AREA
Hawaii
Kilauea
Logs

GEOPHYSICAL LOGS FROM THE KILAUEA GEOTHERMAL RESEARCH DRILL HOLE

by

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Abstract

A borehole has been drilled to a depth of 4123 feet 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 steam eruption, and to maximize the chances of gathering scientific information. The scientific program included a comprehensive suite of geophysical logs for the purpose of determining the physical properties of the rocks penetrated, all of which are basalt. The basalts occurred variously as thin to thick flow units, and massive units which may be sills or frozen lava ponds. Porosities are generally high, ranging from a few percent to near fifty percent. The solid material in the basalt has a nearly uniform grain density over the entire depth of the borehole, the grain density being 3.02 grams per cc. Acoustic wavespeed logs indicate the wavespeed for rocks with zero porosity would be approximately 18,800 feet per second. Young's modulus, as determined from a full-wave-form acoustic log and a gamma-gamma density log, is generally in the range from 2 to 6 $\times 10^{13}$ kilograms per square meter.

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. A major difficulty being faced in the current efforts to locate additional sources of geothermal energy is our lack of understanding of their geologic controls. Geothermal reservoirs are thought to be intimately associated with modern volcanism or intense tectonic activity. This has led to the supposition that heat is supplied to a geothermal system from 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.

Transfer of heat from a magma chamber may take place by conduction or by evolution of volatile materials. When molten rock is intruded, water from the host rock around the intrusive is converted to steam, and in so doing, deposits its mineral content to make an impermeable caprock around the intrusive. Inside the caprock, all the water may be converted to steam above the critical point for 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 efficientcy of conversion to electrical energy would be high. However, no drilling has yet penetrated into such a supercritical temperature regime.

Above such an impermeable caprock, heat transfer to the surface will 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. Many of the geothermal systems presently under development around the world are believed to be in this convective region.

Inasmuch as a great deal of the model described in the preceeding paragraphs is speculative, it is important that the model be tested by drilling in areas of modern volcanism. 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 by Fiske and Kinoshita, 1969). A phenomenon for which Kilauea Volcano may provide a very informative experimental prototype is that of ground water movement in the vicnity of a magma chamber. Extensive geological and geophysical studies carried out by the U. S. Geological Survey over many years have pinpointed an area beneath the summit of Kilauea where the evidence for the existence of a shallow magma chamber is highly persuasive, and this area was selected as a site for the Kilauea geothermal research drill hole (Keller and others, 1974). The site lies within the Hawaii Volcanoes National Park, and so, the energy can never be exploted. The National Park Service permitted this drilling project because the hole was for research purposes only. The location is indicated on Figure 1.

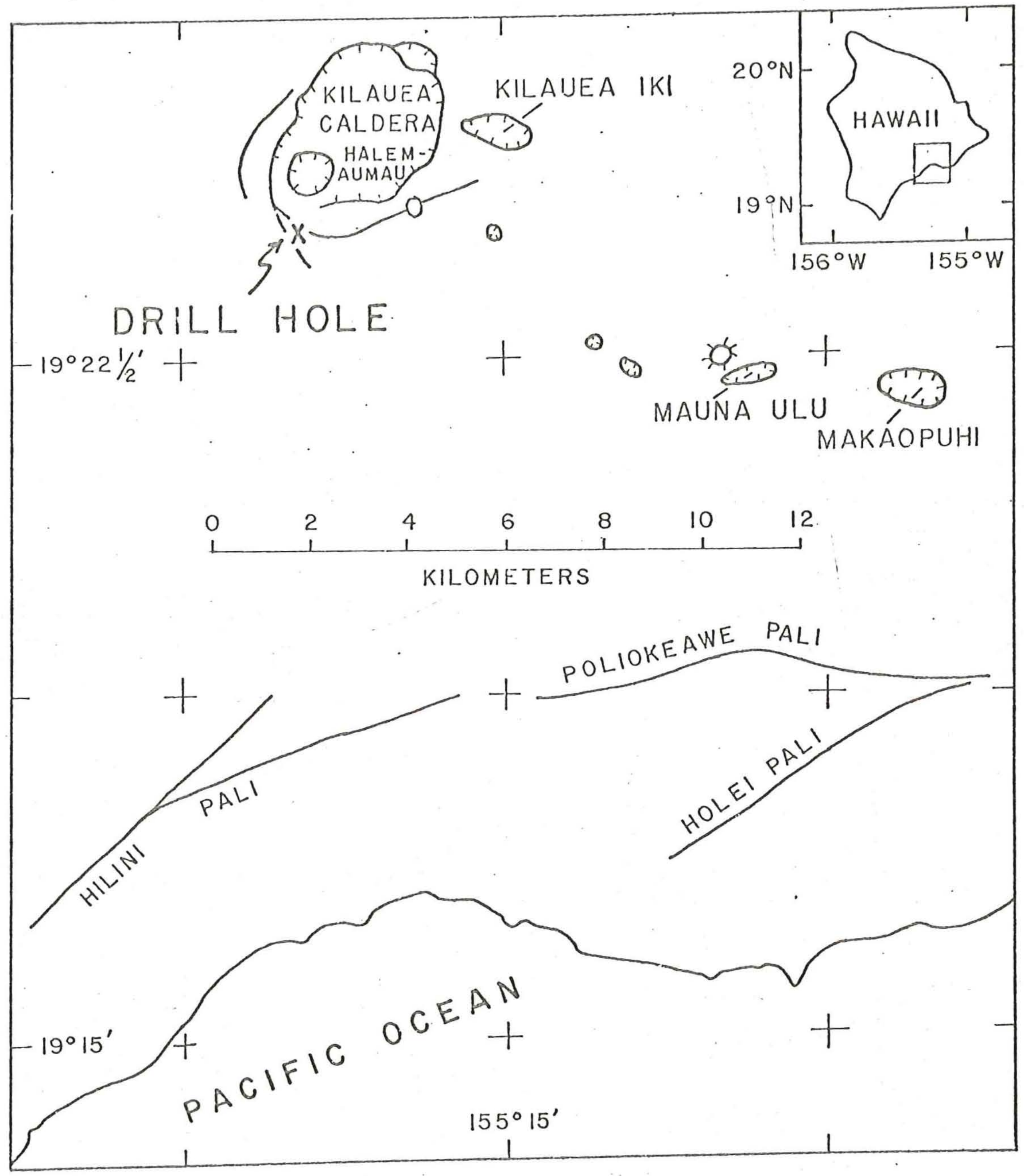

Figure 1. Index map showing the location of drill hole in relation to major features of Kilauea Volcano.

