USGS-OFR-76-538

UNITED STATES (DEPARTMENT OF THE INTERIOR)

GEOLOGICAL SURVEY. [Report(s) - Open file series]

A deep research drill hole at Kilauea Volcano, Hawaii

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Open-File Report 76-538
1976

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ABSTRACT

A 1262-m-deep bore hole was drilled at the summit of Kilauea Volcano, Hawaii, to test predictions based on surface geophysical surveys and to obtain information on the hydrothermal regime above a postulated magma reservoir. Data from the drilling and geophysical borehole logs tend to confirm earlier predictions that a mound of brackish or saline water is present above the inferred magma body. Temperatures within the hydrothermal system are not sufficiently high to indicate deposits of economic interest, but the gradient toward the bottom of the hole (approximately 160 m below sea level) is high, about 370°C per kilometer. The maximum temperature, 137°C, is at the hole bottom.

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INTRODUCTION

National concern over an energy shortage has greatly expanded interest in geothermal power. Commercial geothermal power plants throughout the world are located in areas of recent silicic volcanism, but the obvious supply of heat associated with Hawaii's active basaltic volcanoes is attractive as a possible future source of power. Although Hawaii's volcanoes are among the most thoroughly studied in the world, little is known about whether their subsurface temperature regime and hydrologic and geologic conditions are favorable for geothermal deposits of economic potential. Only drill holes can supply much of the necessary data.

The first deep bore hole at the summit of an active volcano was drilled between April 6 and July 9, 1973, at Kilauea Volcano, Hawaii, with support from the National Science Foundation. The hole, 1.1 km south of Halemaumau Crater ($19^{\circ}23.7'$ N, $155^{\circ}13.3'$ W; Fig. 1), was drilled to a depth of 1,262 m (4,137 ft), measured from the derrick floor located at an altitude 1,102 m (3,616 ft) above mean sea level (depth levels in the hole are given relative to drilling platform datum, 3 m above ground surface). Hole bottom was 160 m below sea level. Although the drill hole is within the boundaries of Hawaii Volcanoes National Park, where by law resources cannot be exploited, the National Park Service permitted the drilling project as the hole was to be used for research only. This report reviews the rationale for site selection and summarizes available data on core samples, temperature measurements, and geophysical logging.

Figure 1 near here

Although it is one of the world's most active volcanoes, Kilauea Volcano's eruptions are usually nonexplosive, and scientific studies generally can be carried out safely at close range during all stages of activity. Kilauea exhibits high seismicity, mainly associated with fault systems on its summit and rift zones and with movement of magma at depth (Koyanagi and others, 1971 and 1972). Because Kilauea's basaltic lava is grossly uniform in chemical and mineralogic composition, variations in its behavior can be interpreted more readily than is possible for volcanoes of variable composition. For these reasons, Kilauea has been intensively studied and provides, and is continuing to provide, a unique field laboratory for carrying out investigations that would not be feasible elsewhere.

Measurements of seismicity, ground tilt, elevation changes, and horizontal ground displacements repeated regularly by the Hawaiian Volcano Observatory show that inflation and deflation of Kilauea's summit area is generally centered in or near the southern part of the caldera (Mogi, 1958; Eaton, 1962; Fiske and others, 1969; Kinoshita and others, 1974). These centers of deformation are interpreted to lie above a complex magma reservoir system. When magma rises to fill the reservoir system, the increased pressure inflates the summit area; when magma drains rapidly from the reservoir complex, especially during certain flank eruptions, internal pressure is relieved and the volcano deflates. Analysis of deformation during these inflations and deflations by elastic models indicates that the magma reservoir system may be about 2 to 4 km below Kilauea's summit region (Mogi, 1958; Eaton, 1962).

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An electromagnetic sounding survey by Jackson and Keller (1972) defined a boundary between zones of contrasting resistivity at a depth of 900 to 2000 meters below the summit area of Kilauea. The resistivity of the upper zone is 10 to 30 ohm-m, that of the lower zone about 2 ohm-m. The boundary has the form of a broad subsurface dome beneath the southwestern edge of Kilauea caldera, whose apex coincides approximately with an area in which ground deformation is frequently centered and one in which shallow caldera earthquakes are concentrated (Koyanagi and Endo, 1971; Koyanagi and others, 1972). Jackson and Keller considered the possibility that the zone of low resistivity might be molten magma. However, because elastic modeling of the deformation data suggests that the reservoir complex is deeper than the 900-m apex of the resistivity boundary, they concluded that the low-resistivity zone was more likely to be saline groundwater domed into a hydrothermal convection cell driven by heat associated with the underlying magma reservoir.

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Figure 2 diagrammatically depicts the configuration speculated for the magma reservoir and associated hydrothermal convection cell prior to drilling. It was anticipated that information from the drill hole would provide a test of the pre-drilling conceptual model (Fig. 2), as well as other ideas. For example, is some of Kilauea's shallow microearthquake activity related to movement of hydrothermal fluids (see Ward, 1972)? Can the information on subsurface temperatures and ground-water compositions be applicable to geothermal research in basaltic terranes elsewhere, both within and outside Hawaii? In addition, drill-hole information on volcanic structure, rock composition, and physical properties near the inferred summit magma reservoir complex could be valuable in interpreting volcanic behavior. The hole also would provide access for future subsurface studies at Kilauea's summit.

Figure 2 near here

DRILLING PROCEDURES AND OPERATIONS

A contract for drilling the Kilauea Research Drill Hole was awarded to Water Resources International, a drilling company located at Honolulu, Hawaii, with experience in drilling water wells in the State of Hawaii. After considering drilling with air or with a stabilized foam, it was decided to drill using conventional water-base drilling mud because the company's experience showed this drilling procedure was best suited for conditions in Hawaii.

