112

A DEEP RESEARCH DRILL HOLE AT THE SUMMIT OF AN ACTIVE VOLCANO, KILAUEA, HAWAII

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Abstract. Drilling and geophysical logging data for a 1,262 m-deep bore hole in the area inferred to overlie the magma reservoir of Kilauea Volcano, Hawaii, support earlier interpretations based on surface geophysical surveys that a zone of brackish or saline water lies above the reservoir. Temperatures encountered within the hole are not sufficiently high to warrant commercial interest; the maximum temperature, 137°C, is at the hole bottom. However, the temperature gradient toward the bottom of the hole (approximately 160 m below sea level) increases sharply to about 370°C/km, perhaps partly reflecting the effect of decreased water circulation as suggested by the geophysical logging data. If this gradient persists or increases with depth, magmatic temperatures would be attained within 3 km from the hole bottom (i.e., approximately 4 km from ground surface)--a depth in accord with data from ground-deformation and seismic studies.

Introduction

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. 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 sea level. Reports covering the rationale for site selection, drilling procedures, and some preliminary data from Schlumberger borehole surveys have appeared in specialized publications (Keller et al., 1974, a, b). This brief report highlights other aspects of the drilling study, including a brief description of the generalized lithologic section penetrated by the hole.

Interest in the internal character of Kilauea Volcano coincides with a growth of national concern over an energy shortage, inasmuch as Kilauea Volcano could provide a means for testing some of the physical concepts that have developed about the nature of geothermal energy systems. Commercial geothermal power plants around 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. The site for this deep test hole was selected on the basis of ground deformation studies and microseismicity data collected over many years by the U.S. Geological Survey's Hawaiian Volcano Observatory (Kinoshita et al., in press), and electrical resistivity surveys carried out jointly by the U.S. Geological Survey and the Colorado School of Mines (Jackson and Keller, 1972). These data collectively suggest that recent eruptions at Kilauea's summit are supplied from a shallow magma reservoir lying at 3 to 4 kilometers depth beneath the southern part of Kilauea Caldera. The drill hole was located near the center of the area inferred to overlie the reservoir.

Discussion of the drilling and coring procedures has been given elsewhere (Keller et al., 1974, a, b), and only a brief summary is given here. Drilling was done using a standard rotary rig and water-base drilling mud. The entire drilling was accomplished "blind", i.e., no return circulation of drilling mud was ever attained, and no cuttings were returned to the surface, because of high permeability of some of the rocks penetrated by the hole. Coring proved to be costly in both time and money because of the inability to maintain mud circulation and of the limited endurance of the diamond bits. Consequently, coring attempts were reduced to only

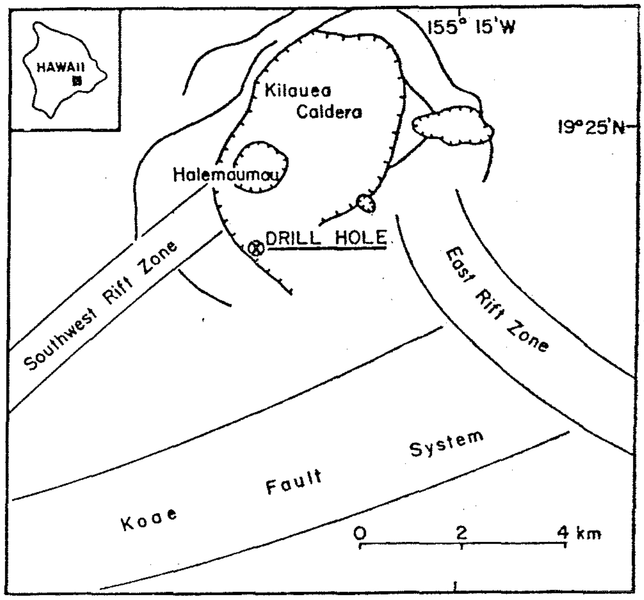

Figure 1. Index map showing location of drill hole in relation to major features of Kilauea Volcano.

