DRILLING AT THE SUMMIT OF KILAUEA VOLCANO

George V. Keller

prepared for National Science Foundation

Colorado School of Mines
Golden, Colorado 80401

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Abstract

A borehole has been drilled to a depth of 1262 m beneath the summit of Kilauea Volcano on the island of Hawaii. The purposes were twofold: to obtain engineering information related to the possible occurrence of geothermal energy in a basaltic volcano, and to obtain scientific information about the internal nature and workings of Kilauea Volcano. Because the location of the borehole is within Hawaii Volcanoes National Park, the drilling could not have as its objective the production of steam. Accordingly, the drilling program was carried out in a manner intended to minimize the chance of a steam eruption, and to maximize the chances of gathering scientific information. The fact that the borehole was drilled without encountering any significant difficulties is in itself a measure of success. It was found that the interior of the volcano was not nearly as inhospitable an environment as some people anticipated. In fact, the only difficulties met in drilling were related to the remoteness of the location from normal sources of supply. Although there are numerous occurrences of very hot surface rocks close around the drillsite, the borehole penetrated only cool rocks until the water table was entered, at a depth of 490 meters. From this level to nearly sea level, at a depth of 1102 meters, a complicated temperature profile was observed, with temperatures varying between 60°C and 90°C. The

groundwater in this zone appears to have a salinity roughly equal to that of sea water. It is thought that a convection system exists over this interval. At greater depths, the permeability of the rock is markedly reduced, though the porosity and water content remain high, in the range from 20 to 25 percent. The bottom-hole temperature is 137°C, and the gradient over the last hundred meters of hole is about 400°C per kilometer. If the hole were located in an area where production of geothermal energy could be undertaken, it is possible that production of commercial-quality steam could be obtained by drilling to depths 200 to 300 meters below the present depth. The major question that would have to be answered if steam production were sought would be whether or not permeability exists or could be induced in rocks at these depths.

Introduction

In recent years, the possibility of using geothermal energy as a supplement to more conventional energy sources has received widespread attention. Estimates of the importance of geothermal energy vary widely. Some have suggested that geothermal energy might account for a major fraction of the electrical energy generated at the end of this century, but a much more common view is that geothermal energy is a curiosity, and in the foreseeable future, will fill only a negligible fraction of our energy needs, as it does at the present time. Geothermal steam is used to generate less than one-one thousandth the electrical energy now being used in the United States. Whether this will remain the case, or whether geothermal energy will become an important energy source of fuel depends on the solution or non-solution of a wide range of problems in exploration, exploitation, and environmental impact.

A major difficulty being faced in the current efforts to locate additional sources of geothermal energy is our lack of understanding of their geologic settings. Geothermal reservoirs are thought to be intimately associated with modern volcanism or intense tectonic activity. This has led to the supposition that heat has been supplied to the geothermal system by an underlying magma chamber. The nature of a magma chamber is very poorly understood, inasmuch as no drill hole has penetrated into one, and indirect methods of study such as geophysics, have tended to indicate that reservoirs filled with molten rock are rare, if they occur at all. A major effort may be required to investigate the nature of magma chambers before the geologic controls on occurrence of geothermal systems can be understood.

Assuming that magma chambers do exist at shallow depths in the crust, say from 3 to 10 kilometers depth, the manner in which heat can be transferred to shallower depths is still poorly understood. If heat is transferred from the molten rock by conduction through a frozen shell, the rate of heat flow is very slow because of the low thermal conductivity of solid rocks. It is possible that mass transfer of heat takes place from the magma chamber by evolution of volatile materials, or by adsorption and release of water from the rock into which a magma chamber has been intruded. This latter mechanism has been suggested by several geologists as the explanation for sealed steam reservoirs. In this model, water from the host rock around an intrusive is converted to steam, and in so doing, deposits its mineral content to make an impermeable caprock around an intrusive. Inside the caprock, all the water is converted to steam above its equilibrium temperature with water, and held in place by the caprock. If such "dry steam" fields exist, they would provide an attractive target for development because of their high temperature, and the efficiency of conversion to electrical energy would be relatively high. However, no drilling has yet penetrated into such a supercritical temperature regime.

Beyond such an impermeable caprock, heat transfer to the surface may be by conduction, if rocks are impermeable, or by convection, if the rocks are permeable. When convection takes place, temperature remains high as water rises through the rock, and water containing considerable amounts of energy can be extracted at relatively shallow depths. The most favorable circumstances occur when permeable zones penetrate into high temperature areas, and carry this high temperature to shallow depths.

In some systems the convecting system may rise to the point where the overburden pressure is not great enough to prevent boiling. At this stage, boiling will occur and the temperature will drop. Often, the temperature vs. depth curve will follow the boiling point curve. In other cases the near-surface rocks may become filled with steam at pressures below equilibrium pressure for conversion from steam to water. It would appear that for most geothermal systems now being used for power production, only the upper part of these convection systems has been tapped by drilling.

Kilauea Volcano, on the Island of Hawaii, is the world's most intensively studied and best understood volcano (MacDonald and Abbott, 1970; Stearns, 1966; Stearns and Macdonald, 1947). It is one of the world's most active volcanoes, but the eruptions are usually non-explosive and scientific studies can be carried out safely at close range during all stages of activity (see, for example, a report on the 1967-1968 eruption of Kilauea (Fiske and Kinoshita, 1969). In addition to being intensively studied, Kilauea Volcano also possesses the advantage of being a geologically simple environment, inasmuch as it is composed of volcanic rocks of uniform composition and physical character. For these reasons, Kilauea Volcano is a unique field laboratory for carrying out investigations that would not be feasible elsewhere.

A phenomenon for which Kilauea Volcano may provide a very informative experimental prototype is that of ground water movement in the vicinity of a magma chamber. With the growth of national concern over an energy shortage, interest in geothermal power has greatly expanded. Kilauea Volcano can provide a means for testing some of the physical concepts that have developed about the characteristics of geothermal systems.

Even though Hawaii's volcanoes have been intensively studied, only drill holes can supply the necessary data about subsurface temperature, hydrology, and geology for evaluation of the potential for geothermal power production. The site selected for the research drill hole lies in the Hawaii Volcanoes National Park, and so the energy cannot be exploited. The National Park Service permitted this drilling project because the hole was for research purposes only.

Selection of the Site

The U. S. Geological Survey has operated the Hawaiian Volcano Observatory (HVO), located on the rim of Kilauea Caldera, for many years and has collected a wide variety of data on the behavior of the volcano (see location map, Fig. 1). The most diagnostic information about the existence of a shallow magma reservoir, such as would be needed to supply heat to a geothermal system, appears to come from ground deformation studies that have been carried out in recent years (Kinoshita and others, 1974). Measurements of ground

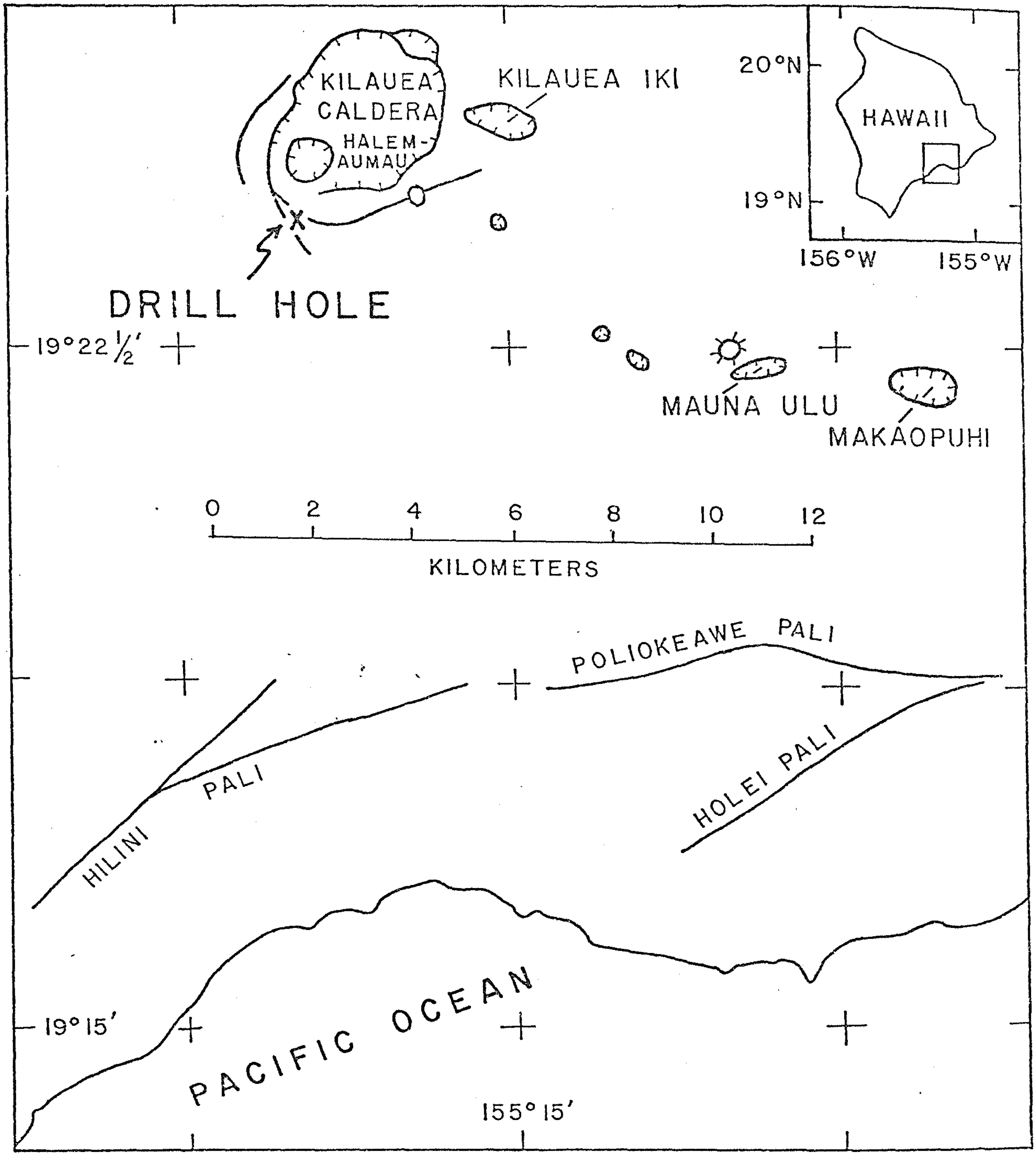

Figure 1. -- Index map showing location of drill hole in relation to major features of Kilauea Volcano.

tilt, elevation changes, and horizontal ground displacements repeated regularly by HVO show that inflation and deflation of Kilauea's summit area are generally centered in and near the southern part of the caldera. The centers of deformation are interpreted to lie above a complex magma reservoir system. When magma rises from great depth to fill this reservoir system, the increased pressure inflates the summit area. Similarly, when magma drains rapidly from the reservoir complex, during most summit and flank eruptions, internal pressure declines, and the volcano deflates. Analysis of deformation during these inflations and deflations using elastic models indicates that the magma reservoir system is probably about 2 to 4 kilometers below the surface (Eaton and others, 1971).

An electromagnetic sounding survey by Jackson and Keller (1972) defined a strong resistivity anomaly directly above the center of inflation associated with deformation during recent volcanic activity (Fig. 2). This anomaly consists of a region of low resistivity with a top surface lying approximately 1 kilometer below the ground surface. Jackson and Keller considered the possibility that the zone of low resistivity might be molten magma, but in view of the fact that deformation studies suggested that the top of the magma reservoir is significantly deeper than 1 kilometer, they concluded that the zone of low resistivity can best be interpreted as representing a mass of rock saturated with hot water. Heated water above a magma reservoir would likely form a convection cell.