The entire drilling operation was carried out "blind"; that is, fluid losses into permeable zones made it impossible to maintain a return circulation of mud to the surface. During actual drilling, water consumption ranged from 38,000 to 114,000 liters per day. A total of 4,500,000 liters of water was used during, which had to be transported 30 km from the nearest water supply. This water was combined with approximately 400,000 kg of bentonite clay to form a high-viscosity, low-density drilling mud.

It had been planned to recover core from most of the interval drilled. A heavy-wall coring barrel with a capacity for recovering up to 20 meters of 9-cm (3.5-inch) core per run was selected on the basis of its successful use on the Deep Sea Drilling Program. Without mud circulation, however, it became necessary to change to a shorter coring barrel with smaller outer diameter. Furthermore, the diamond bits lasted for an average of only seven meters of core drilled. The great amount of time required for coring operations and poor diamond-bit life, led to such high cost that the plan to cut nearly complete cores had to be abandoned. Only occasional cores were cut for a total of 29 core runs that recovered about 47 meters of core or about 3.7 percent of the total hole depth (Table 1).

Table 1 near here

The noncored intervals were drilled with standard rock bits with carbide insets on the cutting edges ("button" bits), which provided much more rapid penetration than the diamond bits. Drilling rates ranged from as low as 1 meter per hour in the dense sections to as high as 60 meters per hour in loose, porous zones. The penetration rate was recorded continuously during drilling, and subsequent comparison of drilling rates with the porosity of recovered cores indicated a good correlation. Bit life averaged 150 meters except for the last 150 meters of the hole, where increasing temperatures and denser rocks apparently shortened the life of the bit.

Table 1. Inventory of 9 cm (3.5-inch) core recovered from the Kilauea research hole (total depth[+], 1,262.0 m).

Date	Core Run[*]	Depth[+] (m)	Core Recovered (m)	Percent Recovery	Depth of Sidewall Cores[‡] (m)
April 6, 1973	1 and 2	12.8 - 14.3	1.1	72.0	10.7 (ash)
7	3 and 4	25.3 - 28.1	1.1	41.1	
8	5 and 6	28.1 - 31.3	2.2	70.5	34.4 (ash)
9	7	41.2 - 44.5	1.4	40.9	
10	8 and 9	82.6 - 87.1	2.2	49.0	101.8
11	10	115.6 - 117.7	1.1	51.4	
12	11	155.1 - 158.4	1.8	52.7	167.6 178.3 (ash) 192.3
13	12	200.4 - 200.6	0.1	42.8	
15	13	251.6 - 252.8	0.2	12.5	272.2 272.8 274.0 274.6 275.8 291.4 299.9
May 1	14	324.2 - 327.1	2.7	92.6	
5	15	387.5 - 390.6	3.0	98.0	
6	16	419.1 - 422.1	3.0	100.0	
7	17	456.6 - 459.6	3.0	100.0	
8	18	489.2 - 492.2	3.0	100.0	
9	19	521.4 - 524.4	3.0	100.0	
10	20	553.3 - 556.3	3.0	100.0	
15	21	596.9 - 599.9	3.0	100.0	
21	22	646.9 - 649.2	1.2	53.3	
23	23	705.8 - 708.7	1.6	53.7	
26	24	795.7 - 797.1	0.2	17.8	
30	25	823.6 - 826.7	1.6	54.0	
June 1	26	895.5 - 898.5	2.9	95.0	
23	27	943.7 - 946.7	1.2	40.0	
27	28	1070.6 - 1071.6	0.3	28.6	
July 8	29	1255.7 - 1258.6	2.9	97.9	
Total			46.8		

*Runs 1-14 used a 20-m-capacity coring barrel; runs 15-29 a shorter coring barrel; 3-m capacity.
+Depth relative to derrick floor, approximately 3 m above ground surface.
‡Schlumberger 2.5-cm (1-inch) coring plugs fired by explosive charges.

Drilling on an 18 hour per day basis started on April 6 and continued until the end of May. A down-interval of 6 hours per day allowed the bottom-hole temperature to be measured. Later, the daily down-interval was eliminated in favor of more efficient scheduling of drilling operations, and bottom-hole temperature measurements were made only during interruptions in the drilling. The nominal diameter of the drill hole was 20.0 cm, but by the time a depth of 315 meters had been reached, some problems with caving were met. The hole was then reamed to a diameter of 53 cm and a casing of 35.6-cm diameter installed. This casing was squeeze-cemented from the bottom, and later grouted from the top when it was found that most of the cement injected during squeezing had spread into the rock near the base of the casing instead of rising along the outside of the casing. From the casing seat at 315 meters to the bottom of the hole, the walls of the borehole appeared to be stable, and no additional casing was needed.

Drilling continued, with minor interruptions caused by shortages of supplies, such as mud, water, and drilling pipe until July 9, when a depth of 1262 m had been reached. Because bit life had shortened to only 30 meters, it was thought that bottom-hole temperature might be rising rapidly. Measurements confirmed this, and it was decided to terminate drilling at 1262 m in order to evaluate drill-hole information collected to date before trying to drill into rock with higher temperature.

DESCRIPTIONS OF CORE SAMPLES

Although core recovery for many of the 29 runs was fair to excellent, the total amount of core recovered was small (47 m, or about 3.7 percent of the total hole depth) as shown by core intervals and recovery given in Table 1. Because no mud circulated back to the surface during drilling, no cuttings were returned. Piston-type sidewall coring was attempted in order to augment the lithologic sampling in the upper 300 m of the hole. The sidewall coring levels were chosen to sample a variety of physical properties indicated by geophysical logging and to sample the section between the core runs. The attempt was largely unsuccessful. Only 13 of the 2.5-cm (1 inch) coring plugs fired by explosive charges recovered in-situ material (Table 1).