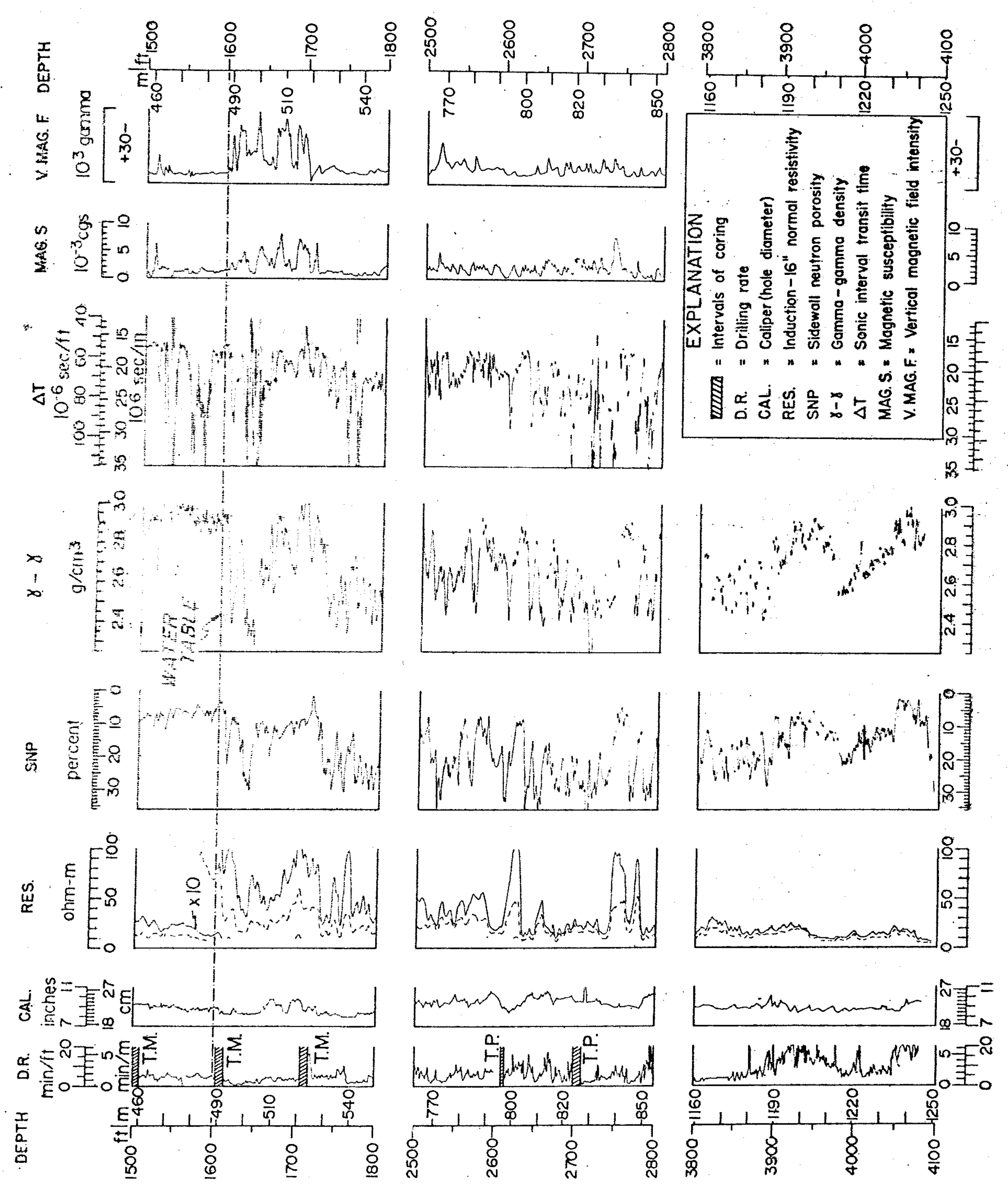

Figure 2. Responses of various geophysical borehole logs obtained in three selected sections of Kilauea drill hole. For the cored intervals: T.M. - thick, massive flows and/or sills; T.P. - thin pahoehoe flows.

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9 runs. Recovery ranged from fair (>40%) to xcellent (100%) for most core runs; a total of 7 meters of core were recovered, about 3.7% of e total hole depth.

