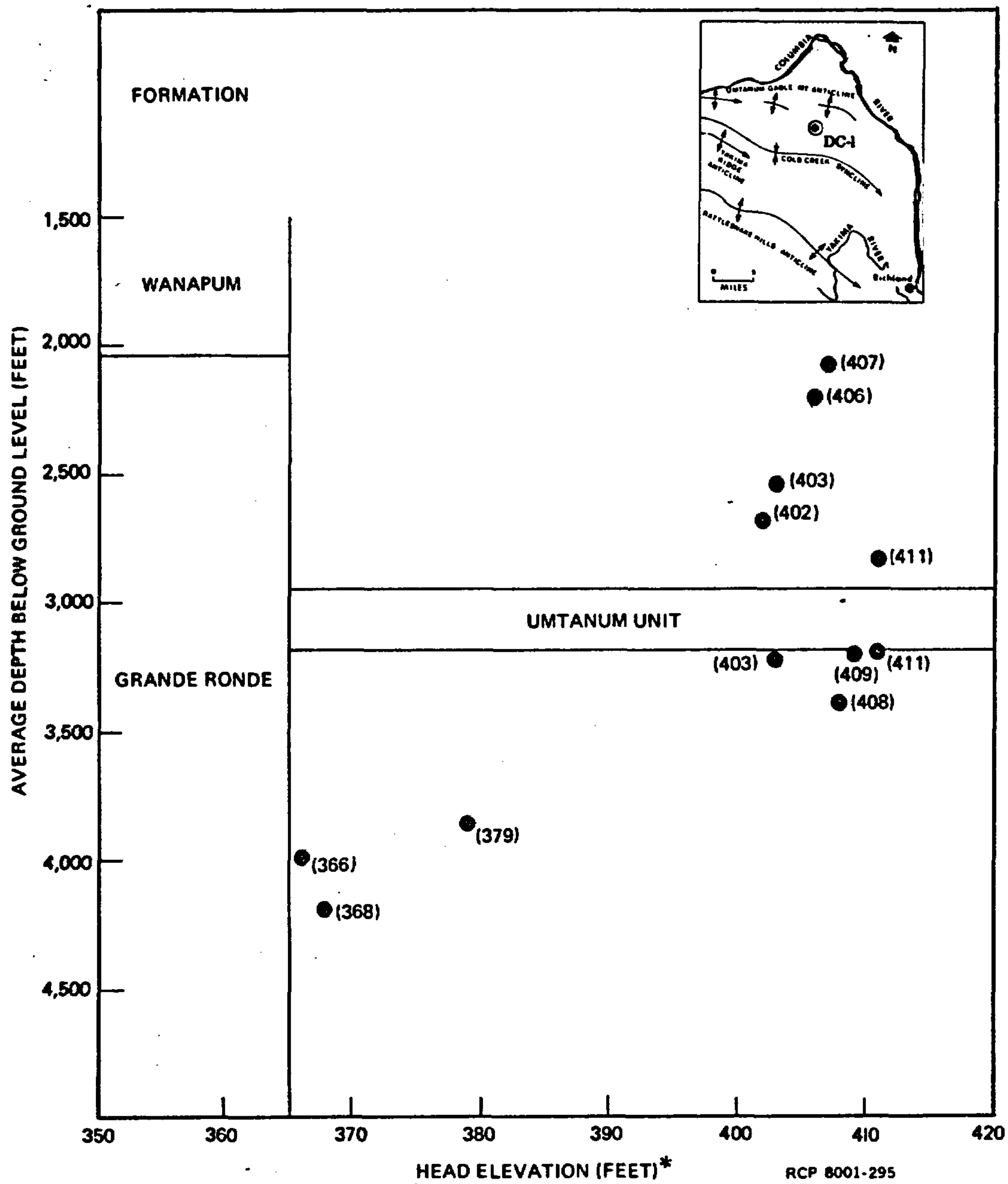
Thus, the DC-1 head measurements in the Grande Ronde Basalt by LaSala and Doty (1971) suggest horizontal groundwater movement above a depth of 3,450 feet and downward movement below this depth.

where does the water go? What is the travel time.

TABLE III-25. Hydraulic Heads within the Grande Ronde Basalt of Borehole DC-1.

Test Interval* (feet below ground level)	Head (feet above mean sea level)	Comment**
1,970 - 2,160	407	Straddles bottom of Wanapum Basalt and top of Grande Ronde Basalt
2,170 - 2,225	406	
2,430 - 2,610	403	
2,600 - 2,780	402	
2,730 - 2,910	411	
3,146 - 3,236	411	
3,166 - 3,196	409	
3,206 - 3,246	403	
3,320 - 3,451	408	
3,774 - 3,934	379	
3,910 - 4,070	366	
4,080 - 4,283	368	

*Data from LaSala and Doty, (1971). Ground level elevation 572 feet.
**Head measurement accuracy ± 20 feet.



* HEAD MEASUREMENT ACCURACY ± 20 feet
ELEVATION ABOVE MEAN SEA LEVEL

FIGURE III-26. Hydraulic Heads within the Grande Ronde Basalt of Borehole DC-1.

History of the DC-1 Piezometers. Rotary drilling of exploratory well DC-1 was completed at 5,661 feet in September 1969. Three years later in April 1972, 5 piezometer tubes were installed (Figure III-27). Piezometers 1 through 4 had 2-1/16-inch outside diameters and were positioned across specific interflows in the Grande Ronde Basalt. Piezometer 5 is 2-7/8 inches in outside diameter and was left open to about 825 feet of Wanapum Basalt plus the upper 100 feet of Grande Ronde Basalt. Piezometers 1 through 4 were set in sand and gravel packs separated by cement plugs. Each tube was completed using 10-foot-long, 2-inch-diameter Johnson well screens reinforced with 1.9-inch-diameter stainless steel, perforated pipe. Pipe perforations were 3/8 inch in diameter, 4 per round, 1 round per vertical inch. Piezometer 5 has no well screen and is an open-ended pipe.