Systematic petrographic and chemical studies of the cores are pending. Although the sampling is undoubtedly biased toward the more competent rocks, some generalizations can be made from megascopic observations of the available core. The entire hole is in basalt, but three broad lithologic zones appear to be represented in the depth intervals 0-300 m, 300-600 m, and 600-1,262 m.

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The uppermost 300 m appears to be composed mainly of thin pahoehoe flows characterized rather uniformly by about 20-45 volume-percent vesicles and a few phenocrysts. Most of the rocks have less than 2 percent olivine phenocrysts; a few samples contain as much as 5 percent olivine, and even fewer contain 10 percent plagioclase phenocrysts. In general, the core recovered is much like the exposed prehistoric lavas of the Puna Volcanic Series in the wall of Kilauea caldera (Stearns and Macdonald, 1946, p. 193).

The side-wall-coring attempts were made in the upper 300 m of the hole at depths chosen on the basis of geophysical-log properties that might represent ash zones: large hole size where drilling had been rapid, low resistivity, high apparent hydrogen content, and low apparent bulk density. The ground surface at the drill site is underlain by about 9 m of unconsolidated to weakly indurated ash and volcanic rubble. A plug was recovered from the surface ash at 11 m (the drill collar was about 3 m above the ground). Another plug obtained from a 2.5-m thick zone at depth of 34 m consists of fine- to medium-grained ash. Its thickness and depth suggest that it could be the Uwekahuna Ash, a unit found low on the northwest caldera wall (Powers, 1948, p. 280-284). An ash zone about 6 m thick was sampled at a depth of 178 m. It is tempting to correlate this zone with the widespread Pahala Ash that occurs at elevations as high as about 670 m above sea level at Hilina Pali, 10 km south of the drill hole. If this correlation is valid, the lavas underlying this ash in the drill hole would be expected to correlate with the Hilina Volcanic Series, which contains numerous ash interbeds (Stearns and Macdonald, 1946, p. 191). All of the other sidewall cores consist of fragmented, partly glassy vesicular lava, most of it probably representing crushed pahoehoe crusts.

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The interval between 300 and 600 m, sampled in core runs 14 through 21 (Table 1), is made up of basalt generally coarser grained and more crystalline than that higher in the hole. Core samples are most commonly aphyric, nearly holocrystalline, and contain slightly greater proportions of megascopic groundmass plagioclase and Fe-Ti-oxides than higher in the hole. The vesicularity of samples is highly varied, ranging from dense rock with only a few percent vesicles less than 1 mm in diameter to varieties in which vesicles as large as 3 cm make up as much as 40 percent of the rock. Some continuous cores show clear gradations from low to high vesicularity, apparently preserving chilled margins of thick, ponded pahoehoe flows or sills. In general, the rock in the 300-600 m interval is more competent than the rock above or below. Some of the core runs, most notably numbers 17 and 19, yield continuous solid core 2 m in length. All runs in this interval were characterized by core recovery not less than 92 percent. The average drilling rate for this interval was slower than that for the first 300 m.

Of particular significance is the first appearance at 488 m of zeolites and calcite partially filling vesicles (core run 18). Data from geophysical logging discussed below indicate that the standing fluid level in the hole is at about the same depth, 488 m. The first occurrence of zeolites at this level is consistent with this fluid level representing the local water table. Diverse crystal habits suggest that several zeolites are present, but these minerals have not yet been studied in detail.

Although less than 2 percent of the bottom half of the hole (600-1,262 m) was cored, the lithology of this interval seems distinct from that of the two overlying zones. In general, the core is slightly darker, locally has a greenish cast, and exhibits virtually no megascopically distinguishable phenocrysts. The bottom half of the hole seems to be composed of alternating thick and thin flows, including at least some aa. Core run 27, for example, recovered mainly rubbly material of the top or bottom of an aa flow.

The densest-appearing rocks recovered were in the bottom half; these fine-grained, essentially nonvesicular rocks may represent chilled zones of sills or thick flows. Perhaps coincidentally, the deepest core recovered (core run 29, Table 1) is also the least vesicular and the only one from below present sea level, which is 1,102 m below the drilling platform. Although this core shows no obvious petrographic or other features typical of submarine lavas, we cannot entirely dismiss the possibility that this dense rock was quenched under relatively high hydrostatic pressure with little attendant degassing.

The core from the 600-1,262 m interval contains a greater variety of secondary minerals than higher cores. In addition to zeolites and calcite in minor amounts, some vesicles and fracture surfaces contain chlorite, montmorillonite(?), opal, chalcedony(?), and fluorite(?) coated with quartz. Much of the rock in core 26 (895-899 m) is amygdaloidal. Although there is greater diversity of secondary minerals in rocks from the bottom half of the hole, available macroscopic and microscopic evidence suggests that the degree of alteration does not appear to increase progressively with depth. Rather, the extent of alteration in individual samples appears to be largely determined by the original fabric, vesicularity, and fracturing of the rock.

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TEMPERATURE MEASUREMENTS

Temperature measurements made both during and after drilling are essential in evaluating the possible presence of a hydrothermal system. Bottom-hole temperature measurements were made frequently during the course of the drilling, whenever operations were interrupted for a few hours so that the bottom-hole temperature could stabilize. These temperatures were recorded by 3 to 6 maximum-reading thermometers attached to a short length of drill pipe lowered to the bottom of the hole on the sand line and permitted to stabilize for 30 minutes to an hour. Coincidence of readings on a majority of the thermometers was accepted as evidence that the thermometers had not shaken down during their return trip to the surface.

Beginning on May 30, and continuing until August 25, continuous temperature logs were run at intervals using a wire-line logging system and a down-hole thermistor probe. Maximum values recorded simultaneously with the thermistor probe and the maximum-reading thermometers generally agreed to within ±2°C. Figure 3 summarizes some of the temperature measurements made during and after drilling.