Drilling

A contract for drilling the Kilauea geothermal research borehole 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 stabilized foam, the decision was made to drill using water-base drilling mud because of the company's extensive experience with this drilling procedure under Hawaiian conditions.

The entire 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. Mud was lost in openings and factures which were too large to be shut off with lost circulation material. During drilling, water consumption ranged from 10,000 to 30,000 gallons per day, all of which had to be transported 30 miles from the nearest water supply well.

Short cores were cut on 29 occasions, with the total amount of core recovered being 154 feet, or about 3.7 percent of the total hole depth. To supplement these cores, piston-type sidewall coring was attempted in the upper 1000 feet of the hole. The attempts were mostly 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 coring bits, with rates ranging from as low as 3 feet per hour in the dense volcanics, to as high as 180 feet per hour in the loose, porous volcanics.

Borehole Surveys

Much of the information provided by the borehole is in the form of physical measurements made in the hole. A wide variety of logs were run, including temperature, gamma-gamma backscattering, neutron irradiation, induction electric, self potential, natural gamma ray activity, acoustic wavespeed, and magnetic permeability and vertical field intensity.

Primary data for evaluating the presence of a geothermal system are the temperature measurements made during drilling and following completion of drilling. Borehole temperature measurements were made at every occasion on which circulation was interrupted for a few hours, giving bottom hole temperatures a chance to stabilize. These temperatures were recorded using maximum-reading thermometers, with six thermometers being used each time. 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.

In addition to temperature measurements made with the maximum-reading thermometers, continuous temperature logs were run at intervals during and following drilling 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 agrred within 2° C. Several of the temperature logs are shown in Figure 2.

As is often the case with temperature profiles in geothermal systems, the temperature profile obtained in the Kilauea geothermal research borehole is complex. The prominent features of the temperature profile are:

1. An essentially isothermal interval between the surface and 1600 feet depth. Other logs indicate water table is present at 1600 feet, and so this isothermal zone probably represents the effect of cool surface waters draining downward to the water table.

2. A rapid rise in temperature between depths of 1600 feet and 2400 feet.

3. A decreas in temperature between 2400 feet and 3200 feet. The rapid rise and then decrease in temperature might be expained as being caused by the residual heat of a dike intruded in the vicinity of the borehole, but more likely, the inversion of temperature is associated with horizontal circulation of fluids at the edge of a convection system.

4. An increasingly steep rise in temperatures between3200 feet and 4100 feet. Extrapolation of the curves shown in Figure 2 indicate that the bottom-hole equilibrium temperature is about 137° C., and that the thermal gradient is about 400° C. per kilometer. Other logs indicate progressively lower fluid permeabilities in the basalts near the bottom the the hole, and so, the steeper gradients are probably related to a transition from conductive heat flow at the greater depths to convective heat transfer at the shallower depths.

Some of the other geophysical logs -- the caliper log, the gamma-gamma density log, the sidewall neutron porosity log, and the induction electric log -- are shown in Figures 3 through 6. The logs are shown in four sections because so much detail is involved, but the four sections also are characterized by different sets of physical properties.

The first interval, from the derrick floor to 1060 feet depth, covers an interval consisting of thin flows. The density varies over short 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 to be undersaturated, as would be the case above the water table. The electrical resistivity in this interval is greater than can be measured, probably being several thousands of ohm-meters. The high resistivity indicates that what water is present must have a low salinity. Mud filtrate probably causes the apparent water content to be higher than the amount of water actually present in these rocks.