Hydraulic heads have been monitored in these piezometers since June 1972. Figure III-28 shows hydrographs of the piezometers over the monitoring period. All head measurements taken in each piezometer since June 1972 are given in Table III-26.

From 1972 to the summer of 1977, the DC-1 site remained undisturbed except for three periods of groundwater development and sampling in each piezometer. These occurred in April 1972 (following piezometer installation), September 1973, and the spring of 1974. Any head disturbance this development may have had on individual piezometers or between piezometers was apparently not recorded, since no water levels were collected in the spring of 1972, 1973, or most of 1974.

not true See III-26 chart USGS LTR 7/14/73

Since installation, piezometers 1, 2, and 3 have responded in unison to head changes. Hydraulic heads have varied no more than about 2 feet from each other with the highest head in piezometer 1 and progressively lower readings in piezometers 2 and 3. This difference has reduced to approximately 1 foot since late 1976. At the same time, piezometers 4 and 5 have behaved independently from the lower 3 piezometers. For the 3 years following installation, the water levels in piezometer 4 were as much as 20 feet higher than piezometer 5, as piezometer 4 equilibrated. By April 1975, the piezometer 4 water level dropped below that in piezometer 5 and this separation continued to increase until 1977.

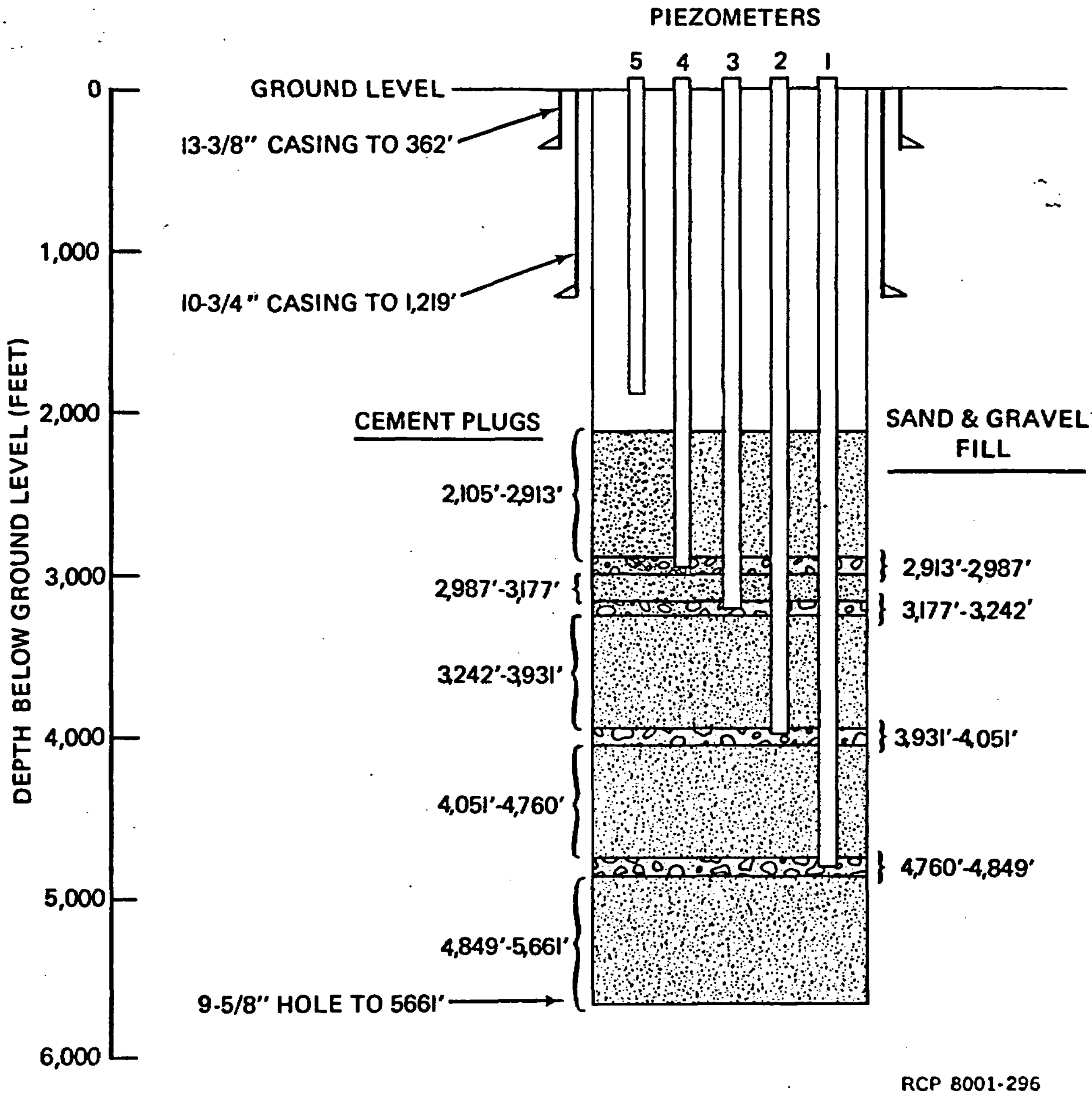


FIGURE III-27. Piezometer Placements in Borehole DC-1.