The temperature profile obtained in the Kilauea research drill hole, like those of many hydrothermal systems, is complex. The prominent features are:

(1) An essentially isothermal interval between the surface and 488 m depth;

(2) A rapid rise in temperature between 488 m and 732 m;

(3) A decline in temperature between 732 m and 976 m;

(4) An increasingly steep rise in temperature between 976 m and the bottom of the hole, 1262 m.

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The large amounts of water injected into the rock around the borehole during drilling (4,500,000 liters at a temperature of 16 to 20°C) could possibly lead to long-term disturbance of the natural temperature profile, particularly if some intervals accepted significantly more of the drilling fluid than other intervals. Twelve temperature logs were run during the interval between July 12 and August 23, using the thermistor probe; four are shown in Figure 3. These temperature profiles show how the in-hole temperature changed as the thermal disturbance due to drilling dissipated. In view of the amount of thermal disturbance that might be expected from the quantity of drilling mud injected, it is noteworthy that all intervals of the borehole appear to have approached close to equilibrium temperatures by the time of the final temperature measurement. Extrapolation of the curves of bottom-hole temperature with time indicate that the bottom-hole temperature will not exceed 140°C with complete thermal recovery.

Figure 3 near here

Temperature measurements made in a single drill hole do not provide a unique determination of the heat flow in the vicinity of the hole because the horizontal component of heat flow is not determined. These temperature data do place limits on the amounts of possible heat flow. For example, the possibility that the temperature profiles shown in Figure 3 are the result of steady-state flow without convection is slight. Reversals and rapid changes in gradient almost certainly require convective transfer of heat or transient conductive transfer.

A minimum estimate of the steady-state heat flow can be obtained if the thermal conductivity of the rock is known over intervals of maximum thermal gradient. The thermal gradient at the bottom of the hole is 0.37°C/m. Measurements of thermal conductivity have not yet been made on core samples, but assuming a reasonable value for the thermal conductivity of porous basalt, conductive heat flow would be about 25 microcalories per square centimeter per second. Similar high rates of heat flow could be computed for the top and bottom of the zone between 488 and 707 m depth. The true heat flow may actually be higher if the transfer is in part convective, or if the flow is not entirely vertical.

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GEOPHYSICAL LOGGING

In addition to the borehole temperature measurements, other physical measurements were made in the borehole using conventional well logging methods (Table 2), which provide a relatively complete suite of information about the rock around the borehole, and make up the primary set of data from the drilling project. The cores recovered represent only a small sample of the section, and are probably biased towards the more competent rock intervals, but they provide a basis for correlating the physical properties measured with the logs with lithologic character of the rocks penetrated by the borehole.

The quality of the logging data was good for most sections of the hole, although large variations in hole diameter in the uppermost 300 meters caused some problems with the response of the sidewall logging devices (gamma-gamma density, neutron porosity, and magnetic susceptibility).

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In this brief report, only certain salient features of the logs are discussed. Figure 4 contains three 92 meter (300 ft) sections of the well logs for zones where significant changes in the average values of physical properties of the rocks are believed to take place. In most logs, the parameters show large variations in value within short intervals, suggesting distinct changes in the character of the rock. Superimposed on these abrupt changes are less obvious changes in the average values.

Recorded resistivities are high in the section above 488 m and significantly lower below that depth (Fig. 4). The 488-m level is the lowest level to which the fluid in the borehole has dropped and probably is the local water table. Progressively lower average resistivities with depth are noted in the three intervals shown (Fig. 4).

Values of porosity from the neutron-porosity log range from less than 2 to 35 percent. The scale shown, however, is based on a limestone matrix and may need to be reivsed after calibration with porosity measurements of the core samples. These data are necessary for determining pore-water resistivities from the resistivity log and for studying the degree of water saturation in the section above the water table. When cross correlated with the density and sonic logs, values for average grain density and matrix velocity can be obtained.

Table 2 and Figure 4 near here

Bulk densities, from the gamma-gamma log, vary from 2.3 to 3.0 gm/cm^3 and correlate well with porosity in the intervals shown (Fig. 4). The sonic interval transit time also is related to porosity. It is affected differently by the matrix and fluid characteristics of the rocks, however; unlike the gamma-gamma density log, the log of sonic interval transit time does not show one-to-one correlation with the porosity log (Fig. 4).

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Table 2. Geophysical borehole measurements in the research drill hole at Kilauea. The magnetic logs were made with equipment developed by the U.S. Geological Survey; other logs were made by the Schlumberger Well Surveying Corp. For description and information on Schlumberger logs, see Schlumberger Manual (1972) or Pirson (1963).

Type of Log	Date Run	Logged Interval (m)
Sidewall neutron porosity	4/16/73	0 - 322
Sidewall neutron porosity	4/20/73	0 - 322
Sidewall neutron porosity	6/3/73	315 - 936
Sidewall neutron porosity	7/9/73	884 - 1248
Induction-electrical log-gamma ray	4/20/73	0 - 322
Induction-electrical log-gamma ray	6/3/73	314 - 936
Induction-electrical log-gamma ray	7/9/73	458 - 1247
Gamma-gamma density	4/16/73	0 - 322
Gamma-gamma density	4/20/73	0 - 322
Gamma-gamma density	6/3/73	313 - 936
Gamma-gamma density	7/9/73	884 - 1244
Borehole compensated sonic	6/3/73	315 - 934
Full waveform display sonic	6/3/73	314 - 933
Magnetic susceptibility	6/20/73	314 - 1128
Vertical magnetic field intensity	6/20/73	314 - 1128

The magnetic susceptibility log reflects the distribution of ferromagnetic minerals, in these rocks primarily magnetite. The average magnetic susceptibility of the section between 488-518 m is more than three times that of most of the other sections logged. The vertical magnetic field intensities in this interval also are large. The lack of a one-to-one correspondence between the vertical magnetic field intensity log and the magnetic susceptibility log, noted in many sections of the hole, indicate that these rocks exhibit large variations in the ratio of remanent to induced magnetization.