Seismic activity in the area provides additional support for

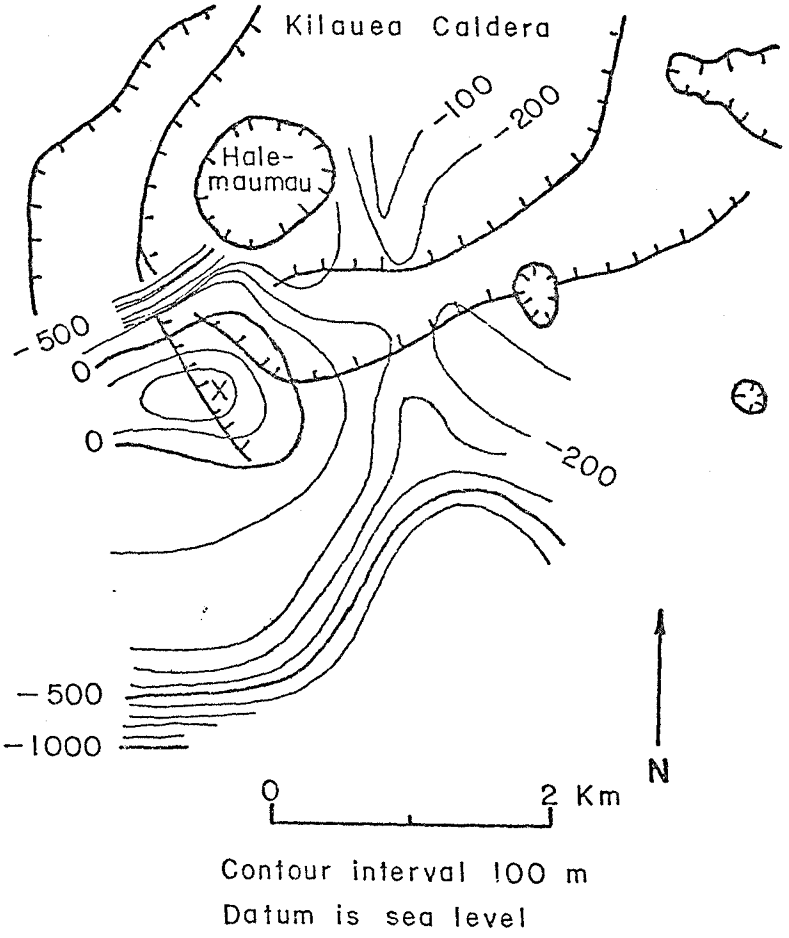

Figure 2.-- Contour map of the top of a low resistivity zone beneath the southwestern margin of Kilauea caldera (after Jackson and Keller, 1972, Fig.7). Contours are in meters relative to sea level. The drilling platform, point X, lay at 1,102 m above sea level.

this interpretation. Kilauea Volcano exhibits high seismicity, and most of the seismic activity is associated with specific fault zones on the volcano and with movement of magma at depth. Certain groups of earthquakes have been observed at very shallow depths, however, and some of these have been concentrated in a zone that lies near the resistivity anomaly and the center of inflations (Koyanagi and Endo, 1969). The data show that this shallow activity, which takes place at depths of a few kilometers,lies on a projection of the deeper loci of activity that are believed to be associated with movement of magma (Fig. 3). Could the shallow activity be associated with movement of fluids other than magma? Ward (1972) has shown that hydrothermal systems do give rise to swarms of micro-earthquakes. It therefore seemed reasonable to test whether the shallow earthquakes at Kilauea might also be associated with the movement of hydrothermal fluids.

Three separate lines of study, deformation, resistivity, and seismicity all support the possibility that a hydrothermal system may be associated with a magma reservoir just south of Kilauea's summit. The accompanying diagram (Fig. 4) illustrates the morphology speculated for the magma chamber and its associated hydrothermal convection cell prior to drilling. The chamber itself may consist of a network of sills and dikes, perhaps formed at the boundary between the surface of the submarine volcanics, which are relatively dense and water free, and the subaerial or shallow submarine volcanics, which contain a greater amount of water and are structurally weaker. The top of the magma chamber in this

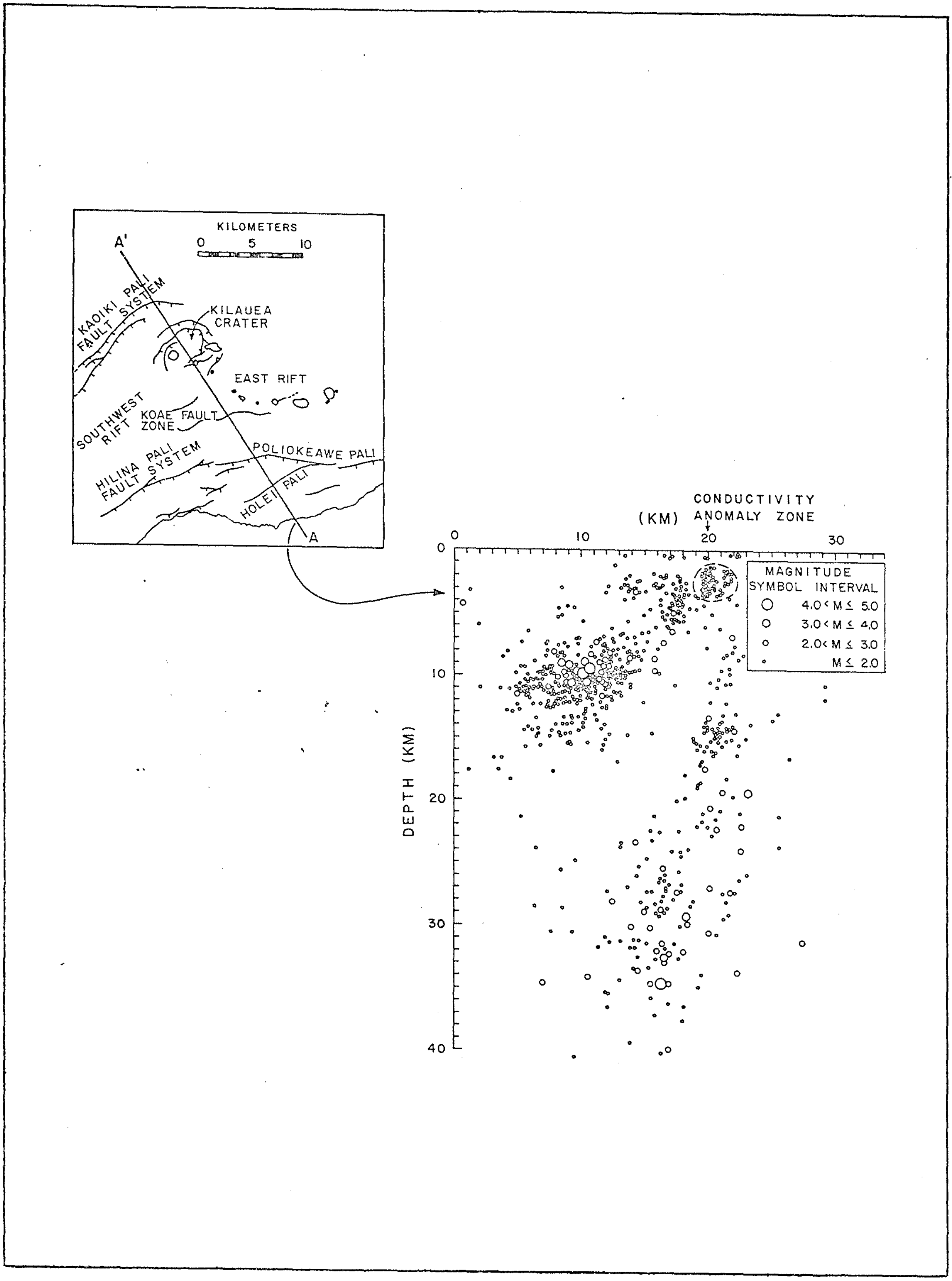

Figure 3. -- Microearthquake locations in plan view and in section through the summit of Kilauea Volcano. Taken from Koyanagi and Endo (1971).

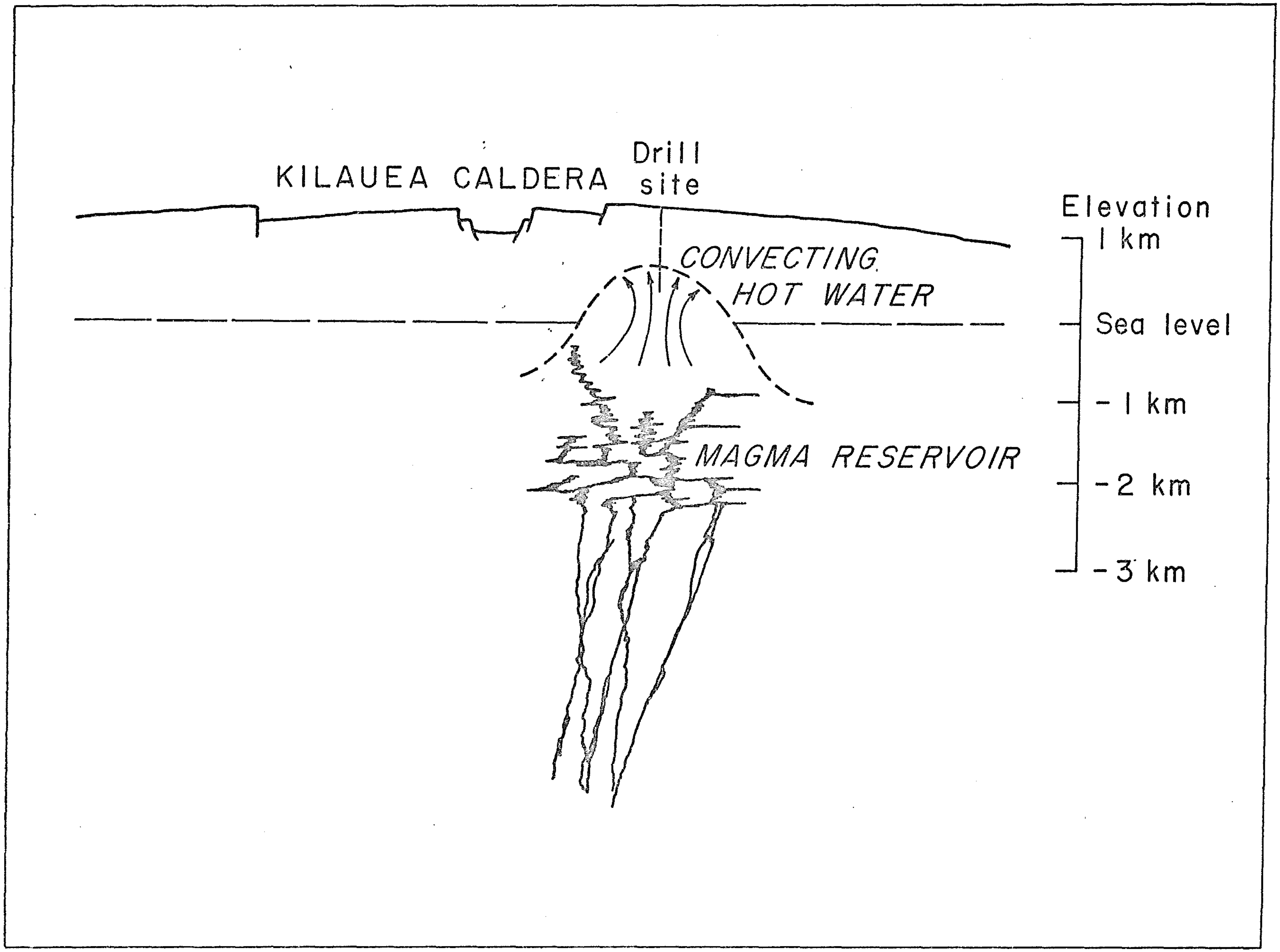

Figure 4. -- Hypothetical cross section through Kilauea Volcano and its near-surface magma chamber, based on information available prior to drilling.

model lies about 1 kilometer below sea level; porous rocks at this depth are the result of subsidence of the volcano. The water in the rock above the magma chamber is heated, and as its density decreases it starts to rise. In this model, it rises for a distance of about one kilometer, and then spreads out horizontally in the rock above the permanent water table, where there is free pore space and less lateral pressure to confine the system. It then percolates downward, cooling and mixing with surface waters as it descends, and ultimately completes the convection cycle.