572.18

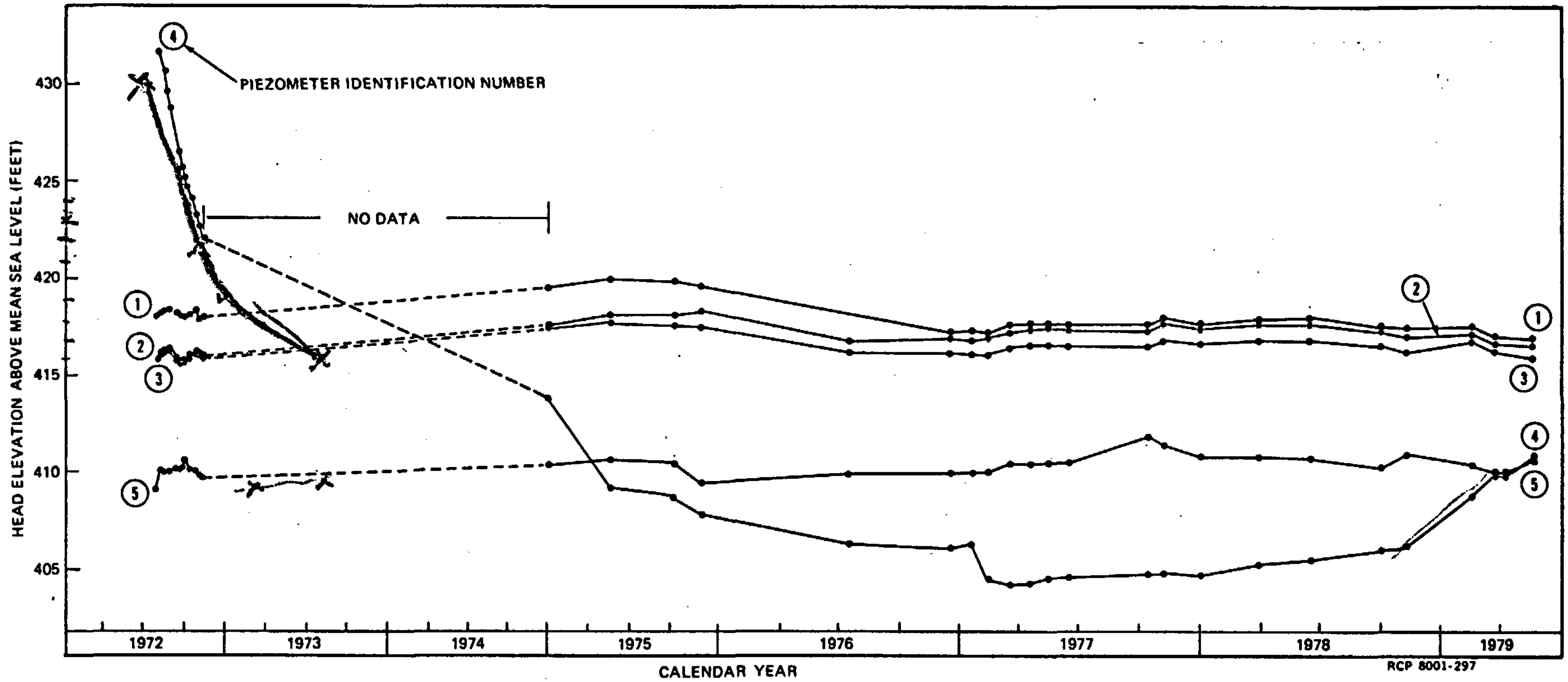


FIGURE III-28. Hydrograph of the Water Levels in the DC-1 Piezometers from 1972 through 1979.

TABLE III-26. Water Level Elevations Reported for the DC-1 Piezometers.*

Measurement Date	Piezometer 1	2	3	4	5
6/29/72	418.07	415.89	415.84	431.62	409.98
7/06/72	418.35	416.21	416.13	430.66	410.16
7/13/72	418.38	416.29	416.23	429.59	410.04
7/20/72	418.49	416.42	416.33	428.75	409.98
8/10/72	418.33	415.92	415.85	426.57	410.20
8/17/72	418.06	415.71	415.65	425.81	410.10
8/24/72	418.13	415.92	415.81	425.24	410.16
8/30/72	417.95	415.75	415.71	424.71	410.68
9/07/72	418.15	416.04	415.97	424.18	410.17
9/21/72	418.43	416.35	416.29	423.30	410.15
9/28/72	417.88	416.17	416.16	422.70	409.92
10/05/72	418.04	416.04	415.98	422.19	409.76
12/30/74	419.67	417.66	417.56	414.09	410.42
4/18/75	420.12	418.32	417.88	409.29	410.74
9/03/75	420.01	418.23	417.79	408.91	410.68
12/06/75	419.81	418.45	417.73	408.03	409.61
7/76	421.58**	416.94	416.35	406.51	410.11
12/76	417.32	417.01	416.28	406.29	410.30
1/17/77	417.40	416.91	416.19	406.59	410.10
2/14/77	417.27	417.01	416.20	404.71	410.11
3/14/77	417.65	417.38	416.56	404.39	410.57
4/15/77	417.73	417.45	416.67	404.44	410.55
5/13/77	417.76	417.49	416.67	404.72	410.61
6/15/77	417.69	417.46	416.58	404.74	410.61
10/11/77	417.68	417.38	416.59	404.89	412.03
11/4/77	418.05	417.75	416.96	404.99	411.46
12/27/78	417.72	417.54	416.69	404.80	410.88
3/27/78	418.03	417.77	416.87	405.46	410.98
6/11/78	418.08	417.75	416.90	405.65	410.83
10/2/78	417.65	417.35	416.69	406.22	410.37
11/6/78	417.67	417.12	416.39	406.32	411.11
2/13/79	417.76	417.30	416.89	409.89	410.61
3/19/79	417.16	416.74	416.25	410.02	410.12
4/3/79	417.15	416.73	416.29	410.01	410.06
5/11/79	416.99	416.63	416.03	410.91	409.78

*Heads in feet above mean sea level.
**Anomalous reading.