A key objective of the logging program was to determine the variation in the salinity of the pore waters with depth in the hole. The basis for such a determination rests on an empirical relation between the resistivity of a rock, ρ_r and the resistivity of the contained water, ρ_w, which in turn is a function of the concentration and mobility of the dissolved salts (Pirson, 1963)

$$\rho_r = a\rho_w \phi^{-m} \qquad (1)$$

where ϕ is the volume fraction of water in the rock (water-filled porosity) and a and m are empirically determined parameters that depend on the pore/interstice distribution within a given type rock.

Note to typesetter: r and w subscript; -m superscript

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No systematic changes in apparent resistivity of the pore water were recognizable for data from the interval between 488 and 1189 m. Near the 1189-m level, however, a decrease in ρ_w is evident, and this decrease becomes more pronounced toward the bottom of the hole. For a single-salt-solution of sodium chloride, the resistivities at the temperatures observed in the hole would be equivalent to a concentration of about 5,000 ppm for fluid in the upper interval and as much as 30,000 ppm for the fluid at the bottom. No samples of formation water were obtained in the borehole, despite several attempts made to use the Schlumberger wire line testing equipment for this purpose. Samples from the top of the fluid column have been and are being collected periodically in the hope of ultimately recovering formation fluids flowing into the hole.

PHYSICAL MEASUREMENTS ON CORES

More than 400 plugs, 2.5-cm in diameters, were cut from the 29 cores recovered during drilling. Physical measurements made on these samples provide a check on the empirical relations used to convert the quantities usually measured in geophysical logging to other parameters describing the rock. Measurements partially completed in the laboratory include porosity, density, fluid permeability, and electrical resistivity. Measurements scheduled to be completed in the near future include thermal conductivity and diffusivity, magnetic susceptibility, remanent magnetization, and acoustic wave speed and elastic moduli. The bulk of the core is stored at the Hawaiian Volcano Observatory and available for further studies.

DISCUSSION OF THE RESULTS

Even though a great deal remains to be done in detailed descriptions of the recovered core material and interpretation of the various borehole logging surveys, a number of results are apparent. On the one hand, it is highly gratifying that the information obtained from the borehole appears generally to substantiate the models derived from the various geophysical surveys carried out around the summit of Kilauea Volcano. On the other hand, it is clear that the temperatures encountered in the borehole are not high enough for an economically viable geothermal reservoir, even if production of geothermal energy were permitted.

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The temperatures encountered can be explained either as the result of transient heat flow from fairly recent intrusions or as the result of a hydrothermal convection cell. Critical evidence is the existence of a water table at 488 meters depth in the hole, an elevation of 614 meters above sea level. A simplified groundwater model for oceanic islands assumes that the water table is in hydrostatic equilibrium, the elevation of the water table above sea level being compensated by the depression of the salt water-fresh water interface below sea level. Because the density difference between salt water and fresh water is slight, elevation of the fresh-water table is one or two meters for each kilometer distance from the shore line. Then, the higher elevation of the water table only 13 kilometers from the ocean must be caused by some other mechanism. In one possible model, the water table is postulated to be locally uplifted by thermal drive above a magma reservoir in a zone of reduced permeability in the vicinity of the magma body. Another possible model postulates that geologic factors such as dike intrusions, low-permeability, compacted and/or altered ash layers, that are not necessarily related to or caused by a magma reservoir at a shallow level, trap and contain high-level water reservoirs. Hence, the elevation of the water table is caused chiefly by regional hydrogeologic conditions. These two models are not necessarily mutually exclusive, and other models may be postulated. With data available, it is not possible to determine uniquely the nature and cause(s) of the apparently impermeable zone(s) required to maintain the high-level water table in the vicinity of the drillhole.

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Permeabilities measured on plugs from the core samples obtained are very low. The samples doubtless are biased toward competent and impermeable units. However, the resistivity logs yield information about the in-situ permeability of the penetrated rocks. The resistivity measured with the short-normal device is considerably larger than that measured with the induction device (Fig. 4). The amount of this difference or "departure" between these two types of resistivity measurement provides an indication of the extent of invasion of permeable wallrock around the borehole by mud filtrate. In most sections of the hole below the water table, the amount of departure between the two resistivity logs gradually diminishes with depth, implying a corresponding decrease in permeability.

The general reduction in permeability toward the hole bottom is of considerable importance in evaluating the geothermal potential of the volcanic edifice. If all the lavas were as permeable as the lavas above the water table, heated groundwater would move quickly through the rock, removing the heat from a magma reservoir too quickly for the temperatures required for an economically viable system to build up. Alteration in the lavas below the water table may represent the action of the self-sealing believed to take place in geothermal reservoirs; that is migrating thermal water causes alteration, reducing the permeability of the rock and trapping the thermal waters in a reservoir in which the temperature can build up to economic levels.

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Considering the steep temperature gradient at the bottom of the hole, it is tempting to speculate about what might be discovered if the hole were deepened. It is possible that temperatures suitable for production of high-energy steam might be encountered. It is even more tempting to speculate on the feasibility of deepening the hole to intersect the magma reservoir supplying the surface activity of Kilauea Volcano, although it is not certain that existing drilling techniques would permit drilling under conditions of such high temperatures. For the present at least, the core and geophysical logging data from this test hole provide key information in refining our understanding of strucutre and behavior of Kilauea Volcano.