The Kilauea Research Drill Hole was drilled to test this concept. It was felt that specific information about subsurface temperatures and ground water compositions might be applicable to geothermal research elsewhere, as well as in Hawaii. In addition, drill hole information on volcanic structure and on rock compositions and properties close to the summit magma-reservoir complex would be extremely valuable in interpreting volcanic behavior. Finally, the hole also can provide access for future subsurface studies at Kilauea's summit.

Prior to drilling, an aerial infrared survey was carried out over the summit of Kilauea by Earth Satellite Corporation, under contract to the Colorado School of Mines. The purpose of the survey was to inventory thermal manifestations in the general vicinity of the borehole, and particularly the surface traces of faults that might be intersected by the borehole. The survey was done on the nights of February 14 and 15, 1973, between 12:00 a.m. and 4:00 a.m. using a Daedalus Quantitative Scanning System. An example of the thermal imagery obtained around Halemaumau Crater is shown in Fig. 5. This image is quantized; that is, each color represents a specific 2° temperature band as seen by the scanning equipment on the aircraft. The hottest temperatures, those above 26°C, are shown as red on the image, while the cooler colors indicate areas that are cooler by 2° increments. It is of interest to note that vertical cliffs exhibit high temperatures, suggesting a high vertical temperature gradient near the surface.

Half a kilometer to the south at the drill site, surface temperatures were observed to be uniformly cool, approximately 16°C. The area for some hundreds of meters to several kilometers around the drill site shows this uniformly cool character, which appears to be associated with the presence of a mantle of Keanakakoi and Kilauea Iki ash on the surface of the ground. This lack of surface manifestations of high heat flow at the drill site was later confirmed by drilling, when it was discovered that the low temperatures persisted to a depth of 490 meters.

Drilling

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, located 1.1 km south of Halemaumau Crater (19°23.7' N, 155°17.3' W; Fig. 1), was drilled to a depth of 1,262 m (4,137 ft), measured from the derrick floor located at an altitude of 1,102 m (3,616 ft) above mean sea level.

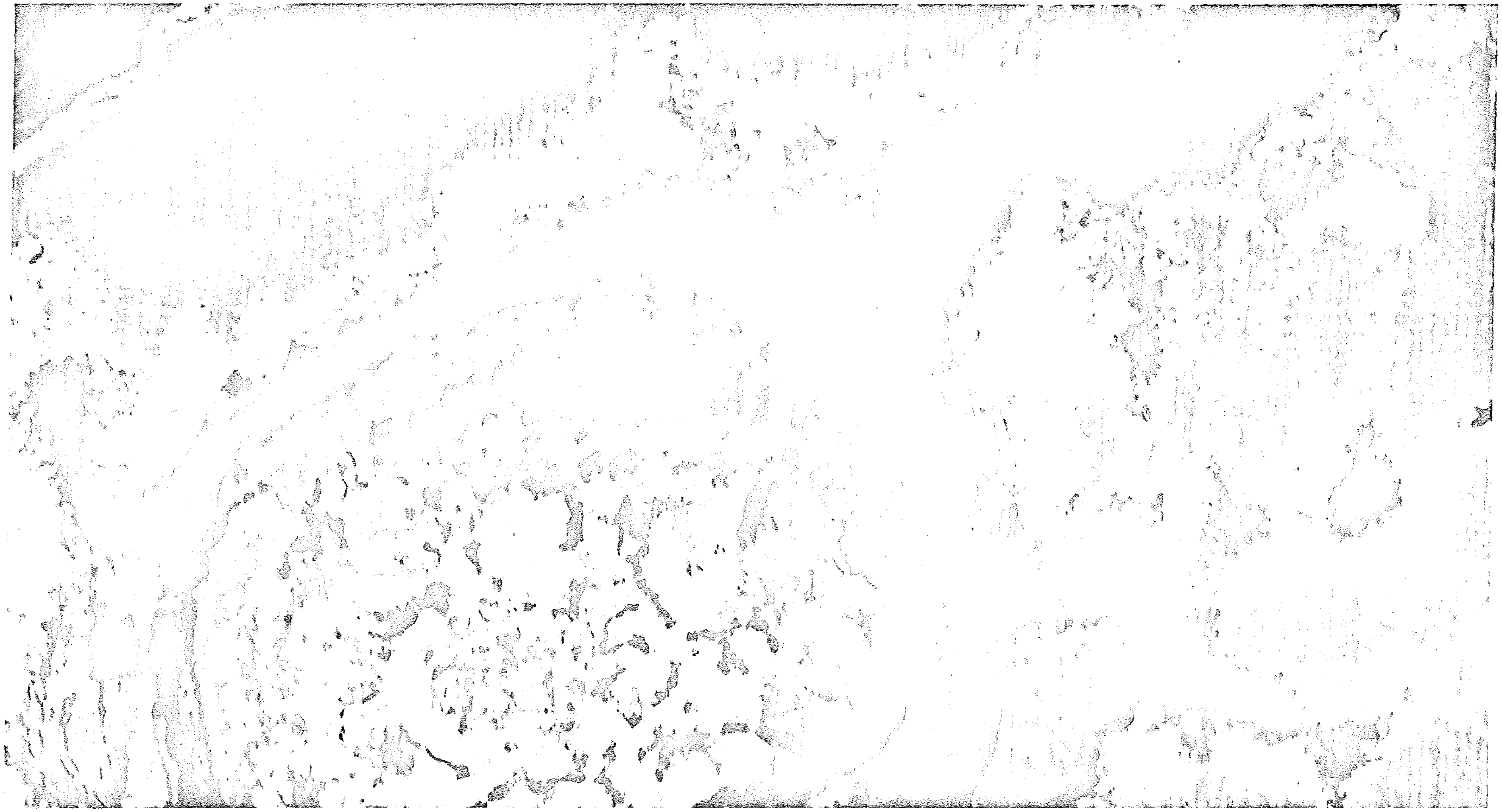

Figure 5. – Infra-red (8-14 μband) image of the area around Halemaumau Crater in Kilauea Caldera. Each color represents a 2° -C temperature band, with red being the hottest, temperatures above 26° C. The circular red feature is caused by the near-vertical walls of Halemaumau Crater. The drill site lies directly south of the Crater, a short distance outside the area covered by this image.

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 giving consideration to drilling with air or with a stabilized foam, the decision was made to drill using conventional water-base drilling mud because of the company's extensive experience with this drilling procedure under Hawaiian conditions.

The entire drilling operation was carried out "blind"; that is, it proved to be impossible to pump drilling mud rapidly enough to maintain a return circulation of mud to the surface. During actual drilling, water consumption ranged from 10,000 to 30,000 gallons per day. The total amount of water used during drilling was approximately 1,200,000 gallons, all of which had to be transported 30 miles from the nearest water supply well. This water was combined with approximately 9000 bags of bentonite clay, to form a high-viscosity, low-density drilling mud.

Initially, it had been planned to recover core from most of the interval drilled. A heavy-wall coring barrel manufactured by Rucker Hycalog was selected, on the basis of the successful use of the same barrel on the Deep Sea Drilling Program. This barrel has a capacity for recovering up to 20 meters of 9-cm (3.5 inch) core per run. However, our inability to maintain mud circulation while coring, combined with the highly fractured nature of most of the rock penetrated resulted in only about 3 meters of core per run. In addition, the endurance of the diamond bits proved to be very limited, with the bits lasting for an average of only seven meters of core recovery. The high cost of coring, measured both in operating time and diamond bit usage, led to the abandonment of a program of nearly complete coring to one in which only occasional cores were cut. Cores were cut on 29 occasions, with the total amount of core recovered being 47 meters, or about 3.7 percent of the total hole depth. To supplement these cores, piston-type sidewall coring was attempted in the upper 300 m of the hole. The attempt was largely unsuccessful, with only 13 out of 60 trials providing recovery of any in-situ material.

Penetration in the non-cored intervals was obtained using standard rock bits with carbide insets on the cutting edges ("button" bits). These bits provided a much more rapid penetration rate than did the diamond bits, with rates ranging from as low as 1 meter per hour in dense volcanics, to as high as 60 meters per hour in the loose, porous volcanics. The penetration rate was recorded continuously during drilling, and subsequent comparisons of drilling rates with the porosity of recovered cores indicated a good correlation between these two quantities. Bit life averaged 150 meters, except for the last 150 meters of the hole, where apparently the increasing temperatures led to the marked shortening of bit life.

Drilling operations started on April 7, with operations being carried on only for 18 hours per day during the following month. A down-interval of 6 hours per day was provided so that bottom hole temperature measurements could be made. Later, the daily down-interval was eliminated in favor of more efficient scheduling of drilling operations, and bottom-hole temperature measurements were made only as opportunities arose during 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 with a diameter of 35.6 cm was 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 at the base of the casing, rather than rising along the outside of the casing. From the casing seat at 315 meters to the total depth of the hole, the walls of the borehole appeared to be quite stable, and no second string of casing was needed.

Drilling continued until July 9, with minor interruptions caused by shortages of supplies, such as mud, water, and drilling pipe. By July 9, a total depth of 1262 m had been reached. Because bit life had shortened to only 30 meters penetration for the last bit used, it was felt that bottom hole temperature might be rising rapidly. This was found to be the case and it was decided to terminate drilling at 1262 m so that the drill hole could be evaluated before rock with higher temperature was encountered.

The deepest holes drilled prior to the Kilauea borehole had been water wells reaching to depths of approximately 1000 feet below the surface. The special equipment for deep drilling, as well as drilling supplies, had to be transported from the mainland, cumstance that caused the cost of drilling to be relatively . The drilling contract was based on an hourly rate for operation of the rig, plus the cost of drilling supplies and rental of ment for deep drilling, including the drill pipe, blowout ter, and accessories. The general breakdown of costs for rilling project is as follows.

A.	Scientific and Management Program (includes EM survey, seismic noise survey and infrared survey)	$80,000
B.	Borehole Logging Program	55,800
C.	Drilling Program	
	1. Mobilization and Site Preparation (includes shipping costs for drilling equipment and supplies)	137,000
	2. Direct Cost of Drilling, excluding coring	344,000
	3. Added Costs of Coring	80,800
	4. Demobilization and Return of Equipment	50,000

Description of Core Samples

ty-nine coring runs were made during the course of the . Although core recovery for many individual runs was excellent, the total amount of core recovered was only , or about 3.7 percent of the total hole depth (Table se no mud circulated back to the surface during drilltings were returned. Piston-type sidewall coring was in order to augment the lithologic sampling in the of the hole. The sidewall coring levels were chosen a variety of physical properties indicated by geophysical [illegible] sample between the core runs. The attempt was [illegible] ssful. Only 13 of the 2.5-cm (1 inch) coring plugs [illegible] sive charges recovered in-situ material (Table 1). [illegible] were examined by geologists at the HVO, and the follow- [illegible] ption of the core samples has been provided by Robert [illegible], Donald W. Peterson, and Robert L. Christiansen [illegible] communication).