It is important to note that between May and September 1977 borehole DC-2 was cored into the basalt about 60 feet to the southwest of DC-1. Since the completion of DC-2, the borehole has remained open (uncased) from approximately 2,200 to 3,300 feet below ground level. This uncased hole crosses the open intervals of piezometers 3 and 4 and is within 100 feet of piezometer 5.

Beginning in late 1977, the head in piezometer 4 has been equilibrating to that in piezometer 5 (Figure III-28). In October 1977, 7 feet separated the 2 water levels. Since March 1979, the water levels in both piezometers have remained about 0.10 foot or less apart. The reasons for this equilibration is unknown. During fiscal year 1980, tests are scheduled at the DC-1 and DC-2 site to address possible cross-hole interference. Other explanations may include structural deterioration of the DC-1 piezometers or natural cyclic down-hole pressure changes.

At present, piezometers 1, 2, and 3 indicate a slight upward hydraulic gradient of 0.001, or about 1 foot per thousand feet. The average head elevation for these 3 piezometers is about 417 feet. Thus, the head in piezometer 3 compares favorably with the 403 to 409 (± 20)-foot head reported by LaSala and Doty (1971) along the same interval of Grande Ronde Basalt. However, LaSala and Doty (1971) reported a 366-foot head for the interval now monitored by piezometer 2. This large difference in head cannot be reconciled at this time and must await future testing. LaSala and Doty did not record head measurements near the 4,760 to 4,849-foot depth of piezometer 1.

The head elevation of about 410 feet in piezometers 4 and 5 compare well with the heads of 402 to 411 (± 20) feet for the same zone reported by LaSala and Doty (1971).

The possibility exists that piezometers 1, 2, and 3 are hydraulically interconnected within DC-1. Water leakage could result from incomplete or deteriorated cement seals along the cement/borehole wall and/or thread leakage. The evidence for such leakage is two-fold. First, as noted earlier, these three piezometers have responded in unison since installation and their heads are close, although their stratigraphic separation spans 1,600 feet. Secondly, and most important, water-level changes were noted in piezometers 1, 2, and 3 during swabbing of the DC-2 interval of 3,243 to 3,273 feet during groundwater sampling by Apps and Others (1979). This interval is immediately beneath the piezometer 3 setting. During swabbing, water levels were lowered several feet in piezometer 3 and a few inches in piezometers 1 and 2. Thus, the representativeness of water levels within each of the DC-1 piezometers is in question. It is not yet resolved whether the uncertainty lies within the structural integrity of the DC-1 borehole or was created by the emplacement of DC-2, or a combination of both. Future hydrologic testing will address these questions.

Borehole DC-2. Table III-27 lists the hydraulic heads recorded by Apps and Others (1979) and Science Applications Inc. (1978) taken across selected intervals of Grande Ronde Basalt in DC-2. These data are plotted on Figure III-29. Packer spacing varied between 30 and 54 feet, although most were 30 feet apart. These short straddles made it possible to isolate single, low-density interflows for head measurements. Measurement accuracy was given at ± 2.5 feet by Apps and Others (1979). The same accuracy is assumed to apply to the Science Applications Inc. data; however, based upon testing results by Science Applications Inc. and Rockwell Hanford Operations during 1979 and early 1980, the measurement is probably about ± 5 feet.

Since DC-2 was open opposite the Grande Ronde Basalt for about 9 months preceding testing, the heads listed for high-density zones (zones having the lowest permeabilities) did not have sufficient time to establish a static value during the test period. Therefore, only those heads taken from low-density interflows were plotted in Figure III-29 for comparison of head values. It is assumed that testing time was sufficiently long for these low-density zones to reasonably establish a static head.

From Table III-27, it is noted that 2 separate heads of 419 and 395 feet were recorded across the Umtanum interflow lying between the depths of 2,945 and 3,000 feet. The first value was reported by Science Applications Inc. (1978) and the second by Apps and Others (1979). At present, it is uncertain as to which is representative of the true static

TABLE III-27. Hydraulic Heads Reported for the Grande Ronde Basalt in Borehole DC-2.

Test Interval (feet below ground level)[c]	Rock Density[d]	Head[e] (feet above mean sea level)
[a]2,269 - 2,299	High	470
2,340 - 2,370	Low	443
2,625 - 2,655	Low	438
2,795 - 2,825	Low	421
2,960 - 2,990	Low	395
3,160 - 3,190	Low	377
3,243 - 3,273	Low	362
[b]2,344 - 2,376	Low	444
2,376 - 2,409	High	423
2,955 - 3,007	Low	419
3,019 - 3,071	High	421
3,069 - 3,122	High	446
3,116 - 3,170	High	423

[a]Apps and Others (1979).
[b]Data from Science Applications Inc. (1978).
[c]Ground level elevation 572 feet.
[d]Low density--Test straddled at least one zone of low-density (≈2.4-2.6 grams/cubic centimeter) basalt. High Density--Test straddled only high-density (≈2.7-2.8 grams/cubic centimeter) basalt. Densities were determined by geophysical log interpretation.
[e]Head accuracy of ± 2.5 feet reported by Apps and Others (1979).