ACKNOWLEDGMENTS

We wish to thank the following individuals who have helped our study in various ways: for his cooperation, encouragement, and patience, G. B. Harry, Superintendent, Hawaii Volcanoes National Park; for valuable assistance during the drilling operations, Jerry Crosthwaite, U.S. Geological Survey, and J. J. and C. K. Skokan, Colorado School of Mines; for reducing some of the geophysical logging data, Floyd Gray and Daniel Laird, San Mateo Community College, D. W. Silsbee, Amherst College, and Josue Delgado, San Jose High School; for helping prepare the illustrations and typescript, Marie Onouye, M. K. Sako, R. T. Holcomb, and J. C. Forbes, U.S. Geological Survey, Hawaiian Volcano Observatory; for critically reading an earlier version of this report and constructive suggestions for its improvement, D. B. Jackson and R. O. Fournier. U.S. Geological Survey. This study was supported by Grant No. GI-34993, Program for Research Applied to National Needs (RANN), National Science Foundation.

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CAPTIONS

Figure 1. Index map showing locations of drill hole in relation to major structural features of Kilauea Volcano (from Zablocki and others, 1974, Fig. 1).

Figure 2. Schematic section through Kilauea Volcano showing the drill site relative to the location of a magma reservoir inferred from ground-deformation and seismic data. The convective hydrothermal system shown above the magma reservoir diagrammatically illustrates the conceptual model prior to drilling (from Keller and others, 1974, Fig. 2). The approximate position of the water table in the Kilauea summit area is estimated from drill-hole data and from surface resistivity surveys (Hawaiian Volcano Observatory, unpublished data).

Figure 3. Depth-temperature profiles for the Kilauea drill hole. Dashed curve links bottom-hole temperatures measured between drilling shifts (generally about 6 to 8 hours after drilling unless otherwise indicated): circles, readings by maximum-reading thermometers; dots, readings by thermistor probe. Solid curves are selected post-drilling temperature profiles obtained with continuously recorded thermistor probe (from Zablocki and others, 1974.

Figure 4. Geophysical borehole logs for three selected sections of the Kilauea drill hole (from Zablocki and others, 1974, Fig. 2). For the cored intervals: T.M.-thick, massive flows and/or sills; T.P.-thin pahoehoe flows.

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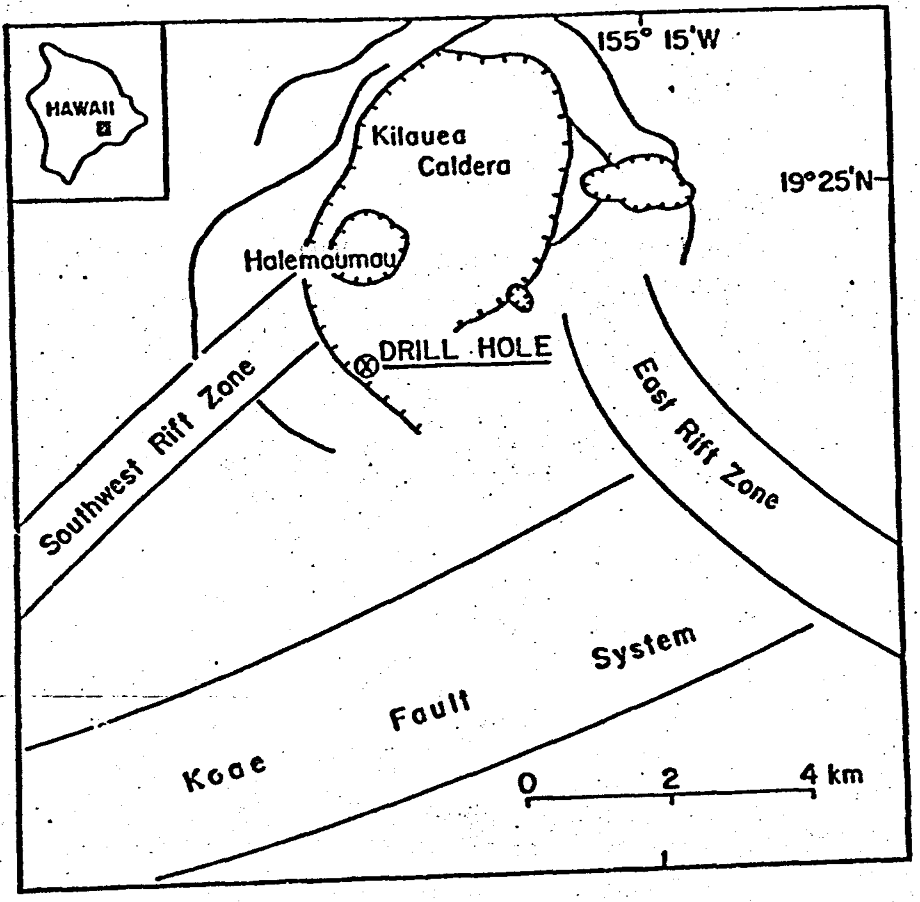
HAWAII
155° 15'W
Kilauea
Caldera
19°25'N
Halemaumau
DRILL HOLE
Southwest Rift Zone
East Rift Zone
Koae Fault System
0
2
4 km