[illegible] uppermost 300 m appears to be composed mainly of thin [illegible] flows characterized rather uniformly by about 20-45 volume- [illegible] vesicles and few phenocrysts. Most of the rocks have less [illegible] percent olivine phenocrysts; a few samples have as much as [illegible] olivine, and even fewer have about 10 percent plagioclase [illegible] sts. In general, the core recovered is much like the [illegible] prehistoric lavas of the Puna Volcanic Series in the wall [illegible] caldera, although perhaps slightly poorer in olivine [illegible].

[illegible] ground surface at the drill site is underlain by about 9 m [illegible] solidated to weakly indurated ash and volcanic rubble. The [illegible] coring attempts were made in the upper 300 m of the hole [illegible] chosen on the basis of geophysical-log properties (large [illegible] where drilling has been rapid, low resistivity, high [illegible] hydrogen content, and low apparent bulk density) that [illegible] sent ash zones. A plug was recovered from the surface [illegible] the drill collar was about 3 m above the ground). [illegible] tained from a 2.5-m thick zone at a depth of 34 m [illegible] fine- to medium-grained ash. Its thickness and depth logging and to sample 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).

Cores were examined by geologists at the HVO, and the following description of the core samples has been provided by Robert I. Tilling, Donald W. Peterson, and Robert L. Christiansen (personal communication).

"The uppermost 300 m appears to be composed mainly of thin pahoehoe flows characterized rather uniformly by about 20-45 volume-percent vesicles and few phenocrysts. Most of the rocks have less than 2 percent olivine phenocrysts; a few samples have as much as 5 percent olivine, and even fewer have about 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, although perhaps slightly poorer in olivine phenocrysts.

"The ground surface at the drill site is underlain by about 9 m of unconsolidated to weakly indurated ash and volcanic rubble. The sidewall-coring attempts were made in the upper 300 m of the hole at depths chosen on the basis of geophysical-log properties (large hole size where drilling has been rapid, low resistivity, high apparent hydrogen content, and low apparent bulk density) that might represent ash zones. 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 a 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. Another 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 should correlate with the Hilina Volcanic Series, which contains numerous interbedded ash layers. All of the additional sidewall cores obtained, however, were fragmented, partly glassy vesicular lava, most of it probably representing crushed pahoehoe crusts.

"The interval between 300 and 600 m, sampled in core runs 14 through 21 (Table 1), comprises 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 with vesicles as large as 2-3 cm making up 35-40 percent of the rock. Some continuous cores show clear gradations from rocks of low vesicularity into coarsely vesicular rock, apparently preserving chilled margins of thick, ponded pahoehoe flows or of 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, yielded continuous solid core 2 m in length. All the runs in this interval were characterized by core recovery of 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 of zeolites and calcite partially filling vesicles, at 488 m (core run 18). Data from geophysical logging discussed below indicate that the standing fluid level in the hole is at about 488 m. The first occurrence of zeolites at this level is consistent with the fluid level representing the local water table. Diverse crystal habits suggest that several different 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, this interval seems distinct from the two lithologic zones in the upper half. In general, the core is slightly darker, locally has a greenish cast, and exhibits virtually no megascopic phenocrysts. Whereas the uppermost 300 m of the hole was characterized mainly by a series of thin pahoehoe flows, and the 300-600 m interval mainly by thick, ponded flows or sills, the bottom half seems to be composed of alternating thick and thin flows, including at least some aa. For example, core run 27 recovered mostly rubbly material of the top or bottom of an aa flow.

"The densest-appearing rocks recovered from the hole 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 has more varied secondary minerals than higher cores. Besides zeolites and calcite, 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 a greater abundance and diversity of secondary minerals in rocks from the bottom half of the hole,there is no apparent progressive increase in the degree of alteration with increasing depth. The extent of alteration in individual samples appears to be largely determined by the original fabric, vesicularity, and fracturing of the rock."

Borehole Surveys

Because core recovery was minimal, most of the information provided by the borehole is in the form of physical measurements made in the hole. A wide variety of such measurements was made, including temperature, density measured with a gamma-ray buckscattering technique, hydrogen content measured with a neutron irradiation technique, electrical resistivity, self-potential, natural gamma ray activity, acoustic wavespeed, and magnetic permeability and vertical field intensity.

Primary data in evaluating the presence of a hydrothermal system are temperature measurements made during drilling and following the completion of drilling. Bottom-hole temperature measurements were made almost daily during the course of the drilling, between April 8 and July 9, at any time that circulation was interrupted for a few hours so that bottom-hole temperature might have a chance to stabilize. These temperatures were recorded using maximum-reading thermometers, with six thermometers being used each time. Usually the thermometers were 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 with the thermistor probe and the maximum-reading thermometers simultaneously generally agreed to within ±2°C. Figures 6 and 7 summarize some of the temperature measurements made during and after drilling.

As is often the case with temperature profiles in hydrothermal systems, the temperature profile obtained in the Kilauea Research Drill Hole is complex. The prominent features of the temperature profile are:

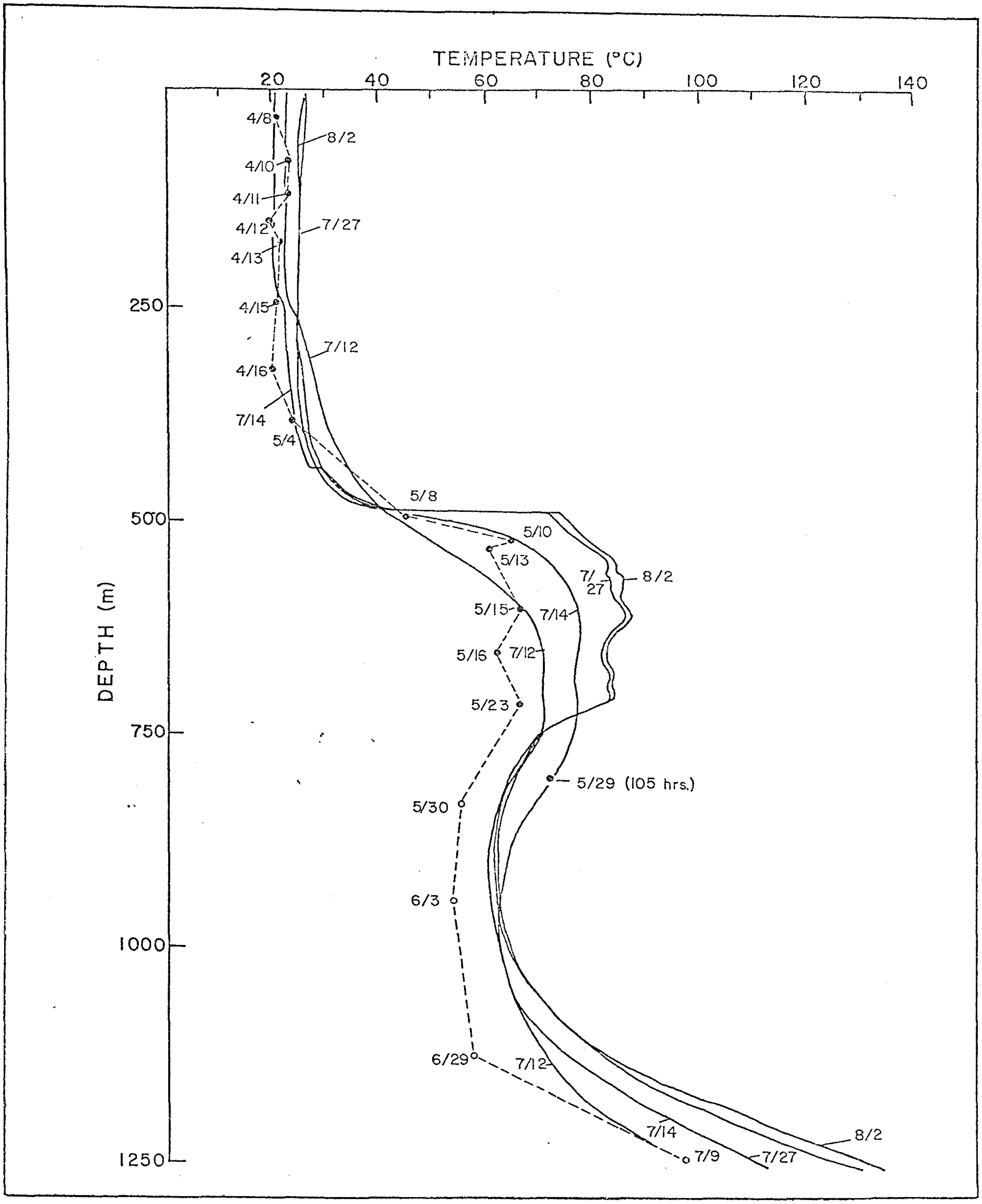

Figure 6. -- Depth-temperature profiles for different times in the Kilauea drill hole. Dashed curve links bottom-hole temperatures measured between drilling shifts (generally about 8 hours after drilling unless otherwise indicated); dots indicate readings by maximum-reading thermometers and circles indicate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

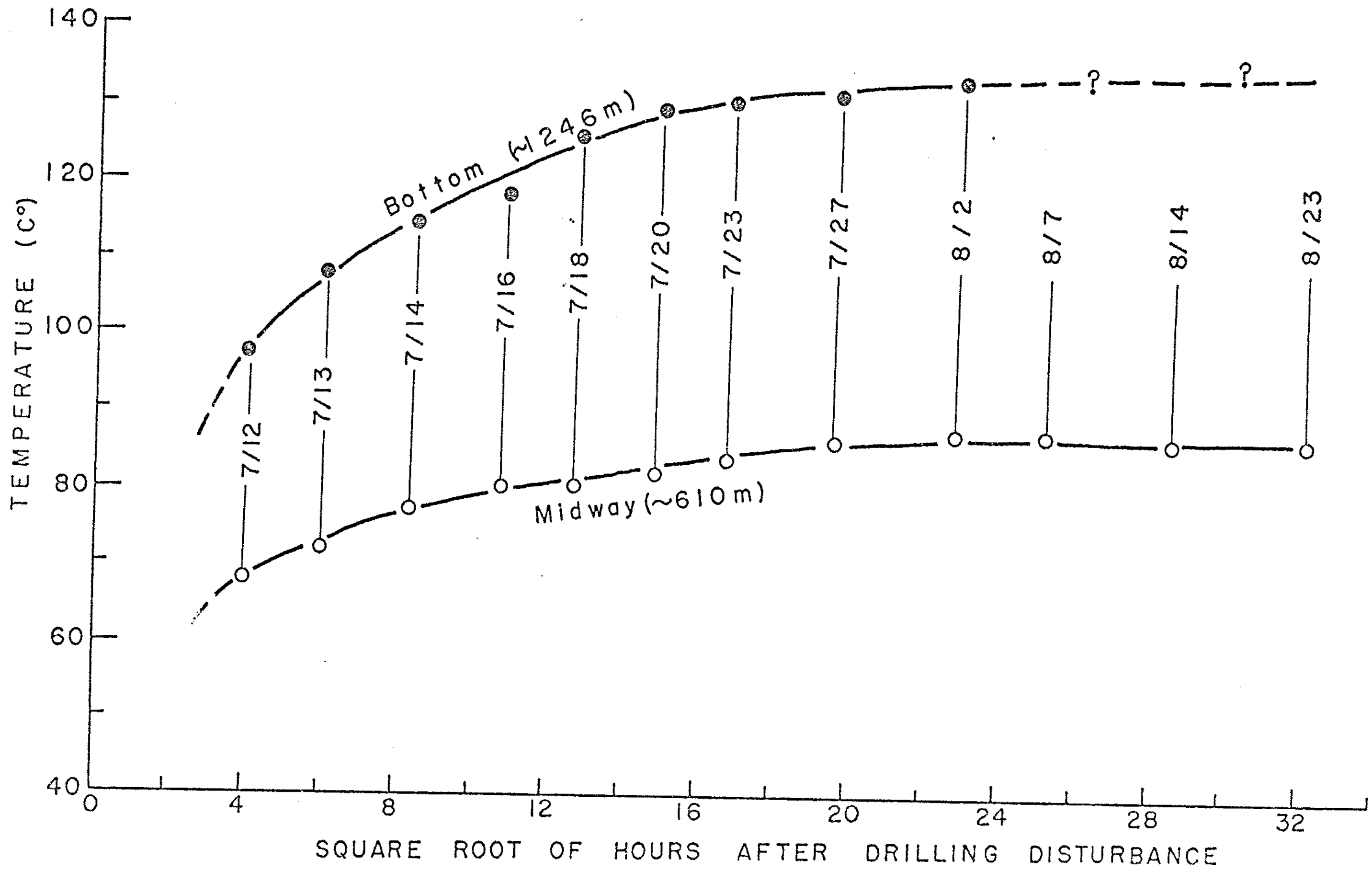

Figure 7. -- Temperatures near hole bottom (∿1246 m) and midway (∿610 m) as a function of time as determined by successive thermistor-probe logs after last drilling disturbance (at 19:30, HST, July 11).