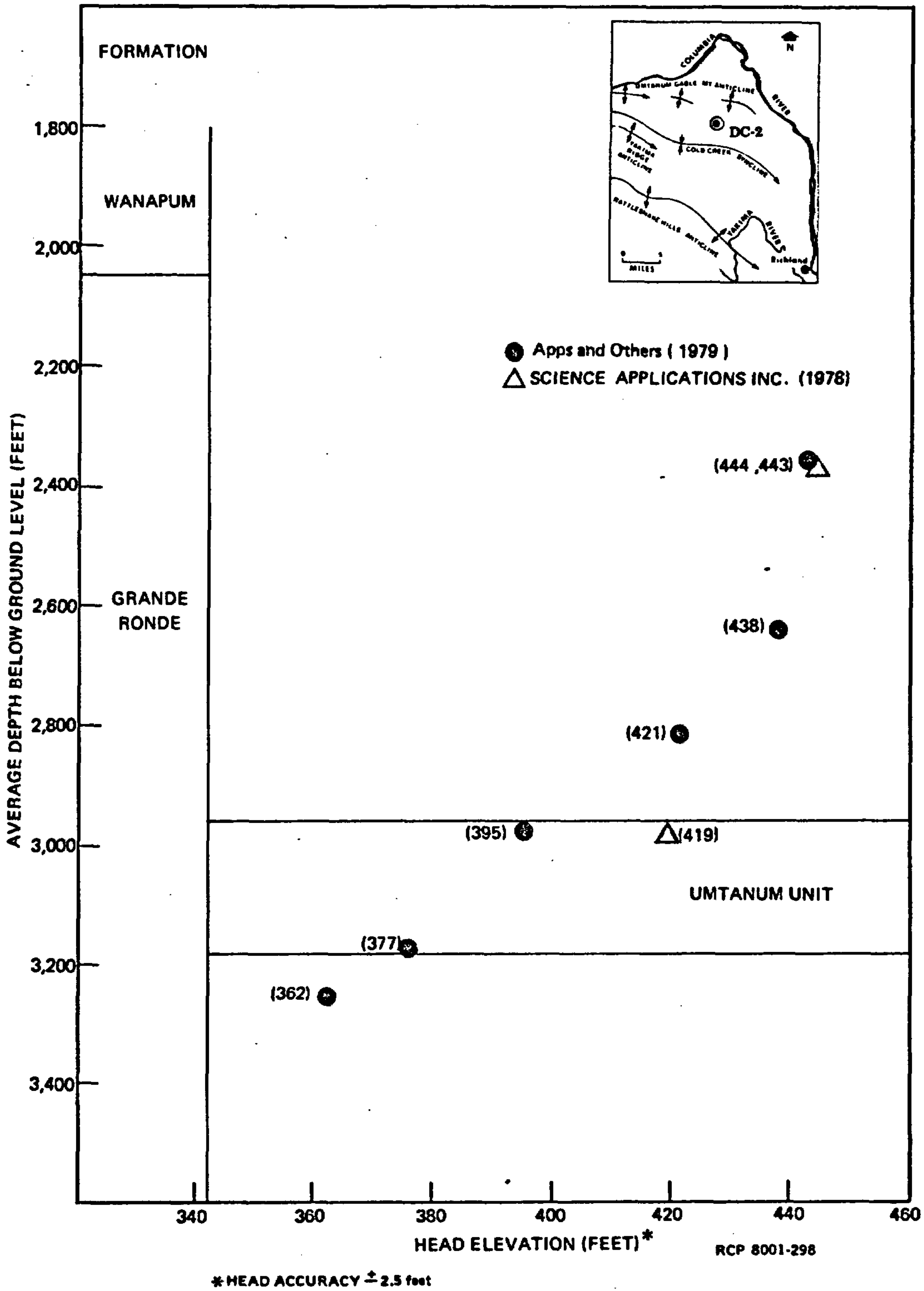


FIGURE III-29. Hydraulic Heads for the Grande Ronde Basalt in DC-2 Plotted as a Function of Depth.

head. Piezometer 4 of DC-1 is also open within this interval and its static head is 411 feet, closely approximating the larger of the 2 head values.

Comparison of Hydraulic Heads in Boreholes DC-1 and DC-2. Figure III-30 is a complete diagram of the Saddle Mountains, Wanapum, and Grande Ronde Basalt heads for DC-1 and DC-2 reported by LaSala and Doty (1971), Science Applications Inc. (1978), Apps and Others (1979), and the DC-1 piezometers. These boreholes are located at the same site about 60 feet apart. As can be seen, there is general disagreement between the heads indicated in the DC-1 piezometer tubes versus both those reported previously for DC-1 and those determined in DC-2. These differences may result from:

a. Non-static heads reported by LaSala and Doty (1971)--This possiblity was noted in the LaSala and Doty report because head determinations were made during permeability testing and groundwater sampling;

b. Non-representative heads within the 5 piezometer tubes of DC-1--As noted earlier, it appears that tubes 1 through 3 are hydraulically interconnected within the DC-1 borehole because of inadequate zone isolation perhaps resulting from a separation of the borehole cement and the rock wall bond; this problem would also have influenced the heads later measured in DC-2 because of the proximity of the 2 boreholes; and,

c. A composite or average head becoming established in DC-2 during the 9 months separating borehole completion and head measurements--The borehole remained hydraulically open to any groundwater cross flow; those interflows contributing water would be recorded with an artificially low head, while those accepting water would have abnormally high heads.

Based upon available information, it is the authors' opinion that, of the 3 head distributions given in Figure III-30, the DC-1 values given by LaSala and Doty should be used, for the time being, as representing site conditions (although none are ideal). This choice is based upon the rationale that:

a. DC-1 heads within the Saddle Mountain Basalt are in general agreement with the head distribution known for the area from other DB wells;

b. Water levels in piezometer tubes 4 and 5 of DC-1 are in close agreement with the heads recorded 10 years earlier by LaSala and Doty;