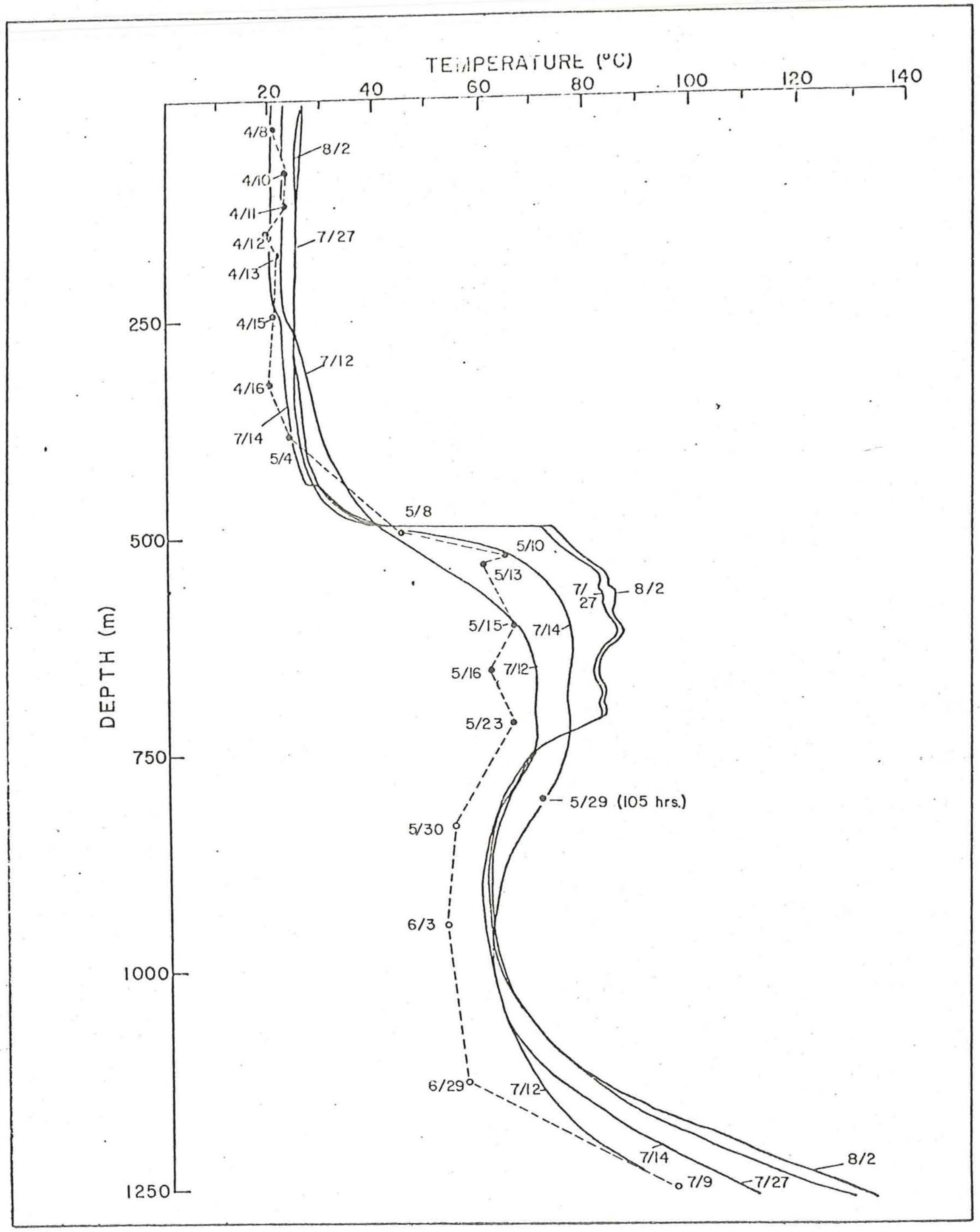

Figure 2. Depth-temperature profiles for different times in the Kilauea drill hole. The dashed curve links bottom-hole temperatures measured between drilling shifts (generally about 8 hours after drilling unless otherwise indicated); dots indicate readings by maximum-reading thermometers and circles indicate readings by thermister probe. Solid curves are selected post-drilling temperature profiles run with the thermistor probe.

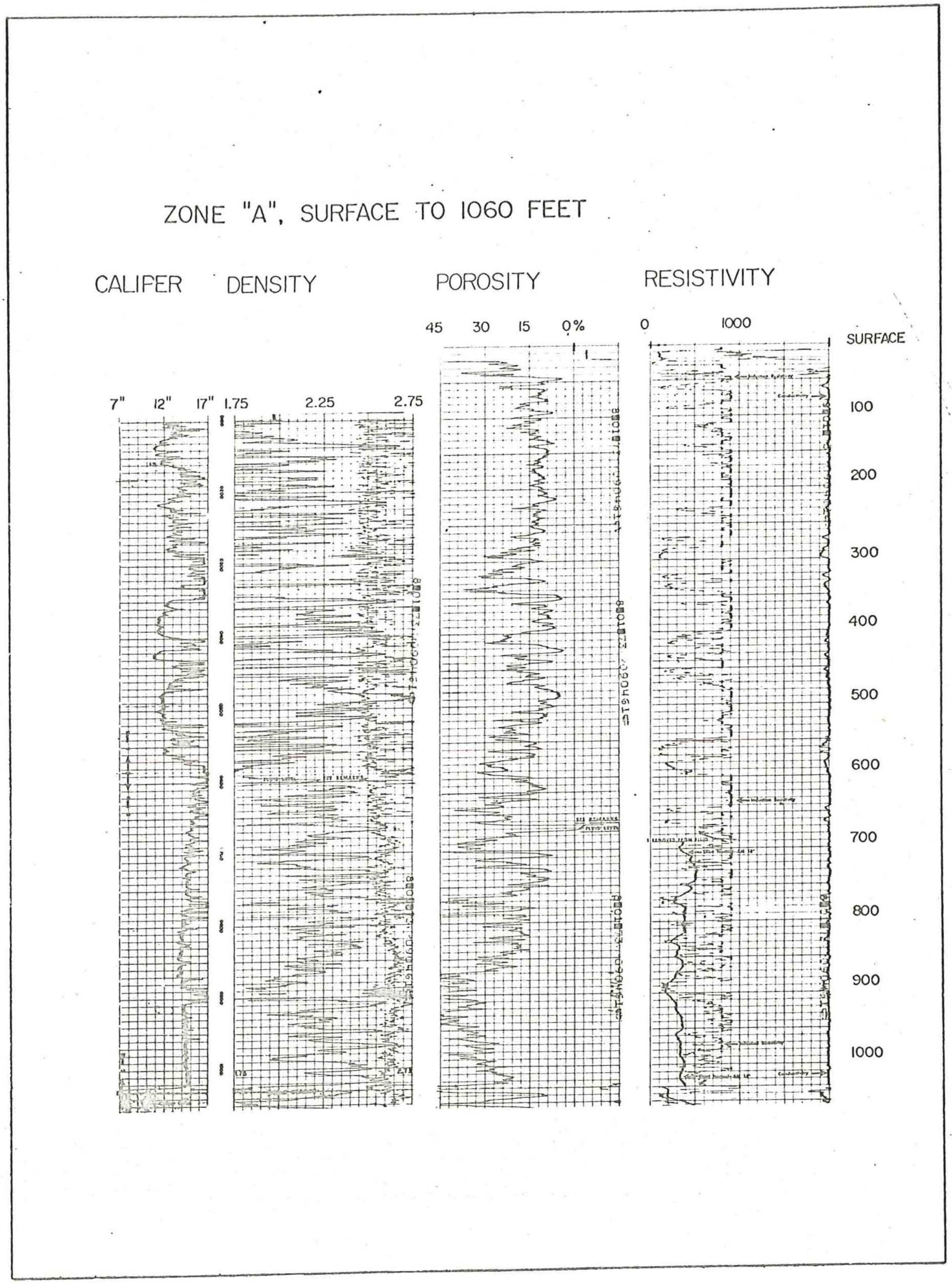

Figure 3. Geophysical logs for the interval from 0 to 1060 feet. The logs are, from left to right, caliper, gamma-gamma density, sidewall neutron porosity, and induction electric.