Geophysical Logging

Figure 2 illustrates the responses of the arious types of borehole measurements from three 2 meter-intervals in the hole. These intervals re representative of the character of the logs rom the other parts of the hole. As the hemical composition of these rocks is grossly niform, the response of these logging tools with the exception of the magnetic logs) rimarily reflect textural changes in the rocks. he extremely large range of values shown in all he logs is in accord with the large variations n vesicularity of the recovered core samples. uperimposed on these conspicuous changes are ess obvious changes in the average properties, hich tend to grossly correlate with observed ithologic changes in the core samples.

Rock Types Encountered in the Hole

From the limited core recovered and the more xtensive geophysical logging data, three broad ithologic zones appear to be represented by the epth intervals: 0-300 m, 300-600 m, and 600-,262 m. The entire hole, of course, is in asalt.

The uppermost 300 m appear to be composed mainy of thin pahoehoe flows characterized rather niformly by about 20-45 volume-percent vesicles nd few olivine phenocrysts (generally less than percent). In general, the core recovered is uch like the exposed prehistoric lavas of the una Volcanic Series in the wall of Kilauea caldea (Stearns and Macdonald, 1946, p. 193), although erhaps slightly poorer in olivine phenocrysts. he ground surface at the drill site is underlain y about 9 m of unconsolidated to weakly induraed ash and volcanic rubble. A sample was obtaind by side-wall coring from a 2.5 m-thick ash zone t a depth of 34 m. Its thickness and depth uggest that it could be the Uwekahuna Ash, a nit found low on the northwest caldera wall Powers, 1948, p. 280-284). Another ash zone, bout 6 m thick and perhaps correlative with the idespread Pahala Ash, was sampled at a depth of 78 m.

The interval between 300 and 600 m comprises asalt generally coarser grained and more crystalline than that higher in the hole. Core samples re most commonly aphyric, nearly holocrystalline, nd contain slightly greater proportions of megacopic groundmass plagioclase and Fe-Ti-oxides han higher in the hole. The vesicularity of amples is highly varied; some rocks are dense ith only a few percent vesicles less than 1 mm n diameter, and other rocks have as much as 40 ercent vesicles that reach 3 cm in diameter. ome continuous cores show clear gradations from ocks of low vesicularity into coarsely vesicular ock, apparently preserving chilled margins of hick, ponded pahoehoe flows or of sills. In eneral, the rock in the 300-600 m interval is ore competent than the rock above or below.

Even though less than 2 percent of the interal from 600 to 1,262 m was cored, the few samples show a lithology distinct from the higher zones. In general, the core is slightly darker, locally has a greenish cast, and exhibits virtuall 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. The deepest core recovered (1256-1259 m) is the least vesicular and the only one from below present sea level, 1,102 m below the drilling platform. This core, however, shows no obvious petrographic or other features characteristic of submarine lavas.

Geophysical logging data indicate that the rocks are fully water saturated below a depth of 488 meters, the level of the top of standing water in the hole and the inferred local water table. A marked decrease in resistivity is noted for rocks below the water table, and average resistivities decrease progressively with depth (Fig. 2). Interpretation of geophysical logs indicates that the water resistivity in the rock is quite low, ranging from 0.15 to 0.25 ohm-meters. (The resistivity of sea water at 20°C is 0.25 to 0.30 ohm-meters).

Many measurements of reservoir properties -- porosity and permeability -- were made on selected