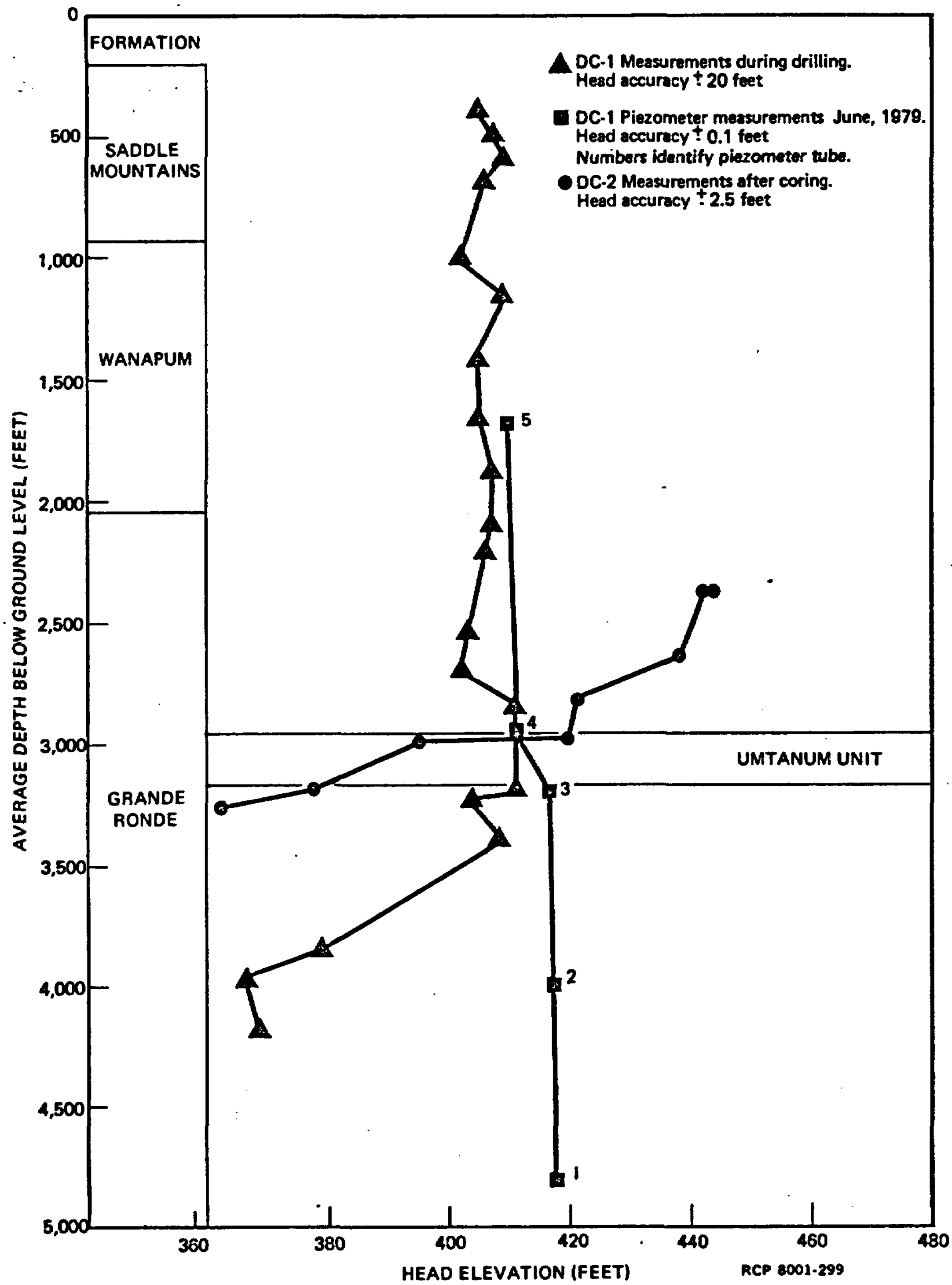


FIGURE III-30. Comparison of Hydraulic Heads Reported for Boreholes DC-1 and DC-2.

c. DC-1 was not open to groundwater cross flow for any length of time between hole drilling and head measurement; and,

d. The hydraulic head record in DC-1 is the most extensive encompassing the Saddle Mountains, Wanapum, and Grande Ronde Basalts; thus, it is the most complete of the 3 data sources.