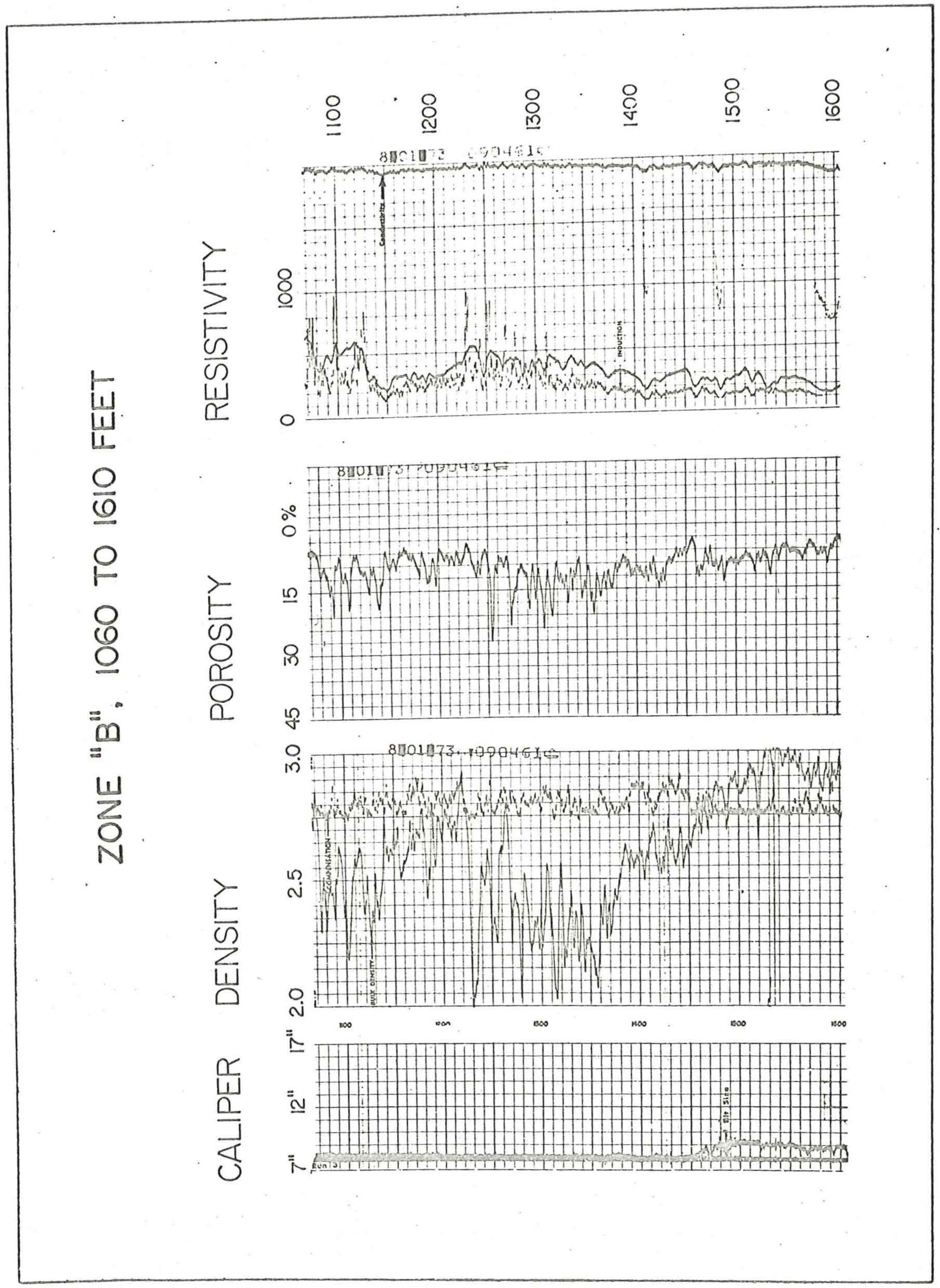

Figure 4. Geophysical logs for the interval from 1060 to 1610 feet depth

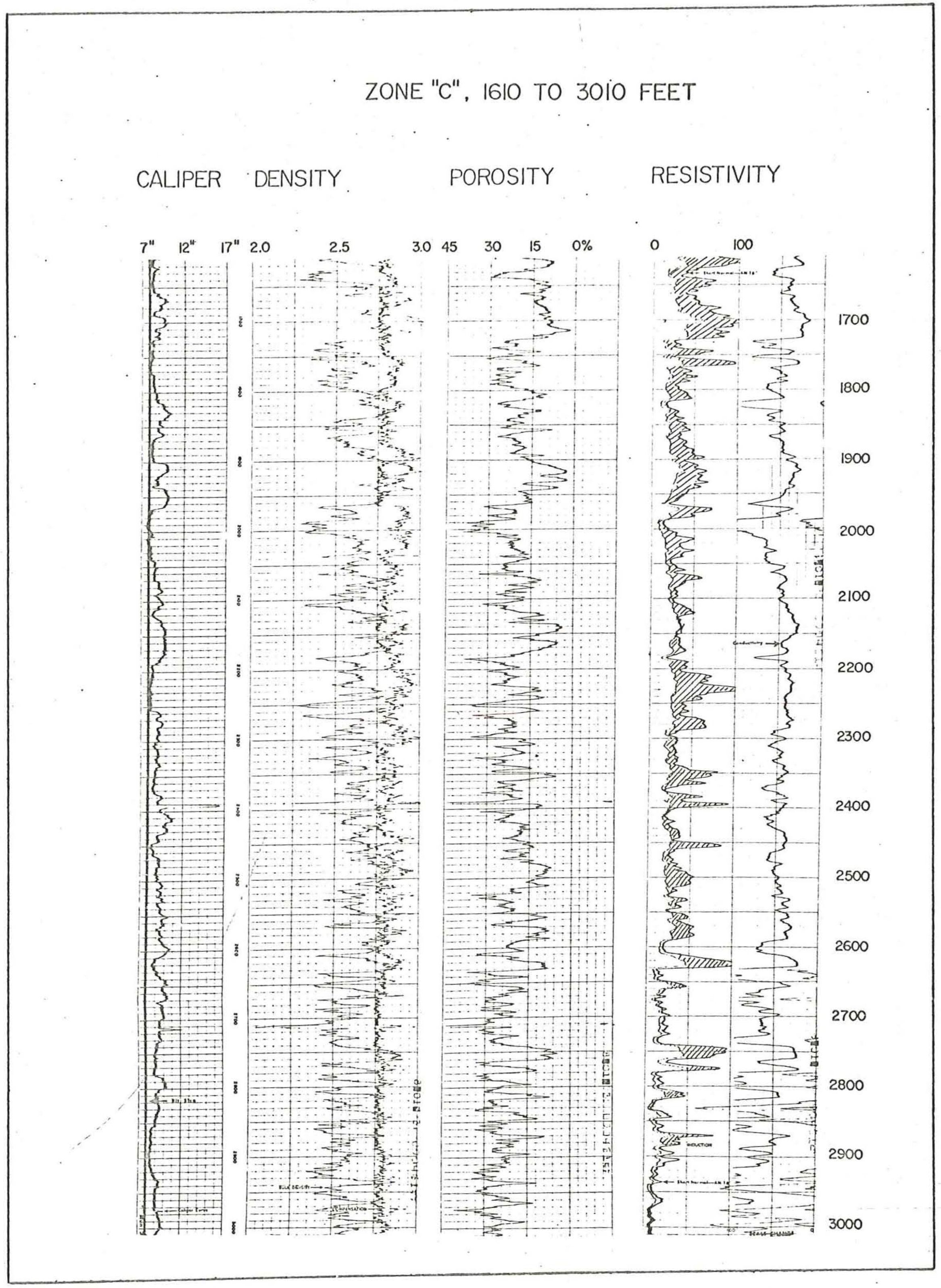