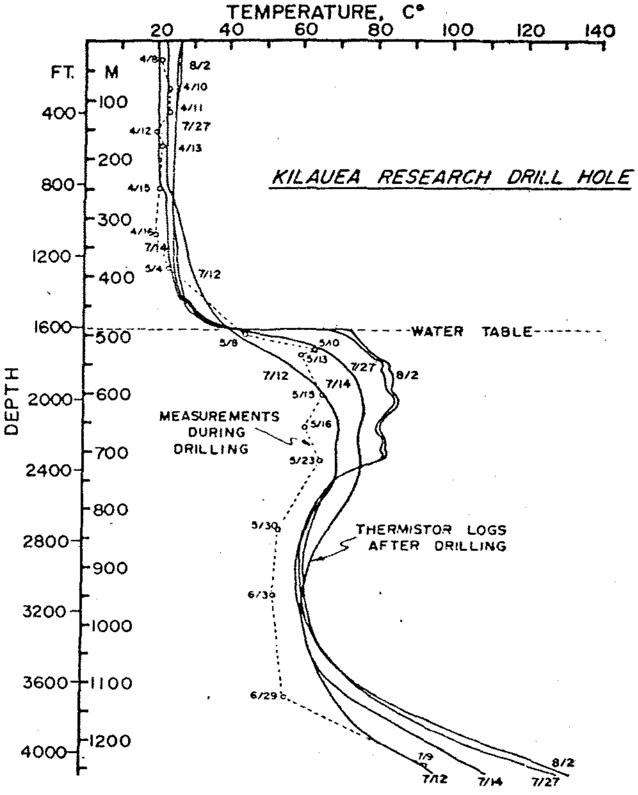

Figure 3. Depth-temperature profiles for different times in the Kilauea Drill Hole. Dashed curve links bottom-hole temperatures measured between drilling shifts (generally about 8 hours after drilling unless otherwise indicated); dots indicate readings by maximum-reading thermometers; and circles indicate readings of thermistor probe. Solid curves are selected post-drilling temperature profiles obtained with continuously recording thermistor probe.

plugs from the limited core. Permeabilities of most samples above water table are very high, in the range from 100 millidarcies to 1 darcy or more. Below the water table, permeabilities become progressively lower at greater depths. Below 1 kilometer, permeabilities are consistently less than 100 microdarcies. However, these measurements may not be representative of the overall characteristics of the reservoir, because fracture porosity and permeability undoubtedly play an undetermined and possibly large role.

Examination of core samples indicates the presence of small amounts of secondary minerals in nearly all samples recovered from below the water table. The minerals are principally calcite and zeolites that partially fill vesicles and fractures. However, the alteration is slight, and broken surfaces of the samples appear to be very fresh, and the degree of alteration does not appear to increase with depth.

Variations in the distribution of ferromagnetic minerals are reflected in the magnetic susceptibility log (Fig. 2). Core samples at 490 and 522 m confirm this interpretation, as they contain the highest concentrations of megascopic Fe-Ti oxides of all core samples and coincide with high values recorded on the magnetic susceptibility log. The vertical magnetic intensity log and the magnetic susceptibility log do not correspond with each other in some intervals, indicating wide variations in the ratio of remanent to induced magnetization.

Borehole Temperature Measurements

Bottom-hole temperatures were obtained during interruptions in the drilling operations, and continuous temperature logs were run with a thermistor probe on numerous occasions both during and after the drilling (see Fig. 3). The last complete temperature log, that of August 2, probably approximates equilibrium because it does not differ markedly from the logs run several days previously. Temperatures above the water table are low, but they rise abruptly at the water table to nearly 80°C (Fig. 3). After remaining in the range 80-85°C in the interval 530 m to 700 m, temperatures decline to a minimum of about 63°C at 900 m, and then increase smoothly to a value of 137°C at the bottom of the hole. The thermal gradient near the bottom of the hole is about 370°C/km, suggesting the approach to a zone of hotter rock below. The cause of the hot zone is unknown but may in part reflect decreased permeability and water circulation, as suggested by the geophysical logging data. If this gradient persists or increases with depth, magmatic temperatures would be attained within 3 km from the hole bottom (i.e., approximately 4 km from ground surface)--a depth in accord with data from ground-deformation and seismic studies.

Discussion

The complicated nature of the thermal profile is most readily explained by convective transfer of heat. High permeability in the rocks above the water table would permit rapid infiltration of cool surface waters, explaining the isothermal character of the upper part of the profile. The temperature reversal observed from 550 to 900 m may be the consequence of the hole being located off center from a rising convection column of water. A rising column would spread out at the water table, leading to a temperature maximum that would be underlain by lower temperatures. Another possibility would be that the upper temperature maximum is the transient heating effect from a recently emplaced intrusive body near the drill hole.

It cannot be assumed that ground water moves through the island as if the permeability were uniformly high. The water table (910 meters above sea level) is much shallower than that expected from the Ghyben-Herzberg model. Its high level may result from low lateral permeability caused by hydrothermal processes related to magma reservoirs (thermal buoyancy and "self-sealing") and/or by intrusive bodies in the vicinity of the drill hole which may impound or impede the flow of ground water. Clearly, data from a single drill hole are not sufficient to understand the geothermal and hydrogeologic environment of Kilauea Volcano's near-surface magma reservoir.

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