FIG. 1

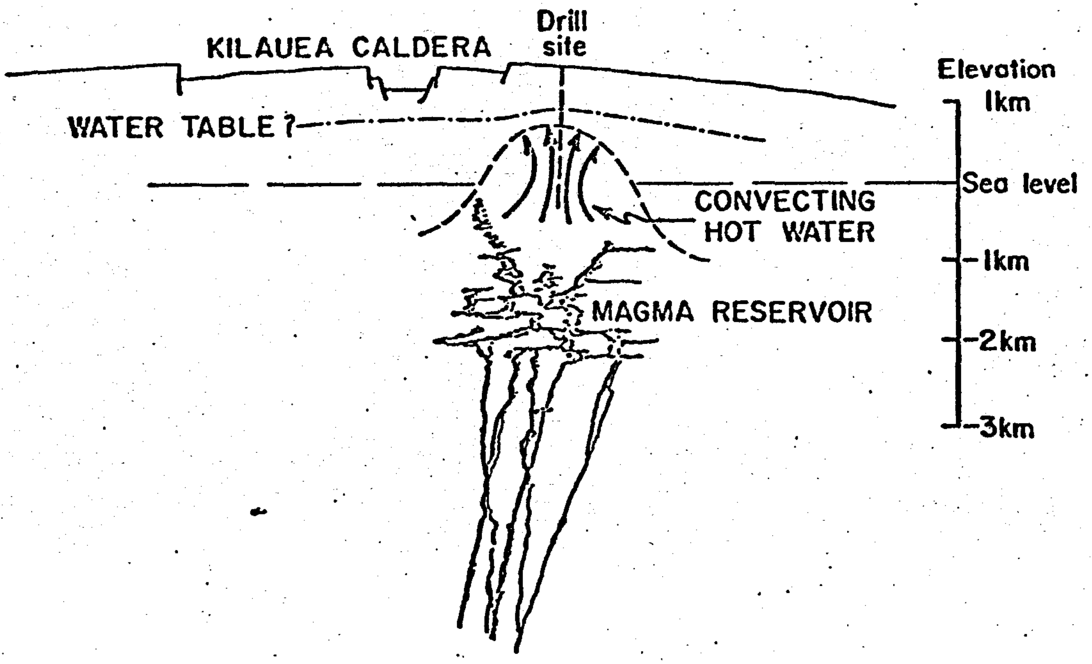
KILAUEA CALDERA
Drill
site
WATER TABLE ?
CONVECTING
HOT WATER
MAGMA RESERVOIR
Elevation
1km
Sea level
-1km
-2km
-3km

FIG. 2

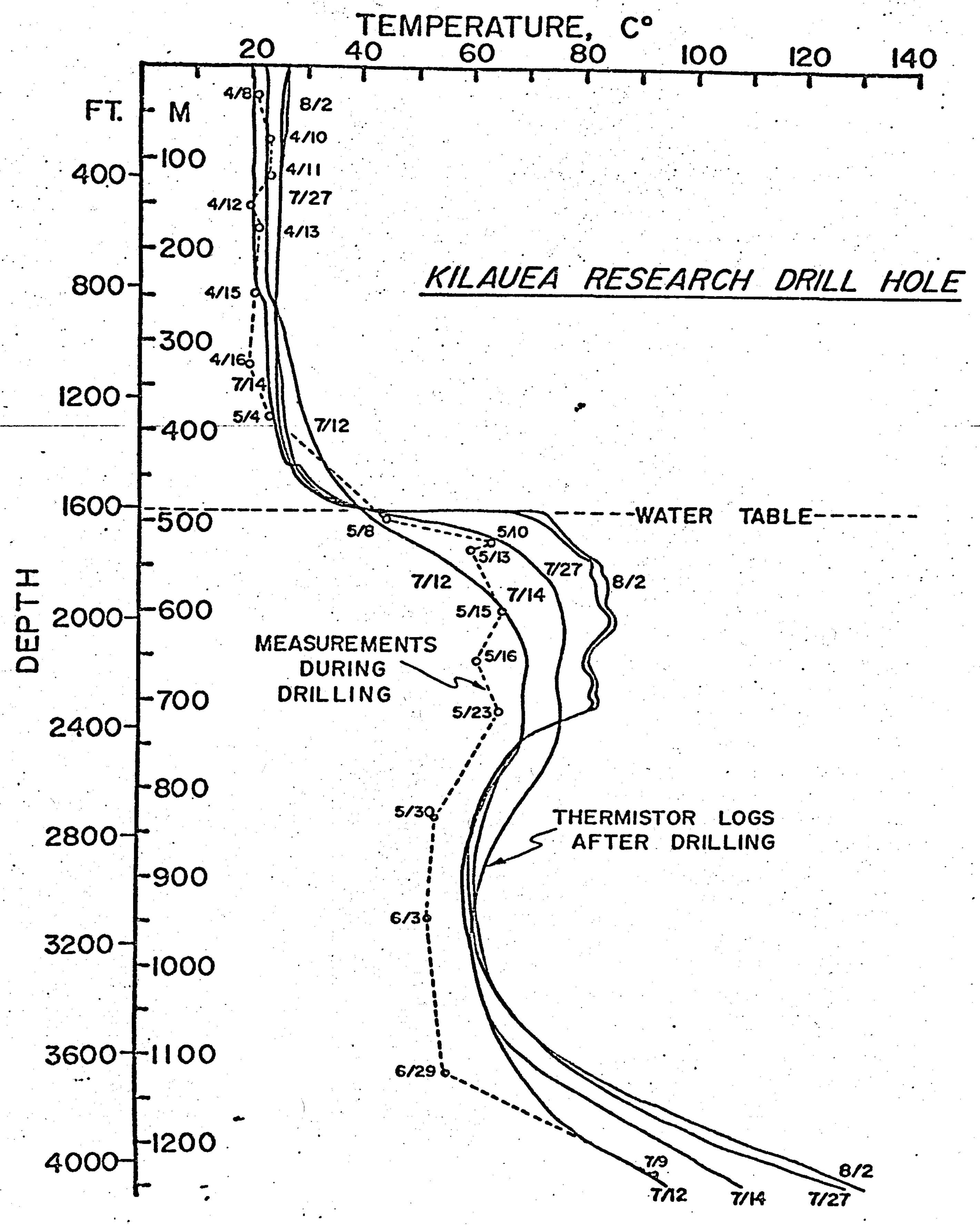
TEMPERATURE, C°
20
40
60
80
100
120
140
FT.
M
DEPTH
100
400
200
800
300
1200
400
1600
500
600
2000
700
2400
800
2800
900
3200
1000
3600
1100
1200
4000
KILAUEA RESEARCH DRILL HOLE
4/8
8/2
4/10
4/11
7/27
4/12
4/13
4/15
4/16
7/14
5/4
7/12
WATER TABLE
5/8
5/10
5/13
7/27
8/2
7/12
7/14
5/15
5/16
MEASUREMENTS DURING DRILLING
5/23
5/30
THERMISTOR LOGS AFTER DRILLING
6/3
6/29
7/9
7/12
7/14
7/27
8/2