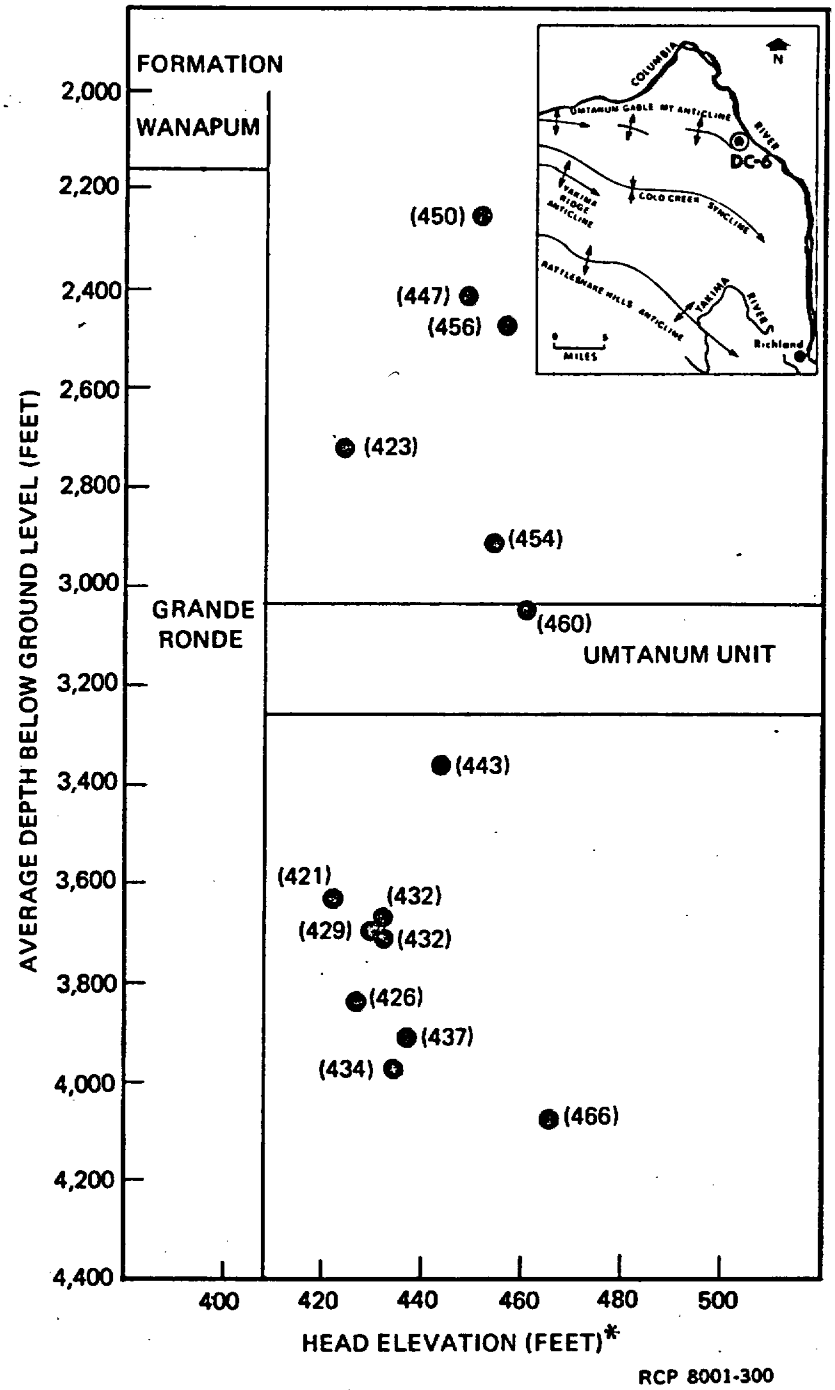
Borehole DC-6. In August 1978, Apps and Others (1979) began head measurements within the Grande Ronde Basalt of DC-6. A standard 30-foot packer spacing was used to straddle selected, low-density interflows between the depths of 2,240 and 3,722 feet. Testing was completed using a single packer set at 4 locations between depths of 3,341 and 3,802 feet. Thus, these last measurements recorded a composite head for the rock interval between the packer and the total depth of 4,331 feet for the borehole. Head measurement accuracy was reported as ± 2.5 feet.

The heads reported are given in Table III-28. Figure III-31 is a plot of the same data. An average depth was used in plotting the last 4 heads. The largest head of 460 feet was recorded at a depth of 3,025 to 3,055 feet. This is within the Umtanum interflow. Three hundred feet above the Umtanum unit, the head reaches a low of 423 feet above mean sea level; thereafter, it rises to between 447 and 456 feet. The uppermost 3 measurement points on Figure III-31 suggest that static head condition (indicating horizontal groundwater flow) are established above the depth of 2,500 feet. Such conditions may extend to atop the Umtanum unit if the 423-foot head elevation reported at the depth of 2,708 to 2,738 feet is too low. (In relation to the surrounding data points, this head measurement of 423 is anomalous and subject to question.) This would result in essentially vertical equipotentials in the Grande Ronde Basalt above the Umtanum unit as suggested by the LaSala and Doty (1971) data for DC-1. Below the Umtanum unit, the head decreases to a 421-foot minimum at the depth of 3,620 to 3,650 feet. Farther down the hole, the heads vary between 426 and 437 feet, except for a final measurement of 466 feet. As noted in Table III-28, this last measurement is a composite head over a 534-foot section of open hole. This indicates that some interval below the 3,802-foot depth has a head elevation of at least 466 feet.

TABLE III-28. Hydraulic Heads Reported for the Grande Ronde Basalt in Borehole DC-6.[a]

Test Interval (feet below ground level)[b]	Rock Density[c]	Head[d] (feet above mean sea level)
*2,240 - 2,270	Low	450
2,400 - 2,430	Low	447
2,454 - 2,484	Low	456
2,708 - 2,738	Low	423
2,896 - 2,936	Low	454
3,025 - 3,055	Low	460
3,343 - 3,373	Low	443
3,620 - 3,650	Low	421
3,650 - 3,680	Low	432
3,683 - 3,713	Low	429
3,692 - 3,722	Low	432
3,341 - 4,336	Several high and low	426
3,477 - 4,336	Several high and low	437
3,601 - 4,336	Several high and low	434
3,802 - 4,336	Several high and low	466

[a]Apps and Others (1979).
[b]Ground level elevation 402 feet.
[c]Low density--Test interval includes at least one zone of low-density basalt which normally corresponds to an interflow zone. High density--Test interval in high-density basalt which normally corresponds to a section of columnar basalt.
[d]Head accuracy ± 2.5 feet as reported by Apps and Others (1979). Head elevations are above ground level. Artesian flow is ~10 gpm.



* HEAD ACCURACY ± 2.5 feet
AVERAGE DEPTH USED TO PLOT LOWER 4 POINTS.
ELEVATION ABOVE MEAN SEA LEVEL

FIGURE III-31. Hydraulic Heads for the Grande Ronde Basalt in DC-6 Plotted as a Function of Depth.

Summary. Figure III-32 shows a comparison of hydraulic heads for boreholes DC-1, DC-6, and DC-8. Data from these 3 sites represent the majority of the head information available for the Wanapum and Grande Ronde Basalts. This figure is a composite of the information previously given (Table III-21 and Figures III-23, III-24, III-26, and III-31) and is centered upon a single stratigraphic horizon, the Umtanum unit. This permits easier correlations between comparable stratigraphic units without the limiting influences of intervening geologic structures and differences in land surface elevations. The data points represent the mid-point of a straddled interflow zone. As previously noted, the DC-1 heads were chosen as most representative of the DC-1/DC-2 site.