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

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

3) A decrease in temperature between 732 and 976 m;

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

It might be expected that the large amounts of water injected into the rock around the borehole during drilling (1,200,000 gallons, at a temperature of 16 to 20°C) would 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. For clarity, only four of these logs are shown in Figure 6. These temperature profiles show the in-hole temperature changes as the thermal disturbance due to drilling dissipated. In view of the amount of thermal disturbance which one might expect from the amount of drilling mud lost, it is surprising that all intervals of the borehole appear to have approached close to equilibrium temperatures by the time the last of the temperature logs had been run. This approach to equilibrium is summarized by two temperature vs. time curves shown in Figure 7. Extrapolation of the curves shown in Figure 7 indicate that the bottom-hole temperature will not exceed 140°C nor be less than 135°C with complete thermal recovery.

Temperature measurements made along 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. However, these temperature data do place limits on the amounts of possible heat flow. For example, the possibility that the temperature profiles shown in Figure 6 are the result of steady-state flow without convection is quite small. In order to have reversals in gradient and rapid changes in gradient, one almost certainly has to consider convective transfer of heat or transient conductive transfer. In such a case, a minimum estimate of the steady state heat flow can be obtained if one knows the thermal conductivity of the rock over intervals of maximum thermal gradient. For example, the thermal gradient at the bottom of the hole is 0.41°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, this would correspond to a conductive heat flow of 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.

In addition to the borehole temperature measurements, a number of other physical measurements were made in the borehole using more or less conventional well logging methods (Table 2). Because the borehole surveys provide a relatively complete suite of information about the rock around the borehole, they comprise the primary set of data from the drilling project. The cores recovered

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.

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

represent only a small sample of the section, and are probably biased towards representing the more competent rock intervals, but they provide a basis for correlating the physical properties measured with the logs with the lithologic character of the rocks penetrated by the borehole.

Some of the geophysical logs -- the caliper log, the gamma-gamma density log, the sidewall neutron porosity log, and the induction electric log -- are shown in Figures 8 through 11. The logs are shown in four sections because so much detail is involved, but the four sections are also characterized by different sets of physical properties.

The first interval, from the derrick floor to 323 meters depth (0 to 1060 feet), is characterized by thin flows. The density varies over short vertical intervals from values of 1.75 to 2.50 grams/cc. The neutron log shows associated variations in water content, from 10 percent to 45 percent. Comparison of density values with neutron porosity values indicates these rocks are undersaturated, as would be the case above the water table. The electrical resistivity in this interval is greater than can be recorded, probably being several thousands of ohm-meters. The high resistivity indicates that what water is present must have a low salinity.

The second interval, from 323 to 490 meters depth (1060 to 1610 feet), is characterized by more massive units, possibly ponded lava or sills. The densities range from 2.1 to 3.0 grams/cc, while the water content ranges from 6 to 12 percent, for the most

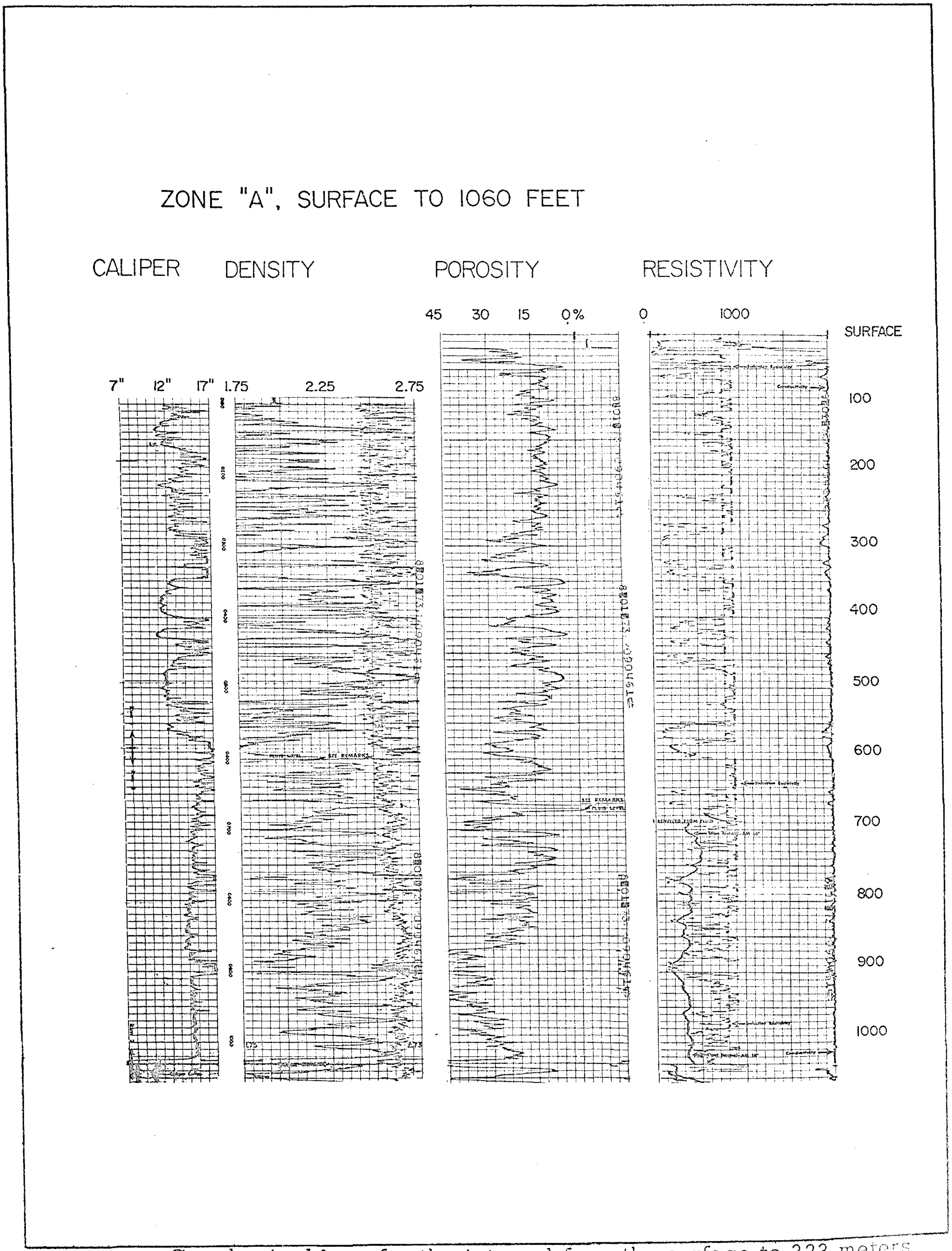

Figure 8. -- Geophysical logs for the interval from the surface to 323 meters depth (0 to 1060 feet). The logs are, from left to right, caliper, gamma-gamma density, sidewall neutron porosity, and induction electric.

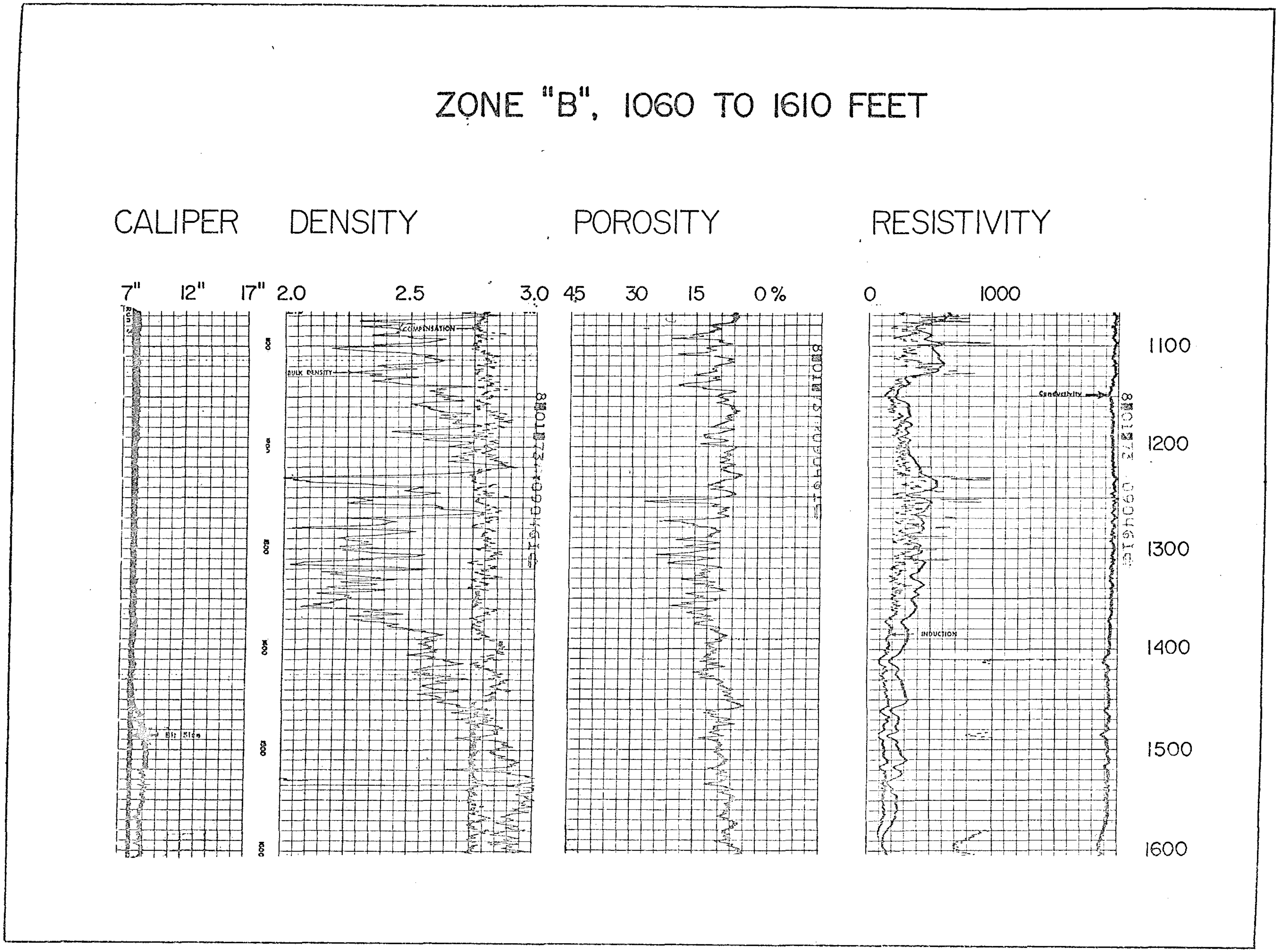

Figure 9. -- Geophysical logs for the interval from 323 to 490 meters depth (1060 to 1610 feet).