FIG. 3

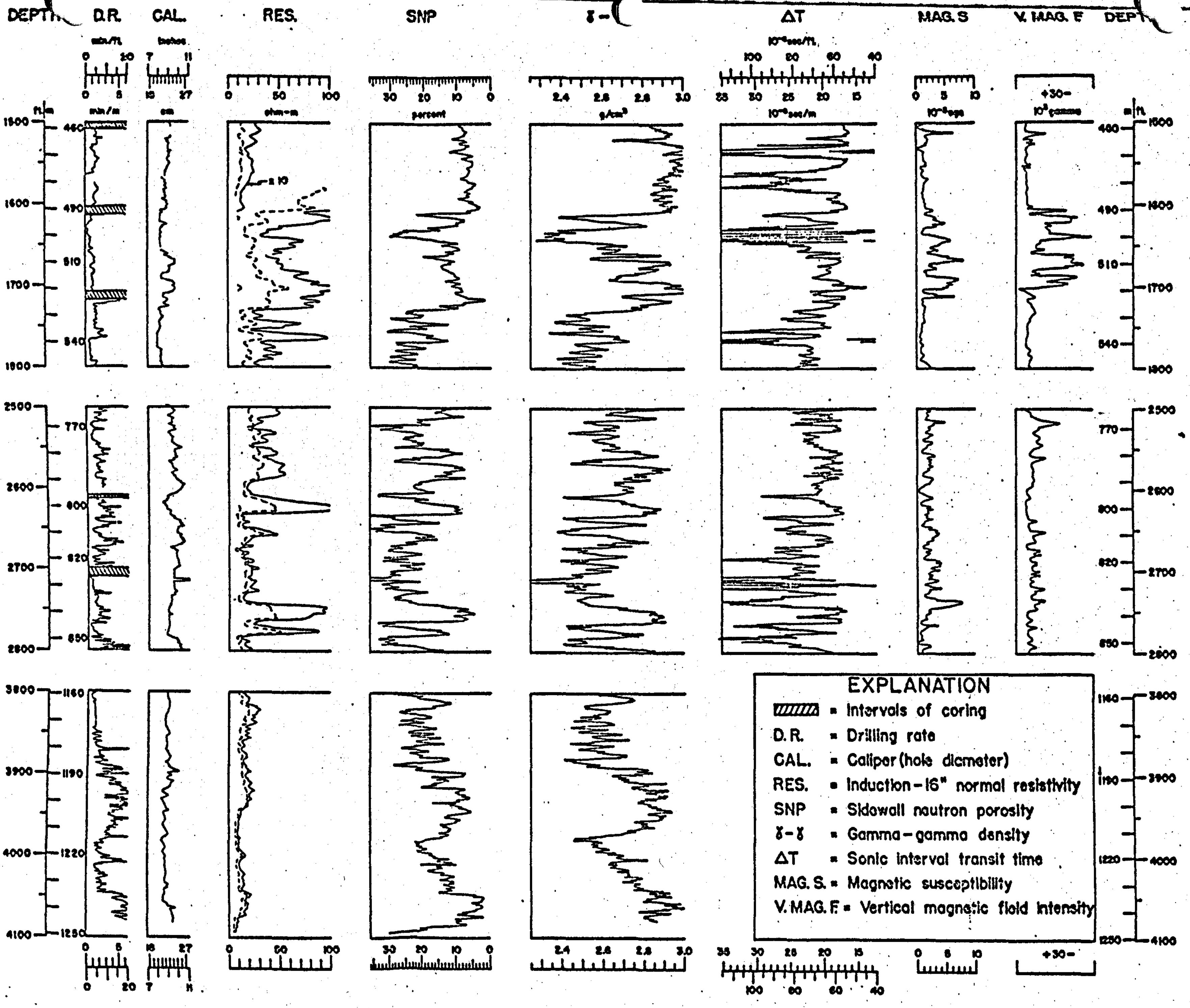
DEPTH
D.R.
CAL.
RES.
SNP
γ-γ
ΔT
MAG. S
V. MAG. F
min/ft
inches
0 10 20
7 11
0 5
16 27
min/m
cm
0 50 100
ohm-m
30 20 10 0
percent
2.4 2.6 2.8 3.0
g/cm³
10⁻⁶ sec/ft
100 80 60 40
35 30 25 20 15
10⁻⁶ sec/m
0 5 10
10⁻³ cgs
+30-
10³ gamma
ft m
1500 1600 1700 1800
460 490 510 540
2500 2600 2700 2800
770 800 820 850
3800 3900 4000 4100
1160 1190 1220 1250
x 10
EXPLANATION
▨ = Intervals of coring
D.R. = Drilling rate
CAL. = Caliper (hole diameter)
RES. = Induction - 16" normal resistivity
SNP = Sidewall neutron porosity
γ-γ = Gamma - gamma density
ΔT = Sonic interval transit time
MAG. S. = Magnetic susceptibility
V. MAG. F = Vertical magnetic field intensity

FIG. 4