Figure 5. Geophysical logs for the interval from 1610 to 3010 feet depth.

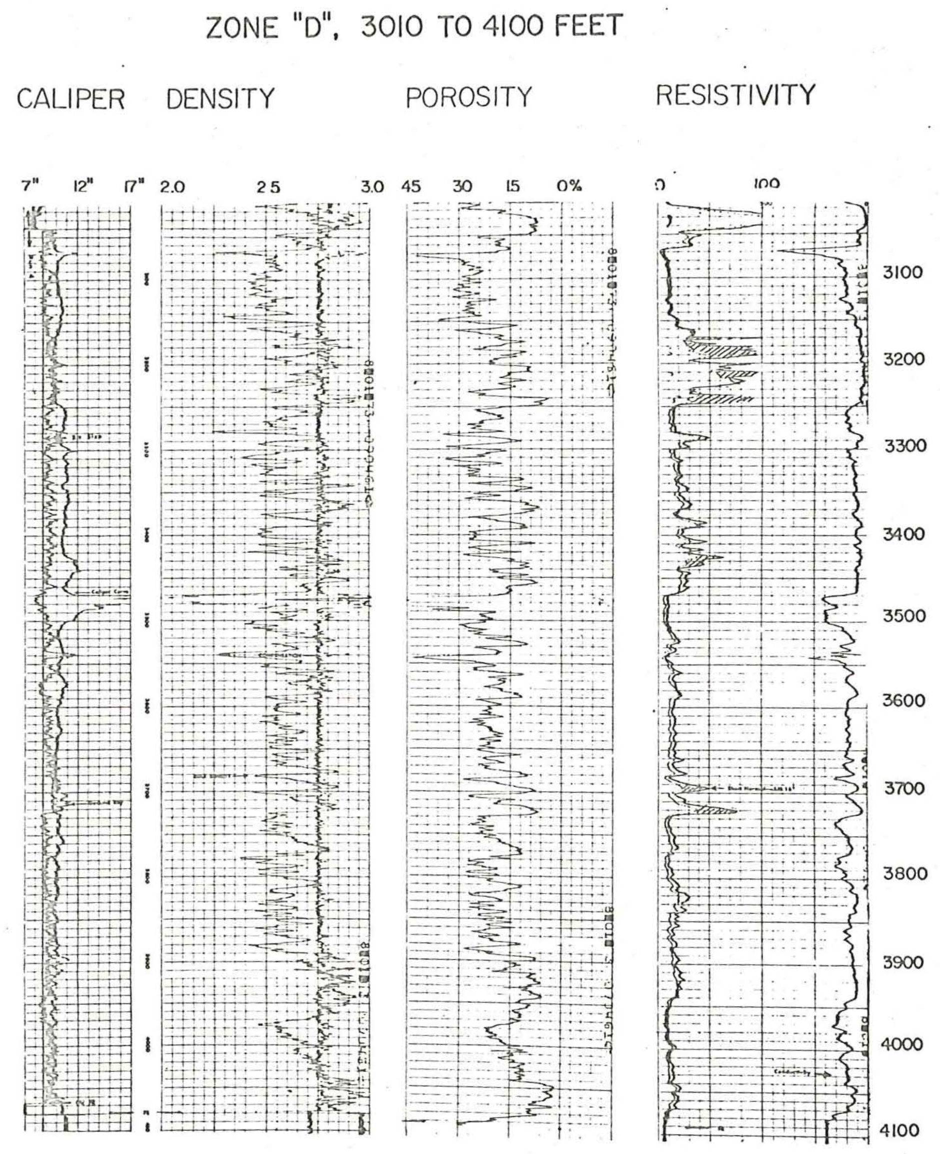

Figure 6. Geophysical logs for the interval from 3010 to 4100 feet depth.