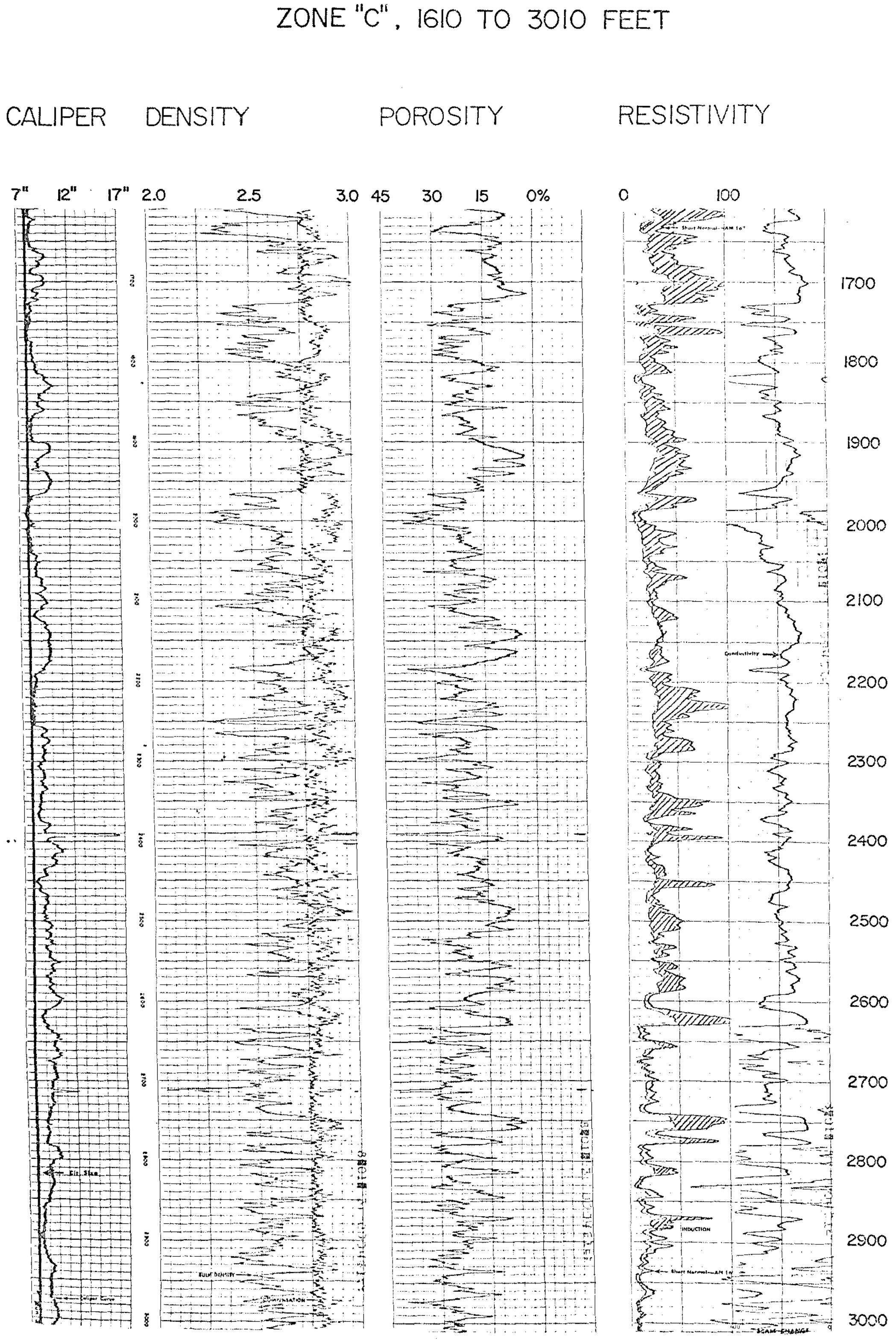

Figure 10. -- Geophysical logs for the interval from 490 to 917 meters depth (1610 to 3010 feet).

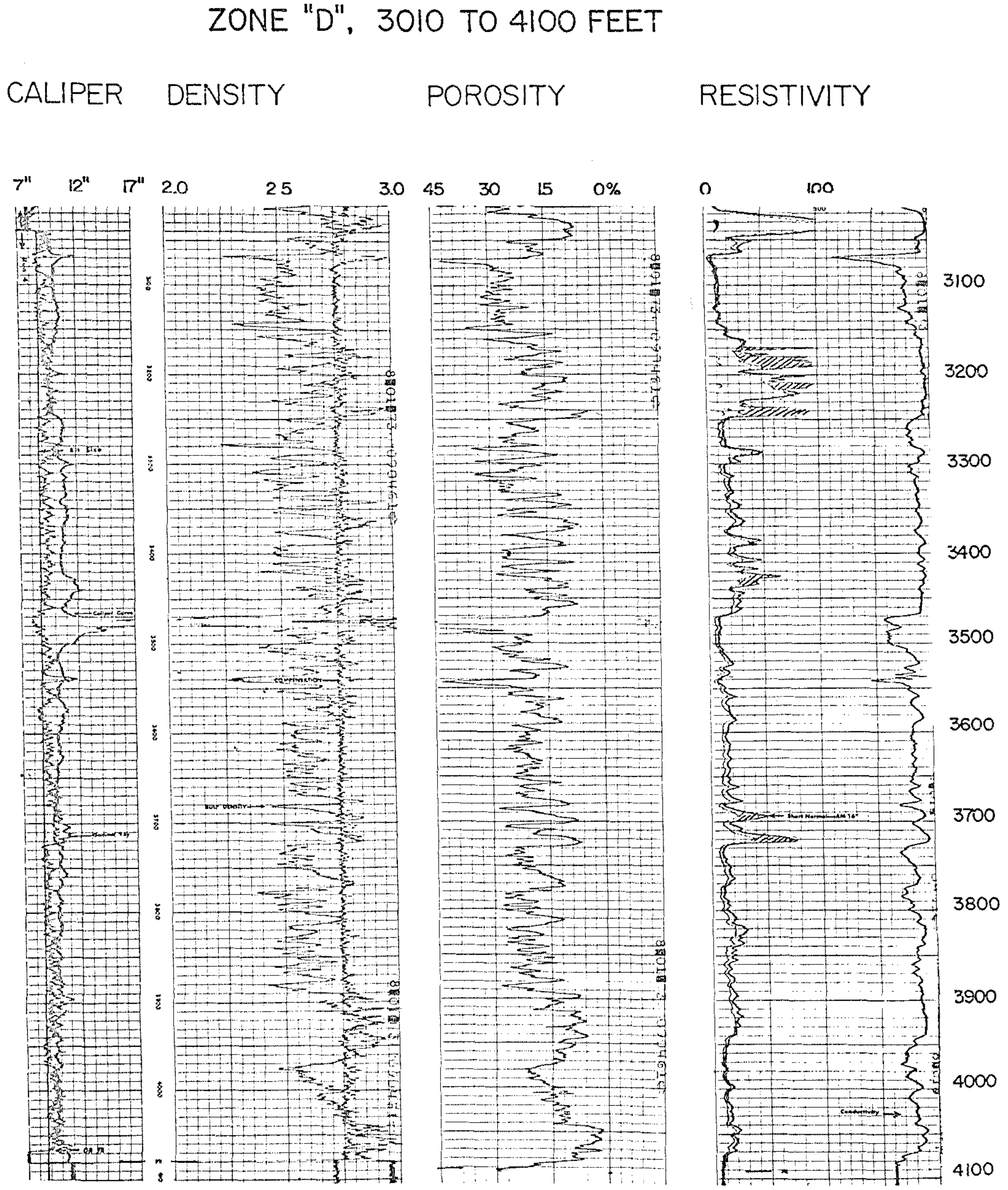

Figure 11. -- Geophysical logs for the interval from 917 to 1250 meters depth (3010 to 4100 feet).

part. Resistivities are high, though not as high as in the upper zone. Resistivity ranges from less than 200 ohm-meters to more than 800 ohm-meters. This zone also appears to be undersaturated, but the water table is present at a depth of 490 meters. This level is marked by a sharp decrease in resistivity and is, as well, the depth to which the static water level in the well returns.

The third interval, from 490 to 917 meters (1610-3010 feet) is characterized again by layered rocks, but the individual units are thicker than in the case of the upper zone. Densities are in the range from 2.4 to 2.9 grams/cc, and water contents range from 9 to 30 percent. Resistivities are far lower than in the upper units,with values ranging from less than 10 ohm-meters to rare values of 100 ohm-meters. Through most of this interval, the resistivity measured with the short-normal device is considerably larger than the resistivity measured with the induction device. This "departure" is characteristic of invasion of the wall rock around the borehole by mud filtrate, a phenomenon which takes place in permeable rocks. It is important to note that the amount of departure, shown as the shaded area between the two resistivity logs, gradually diminishes with depth.

The fourth interval, from 917 to 1250 meters depth (3010-4100 feet) is also characterized by layered rocks with relatively thick individual units, very similar to those in the interval from 490 to 917 meters depth. Densities fall mostly in the range from 2.5 to 2.9, and water contents vary from 9 to 29 percent. The resistivity falls in the range from less than 10 ohm-meters to 40 ohm-meters. There are very few intervals with significant departure between the two resistivity curves, indicating that the permeability is low in this interval.

Physical Measurements on Cores and Estimates of Pore Water Salinity

More than 400 one-inch diameter plugs were cut from the 29 cores recovered during drilling. One purpose of physical measurements made on these samples will be to provide a check for the empirical relationships commonly used to convert the quantities usually measured in geophysical logging to other parameters describing the rock. Measurements already 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, remnant magnetization, and acoustic wave speed and elastic moduli. It is likely that other studies will be carried out on the samples that are not now scheduled. The core is being stored at the Hawaiian Volcano Observatory so that such studies can be made by interested parties.

The average value for the porosity of samples taken from each core run is plotted as a function of depth in Figure 12. The average porosity for all the plugs is approximately 18 percent (by volume). The very low porosity measured on the deepest sample -- less than 2 percent -- probably does not represent a significant decrease in porosity for other than the cored interval.

Fluid permeability measurements have been completed on 64 samples, using conventional permeability measuring equipment, with water as the moving medium. Because of the wide variance between permeability values measured on the various subsamples from each core run, individual permeability values are shown plotted against depth in Figure 13, rather than average values.

Resistivity measurements were made on more than 400 of the plug samples, after they were resaturated with a saline solution containing 0.25 normal sodium chloride salt in solution. The amount of water taken during resaturation was used to determine the porosity of these samples. The results are summarized in Fig. 14, where the data have been grouped according to porosity, and the average formation factor -- formation factor is the ratio of the resistivity of a rock to the resistivity of the brine saturating that rock -- for each porosity interval is plotted. The resultant correlation between formation factor and porosity can be represented by the equation:

$$F = 18\ \phi^{-1.05}$$

where ϕ is the fractional pore volume (assumed to be fully saturated with brine).