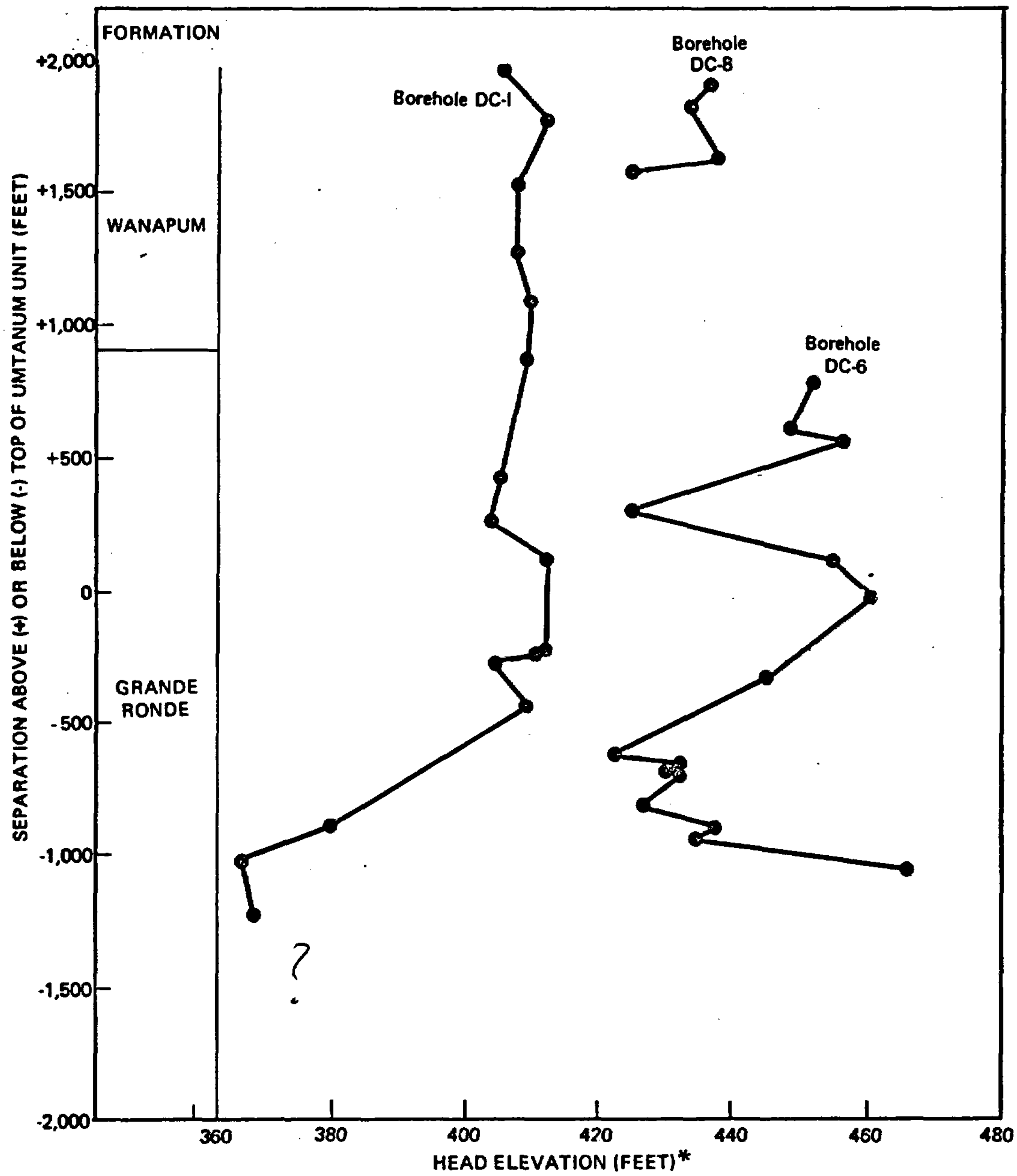
The scarcity of available data limits the conclusions that can be drawn about the distribution of heads in the deep basalts beneath the Hanford Site. However the following trends are suggested:

a. Hydraulic equilibrium apparently exists across the entire Wanapum Basalt in DC-1 and in the upper Wanapum Basalt in DC-8. A zone of sligthly lower head occurs in DC-8 along the Roza-Frenchman Springs contact, but the areal extent and significance of this must await further study.

b. Hydraulic heads within the Wanapum Basalt of DC-8 appear to be several feet higher than those in DC-1. This does not imply northward groundwater flow between the 2 sites, since the overall potentiometric surface of the Wanapum Basalt is not known. However, the outline of this surface (at least in the upper Wanapum Basalt) is expected to approximate that shown in Figure III-22 for the Saddle Mountains Basalt.

c. With the exception of one low head elevation in DC-6, a hydraulic equilibrium appears to exist in the Grande Ronde Basalt above the Umtanum unit. Below the Umtanum unit in both DC-6 and DC-1, there is generally a head decrease of perhaps 40 feet, reaching its lowest value 500 to 1,000 feet below the Umtanum flow top.

d. Generally higher hydraulic heads are apparent in the Grande Ronde Basalt in DC-6 compared to DC-1. A possible explanation for this is that the Umtanum-Gable Mountain anticline separating the two sites is forming a structural impediment to groundwater flow from the north. This barrier might result from tight basalt folding, faulting, or a combination of both. This anticline may interrupt groundwater flow moving southward from Sentinel Gap and the Saddle Mountains, perhaps diverting it to the southeast away from the Cold Creek syncline. If this does occur, then the Umtanum-Gable Mountain anticline would have a significant effect on the deep basalt hydrology beneath the Hanford Site.



* HEAD ACCURACY IN BOREHOLE DC-1 IS ± 20 FEET
HEAD ACCURACY IN BOREHOLE DC-6 AND DC-8 IS ± 2.5 FEET
ELEVATION ABOVE MEAN SEA LEVEL

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FIGURE III-32. Comparison of Hydraulic Heads in Boreholes DC-1, DC-6, and DC-8.