The second interval, from 1060 to 1610 feet depth, consists of more massive basalt units, possibly ponded lava or sills. The densities range from 2.1 to 3.0 grams per cc, while the water content ranges from 6 to 12 percent, for the most 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. The water table is present at a depth of 1610 feet. 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 1610 to 3010 feet depth, again consists of flows with alternating properties, but the individual flow 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 as high as 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 permeable wallrock around the borehole by mud filtrate. 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 3010 to 4100 feet depth, also consists of alternating flows with relatively thick individual units, very similar in character to those in the interval from 1610 to 3010 feet depth. Densities fall mostly in the range from 2.5 to 2.9, and water contents vary from 9 to 29 percent. Resistivity varies from values less than 10 ohm-meters to about 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.

Log-derived rock properties

Various physical properties for the basalts penetrated by this borehole were determined by cross-plotting the responses on various logs, or of log data with core data. One such cross plot between neutron porosity data and gamma-gamma density data is shown in Figure 7. The plotted points were taken from the logs for units characterized by good responses on the two logs, between depths of 1610 and 4000 feet. Because all data pertain to rocks from below the water table, the neutron response can be considered to be a measure of the porosity of the rock. The solid lines in Figure 7 represent the relationship between porosity and bulk density for various assumed values of grain density. The median value for grain density appears to be 3.02 grams/cc. This is relatively high for basalt, which might normally be expected to have a density close to that of labradorite, which is 2.71 grams/cc.

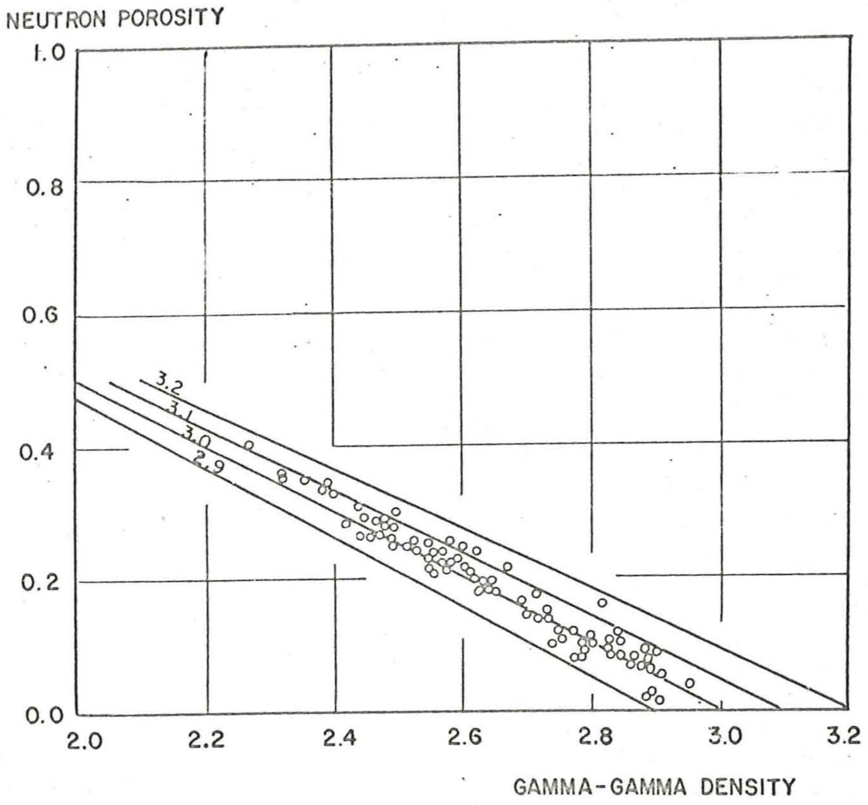

Figure 7. Cross plot of values from the neutron porosity and gamma-gamma density logs for depths between 1610 and 4100 feet. The solid lines indicate the expected relationship for the indicated values of grain density.

A second cross plot is shown in Figure 8. Here, values of interval transit time from the acoustic wavespeed log are correlated with the porosities from the neutron log for the interval from 1610 feet to 3010 feet. The solid lines on the cross plot indicate the expected relationship if the interval transit time recorded on the log is the linear average of the transit time in the minerals comprising the framework of the rock and the transit time in water. As may be seen, the data do not fall along a single curve, but indicate a zero-porosity wavespeed that increases with increasing porosity. At porosities above 15 percent, the data indicate a wavespeed of 27,000 feet per second, while at zero porosity, the data indicate a wavespeed of 18,800 feet per second. The latter value seems to be more appropriate for dense basalt. Probably, the simple averaging of transit times does not properly express the dependence of wavespeed on porosity.