This relationship can be used with the induction electric log and the neutron porosity log to estimate the resistivity of the pore water in the rocks penetrated by the borehole. The responses from these two logs were averaged over 200-foot intervals, as shown in Fig. 15. Then the neutron porosity values were used with the relationship in Fig. 14 between porosity and formation factor

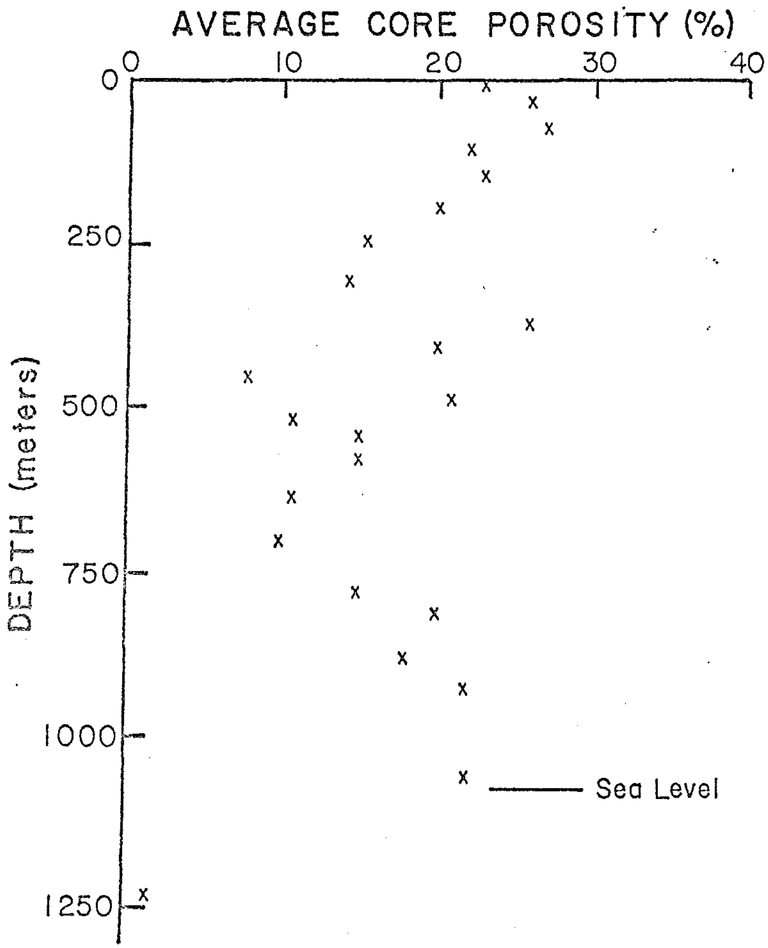

Figure 12. -- Average porosities measured on plugs cut from cores recovered in the Kilauea Research Drill Hole.

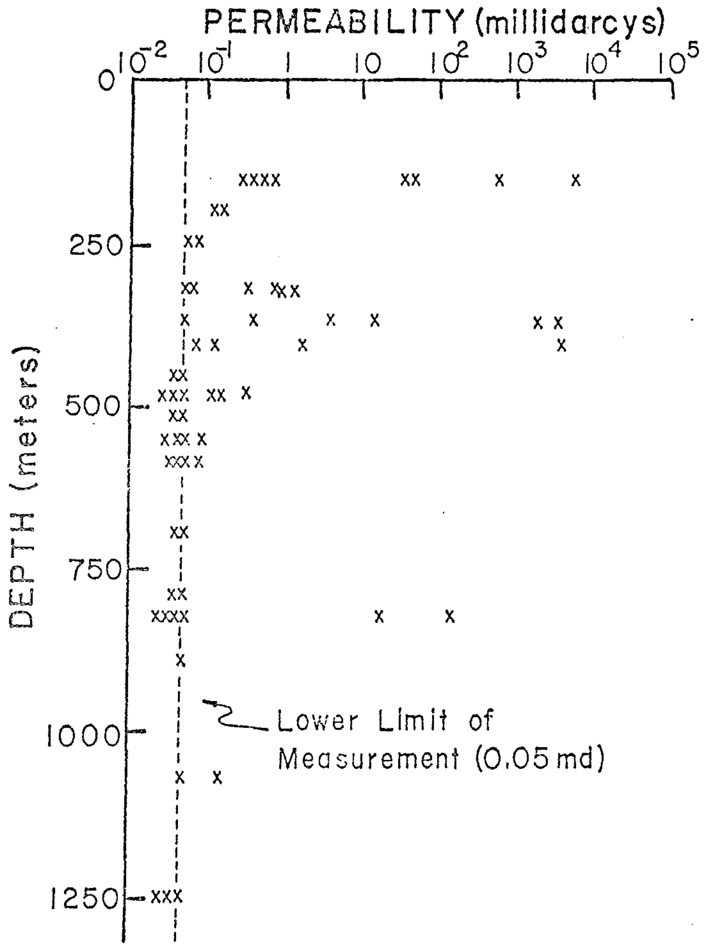

Figure 13. -- Individual values of fluid permeability measured on plugs cut from cores recovered from the Kilauea Research Drill Hole.

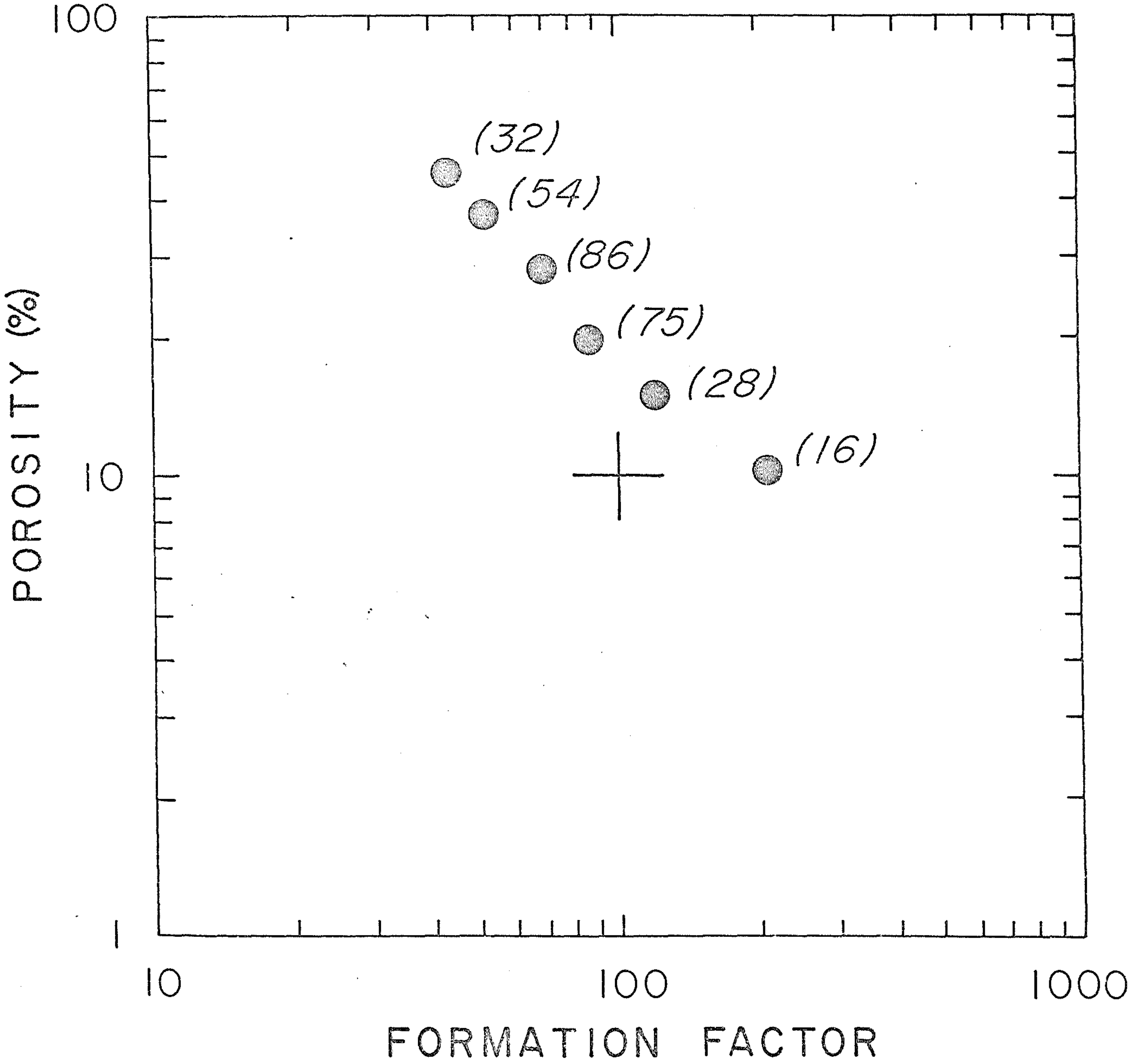

Figure 14. -- Log-log plot of measured porosity vs. formation factor.

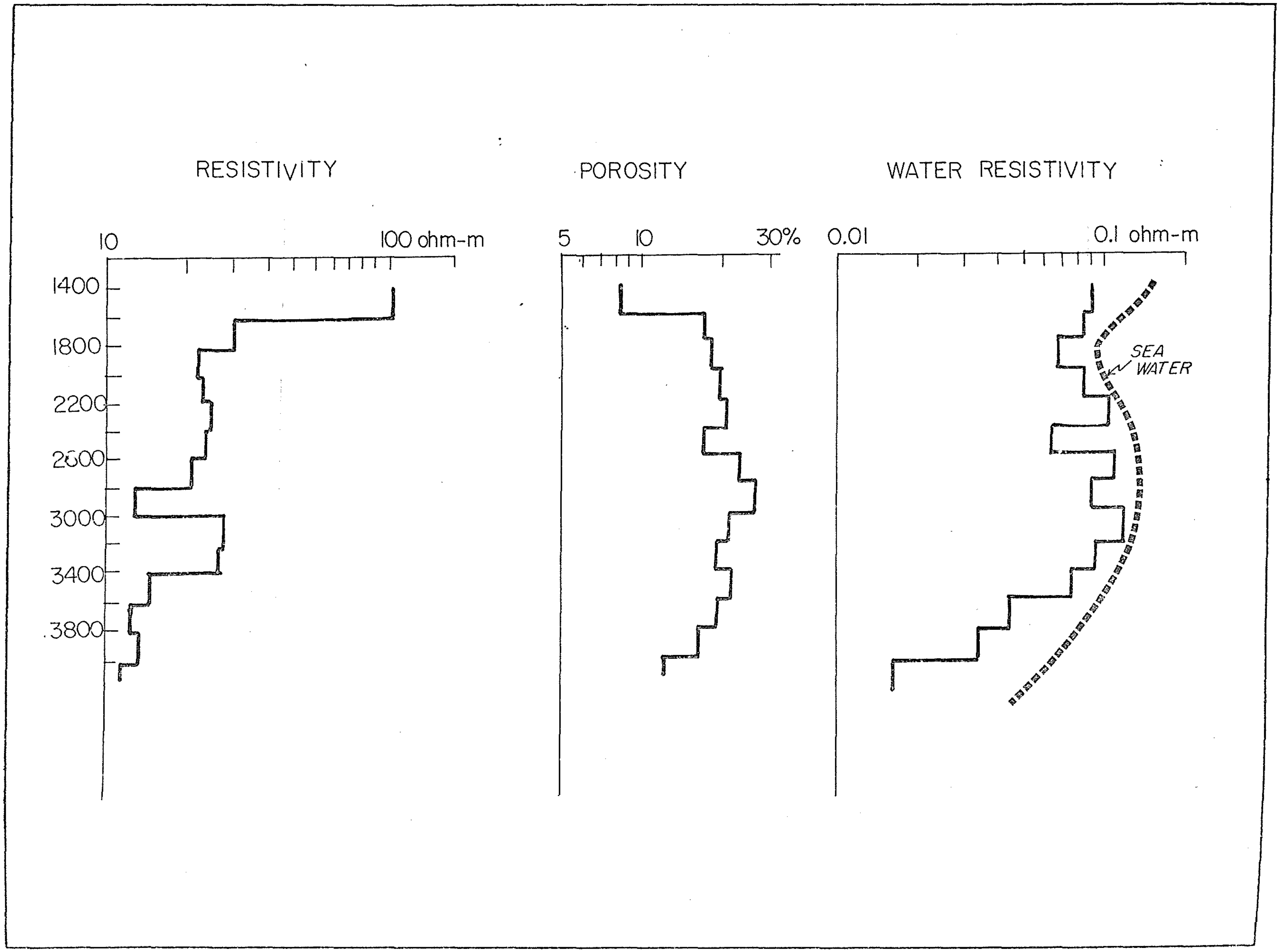

Figure 15. – Method for estimating pore-water resistivity. The two bar-logs on the left were obtained by averaging the neutron-porosity and induction electric logs over 200-foot intervals. The bar-log of water resistivity was obtained from these two logs in combination with the correlation shown in Figure 14. The dashed line shows the resistivity of sea water for the temperatures observed in the well bore.

to determine the average formation factor for each 200-foot interval. The resistivity value from the induction electric log was then used to convert the formation factor to a value for pore-water resistivity, as shown by the third bar-log in Fig. 15. The resistivity that sea water would have at the temperatures observed in the well bore is shown as a dashed line on Fig. 15 for comparison.

Part of the bore-hole measurement program consisted of attempts to extract samples of pore-water directly from the wall rock around the borehole. During drilling, a small amount of cadmium sulfate had been added to the drilling mud to serve as a tracer, so that dilution of fluid samples by mud filtrate could be estimated. The attempts at obtaining fluid samples were made using a Schlumberger sidewall formation tester. This instrument has a pair of small ports which are sealed against the wall of the borehole, and fluid from the wall rock is extracted by opening the ports to a chamber in which the pressure is sub-atmospheric. Eight such tests were run, all at depths below 800 meters, or in the interval shown to have low permeabilities by the geophysical logs. It was not possible to operate the equipment at shallower depths because it was necessary to have a minimum height of mud column above the instrument to accomplish a tight seal against the wall rock. Remarkably small volumes of water were extracted from the wall rock, and chemical tests for cadmium indicated that the samples were diluted at least 10- to 20-fold by mud filtrate. Analyses indicated that the samples did not have the ratios of ions normally found in sea water, being deficient in chloride.

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 already apparent. On the one hand, it is highly gratifying that the information obtained from the borehole appears to substantiate the models derived beforehand 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 to comprise a commercially viable geothermal reservoir, even if production were permissible.

While the temperatures encountered can be explained merely as the result of transient heat flow from fairly recent intrusions, the evidence favoring the existence of a hydrothermal convection cell is persuasive. A major part of this evidence is the existence of a water table at 488 meters depth in the hole, or at an elevation of 614 meters above sea level. It is usually assumed that water table beneath the Hawaiian Islands is in hydrostatic equilibrium, with 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, this leads to an elevation of the fresh water table by an amount of one or two meters for each kilometer distance from the shore line. Elevation of the water table by 614 meters requires some other mechanism, which here is assumed to be a combination of thermal forces supplied from a magma chamber beneath the summit of Kilauea and zones of reduced permeability caused by hydrothermal activity.

There is a marked reduction in permeability at a depth of 488 m, where the water table appears to be present. This in itself is a favorable circumstance for the existence of geothermal reservoirs in the Hawaii geological environment. If all the lavas were as permeable as the surficial lavas, heated groundwater would move quickly through the rock, removing the heat from a magma reservoir too quickly for the temperatures required for a commercially viable system to build up. The presence of alteration in the lavas below the water table may represent the action of self-sealing which is believed to take place in geothermal reservoirs; that is, migrating thermal waters cause alteration which in turn reduces the permeability of the rock, trapping the thermal waters in a reservoir in which the temperature builds up to economic levels.

Adequate permeability is required for production of geothermal fluids. Permeability measurements made on samples from the Kilauea Research Bore Hole are very low, but in many geothermal reservoirs, permeability is provided by fractures rather than by pore channels through the rock matrix. Some evidence of permeability is available for the Kilauea Research Bore Hole from the rate at which mud level dropped following cessation of drilling activities (see Fig. 16). Drilling operations were suspended temporarily when the hole had reached a depth of 979 m, and then drilling was halted again when the total depth of 1262 m was reached. On each occasion, the mud level stood at a depth of 244 m in the casing when drilling was stopped, but the level dropped gradually to a stable level at 488 m depth with time. The mud level dropped much more rapidly

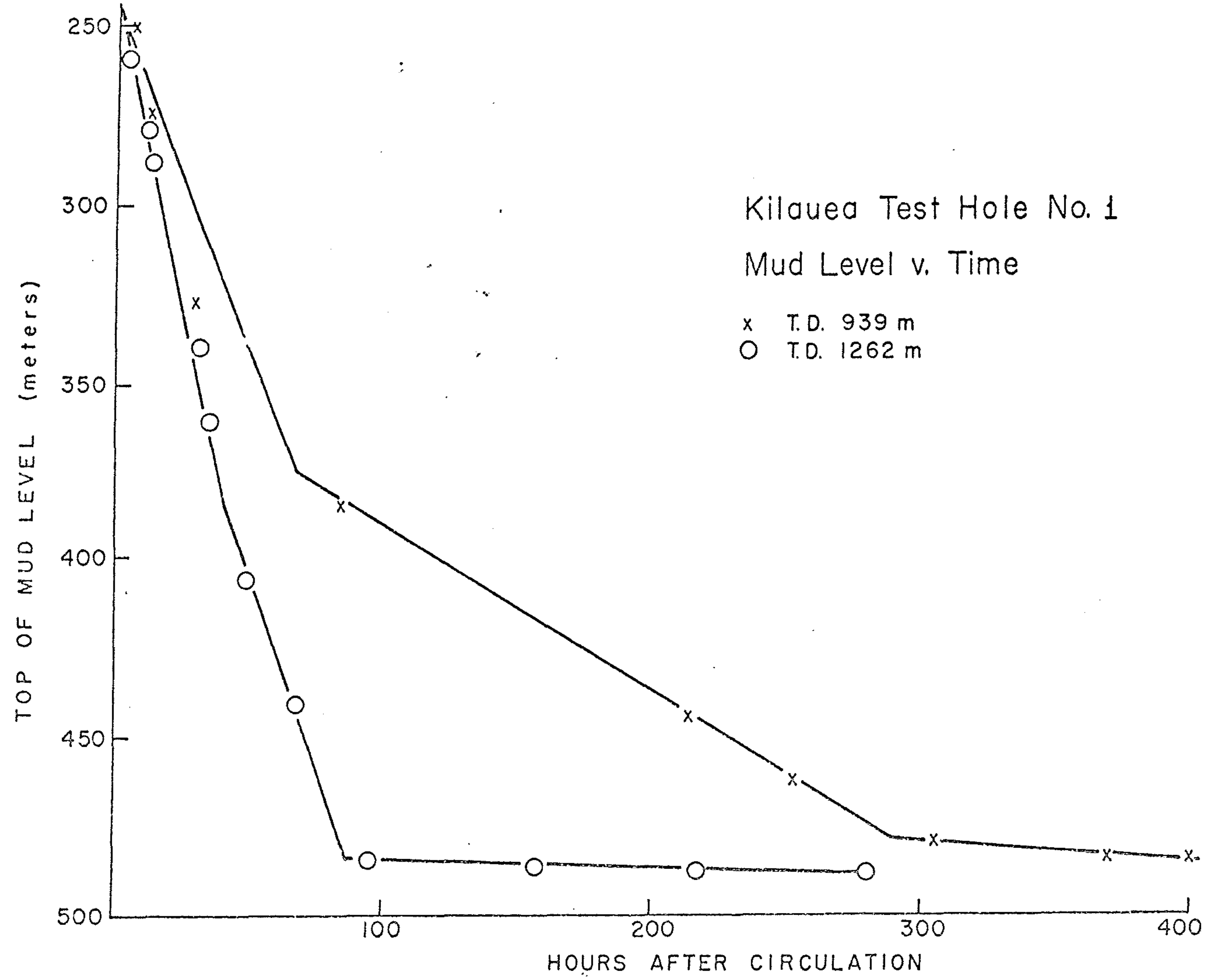

Figure 16. -- History of drop in mud level in the Kilauea Research Drill Hole during suspension of drilling at depths of 939 and 1262 m.

when the hole was completed than when drilling was stopped at a depth of 939 meters, indicating relatively more permeability in the interval opened by the additional drilling than was available in the shallower interval. Assuming the fluid flowing into the rock is mud filtrate with a viscosity equal to that of water, the rate of drop is appropriate for a cumulative permeability of only 0.060 darcy-meters for the bottom 300 meters of section. However, this is the cumulative permeability for a well-bore which has been "mudded off" by drilling mud.

Considering the rate at which temperature is increasing with depth at the bottom of the hole, it is tempting to speculate what might happen if the hole were deepened another few hundred meters, or even a kilometer. It appears that temperatures suitable for production of high-energy steam would be present. 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, though it is not clear that the drilling techniques yet exist which would permit drilling under such high temperature conditions.

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References

Eaton, J. P., E. T. Endo, and R. Y. Koyanagi, Earthquakes and magma sources in the upper mantle beneath Hawaii, *Am. Geophys. Union Trans.*, *52*, 372, paper presented at 15th General Assembly in Internat. Union Geodesy and Geophys., Moscow, USSR, 1971.

Fiske, R. S., and W. T. Kinoshita, Inflation of Kilauea Volcano prior to its 1967-1968 eruption, *Science*, 165, 341-349, 1969.

Jackson, D. B., and Keller, G. V., An electromagnetic sounding survey of the summit of Kilauea Volcano, Hawaii: *J. Geophys. Res.*, 77 (26), 4957-4965, 1972.

Keller, G. V., Murray, J. C., Zablocki, C. J., Tilling, R., Christiansen, R., and Peterson, D., A deep research drill hole at Kilauea Volcano, Hawaii: Progress Report, *Science* (submitted), 1974.

Kinoshita, W. T., Swanson, D. A., and Jackson, D. B., The measurement of crustal deformation related to volcanic activity at Kilauea Volcano, Hawaii: *in* P. Gasparini, L. Civetta, A. Rapolla, and G. Luongo (Editors), *Physical Volcanology*, Elsevier, Amsterdam (in press), 1974.

Koyanagi, R. Y., and E. T. Endo, Hawaiian seismic events during 1969, *U.S. Geol. Survey Prof. Paper 750-C*, C158-C164, 1971.

Macdonald, G. A., and A. T. Abbott, *Volcanoes in the sea*, Univ. Hawaii Press, Honolulu, 441 pp., 1970.

Stearns, H. T., *Geology of the State of Hawaii*, Pacific Books, Pub., Palo Alto, Calif., 266 p., 1966.

Stearns, H. T., and G. A. Macdonald, Geology and ground-water resources of the Island of Molokai, Hawaii, *Hawaii Div. Hydrography Bull.* *11*, 113 pp., 1947.

Ward, P. L., Microearthquakes: Prospecting tool and possible hazard in the development of geothermal resources: Geothermics, vol. 1, no. 1, 1972.