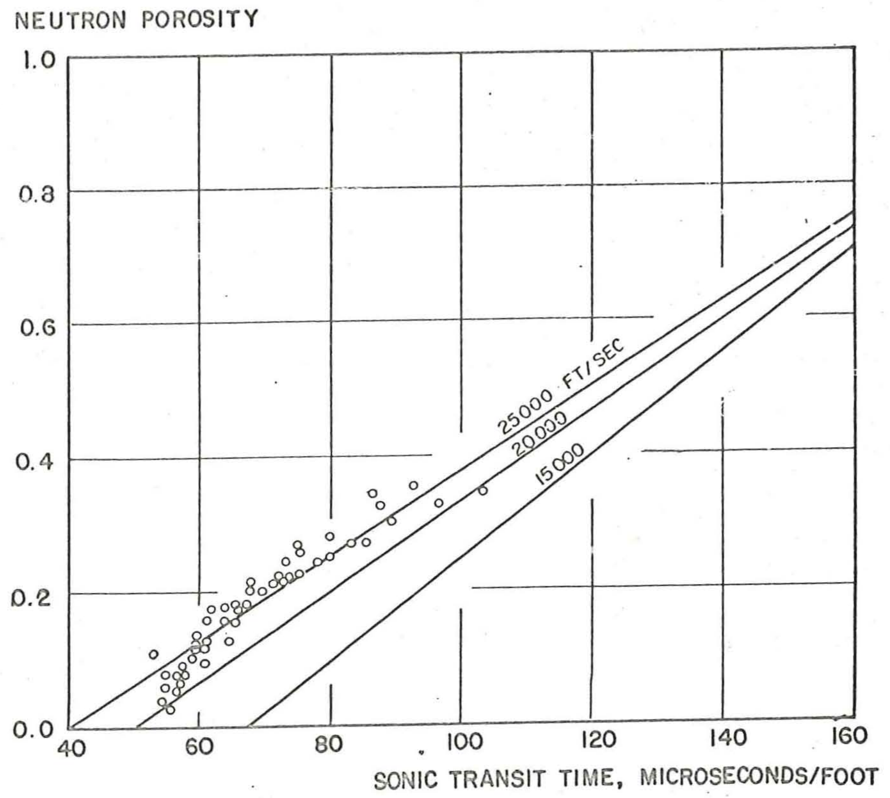

Figure 8. Cross plot of values of acoustic transit time for the acoustic log and the neutron porosity for depths between 1610 and 3010 feet. The solid lines indicate the expected relationship for simple transit time averaging with various wavespeeds assumed for basalt with zero porosity.

Responses from the full-wave-form acoustic log, the interval transit time log and the gamma-gamma density log were used to determine values for Young's modulus for the basalt layers penetrated by the borehole. Arrival times for compressional waves and shear waves were determined from the full-wave-form acoustic log, recorded in a variable density format. However, these arrival times, which represent the travel time from the transmitter to a single receiver, include an unknown delay time for travel in the mud column. This delay time was determined by comparing the transit times for the single-receiver full-wave-form log with the transit times recorded with the two-receiver acoustic log. Then, Young's modulus was calculated from the formula:

$$E = \frac{V^2 \rho}{1 + \frac{2\sigma^2}{1-\sigma-2\sigma^2}}$$

where V is the compressional wavespeed, σ is Poisson's ratio, determined from the compressional and shear wavespeeds, and ρ is the bulk density. Values for Young's modulus so determined are given in Table 1.

Table 1.

Depth	σ	ρ (gm/cc)	E (Kg/m²)
1420-55	0.25	2.60	3.2 x 10^{13}
1455-1520	.25	2.85	7.45
1580-1605	.30	2.90	6.35
1605-1612	.30	2.40	2.10
1680-1690	.30	2.55	3.70
1690-1705	.35	3.00	2.47
1780-1800	.30	2.50	3.16
1800-1825	.30	2.70	4.16
1880-1900	.35	2.65	3.85
1940-1960	.30	2.75	5.09
1960-1970	.33	2.40	2.52
1970-1985	.34	2.55	3.72
2130-2180	.36	2.85	4.74
2410-2440	.30	2.65	4.45
2590-2600	.35	2.70	2.61
2610-2630	.31	2.80	5.39
2632-2638	.30	2.45	2.02
2645-2655	.30	2.40	2.66
2655-2670	.30	2.75	4.63
2730-2740	.27	2.50	1.65
2742-2760	.30	2.90	4.59
2815-2830	.25	2.55	3.00
2870-2885	.25	2.57	4.15

Resistivity measurements were made on more than 400 plugs cut from the cores, after they were resaturated with a saline solution containing 0.25 normal sodium chloride. The amount of water taken during resaturation was used to determine the porosity of these samples. The results are summarized in Figure 9, in which the data have been grouped for samples having similar porosities, and the average value of formation factor for each porosity group is plotted. The 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 basalts penetrated by the borehole. The responses from these two logs were averaged over 200-foot intervals, as shown in Figure 10. Then, the neutron porosity values were used with the formation factor relationship given above to determine the average formation factor for each 200-foot interval. The resistivity value from the induction log was then used to convert the formation factors to values for pore-water resistivity, as shown by the third bar-log in Figure 10. The resistivity that sea water would have at the temp-

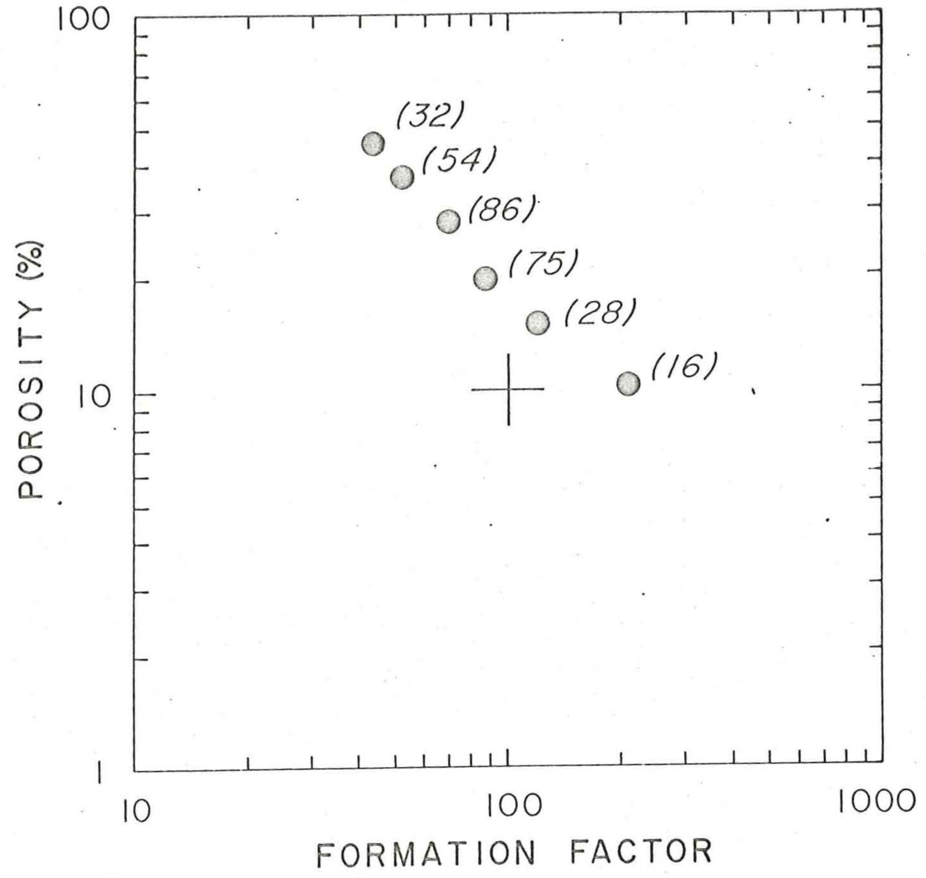

Figure 9. Correlation between porosity and formation factor determined on core samples. Each dot is the average for the number of determinations indicated in parentheses.

Discussion of results

The temperatures encountered in the Kilauea geothermal research borehole are not high enough to comprise a commercially viable geothermal system, at least at the depths reached in drilling. However, considering the rate at which temperature is increasing with depth at the bottom of the hole, it is tempting to speculate what might be found if the hole were deepened another 1000 feet, or even further. It appears that temperatures suitable for production of high-energy steam would be present, though it must be remember that commercial steam production could not be undertaken within the confines of the Hawaii Volcanoes National Park. It is even more tempting to speculate about 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

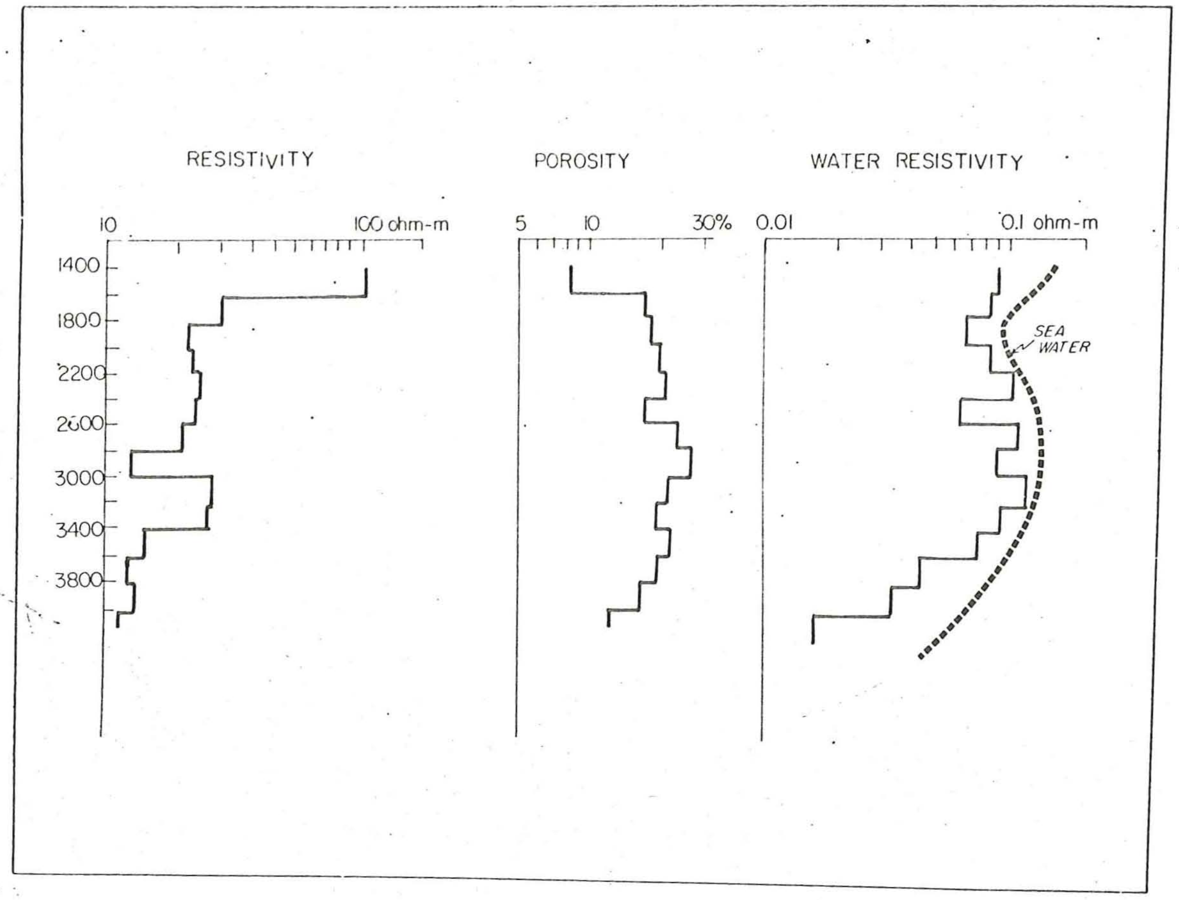

Figure 10. Method for estimating pore-water resistivity. The two bar-logs on the left were obtained by averaging the neutron porosity and induction electric logs over 200-foot intervals. The bar-log of water resistivity was obtained from these two logs in combination with the core sample measurements shown in Figure 9.

permit drilling under such high temperature conditions.

The reduction in permeability which is observed over the lower 1000 feet penetrated by this borehole is of considerable importance in evaluating the geothermal potential of basaltic volcanoes such as are found in Hawaii. The near-surface lavas found on Hawaii are normally so permeable that one would expect heated ground water to 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 and reduced permeability in the basalts 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.

Acknowledgements

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