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A deep research drill hole at Kilauea Volcano, Hawaii

7M  
Journal

By

Charles J. Zablocki, 1926 -  
Robert I. Tilling 1/  
Donald W. Peterson 2/  
Robert L. Christiansen 2/  
George V. Keller 3/

U.S. Geological Survey, Denver, Colorado 80225

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey Standards.

1/U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii  
-National Park, Hawaii 96718

2/Present address: U.S. Geological Survey, 345 Middlefield Road,  
Menlo Park, CA 94025

3/Colorado School of Mines, Golden, Colorado 80401

270800

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ABSTRACT

1  
2 A 1262-m-deep bore hole was drilled at the summit of Kilauea  
3 Volcano, Hawaii, to test predictions based on surface geophysical  
4 surveys and to obtain information on the hydrothermal regime above a  
5- postulated magma reservoir. Data from the drilling and geophysical  
6 borehole logs tend to confirm earlier predictions that a mound of  
7 brackish or saline water is present above the inferred magma body.  
8 Temperatures within the hydrothermal system are not sufficiently high  
9 to indicate deposits of economic interest, but the gradient toward the  
10- bottom of the hole (approximately 160 m below sea level) is high,  
11 about 370°C per kilometer. The maximum temperature, 137°C, is at the  
12 hole bottom.  
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INTRODUCTION

1  
 2 National concern over an energy shortage has greatly expanded  
 3 interest in geothermal power. Commercial geothermal power plants  
 4 throughout the world are located in areas of recent silicic volcanism,  
 5 but the obvious supply of heat associated with Hawaii's active  
 6 basaltic volcanoes is attractive as a possible future source of power.  
 7 Although Hawaii's volcanoes are among the most thoroughly studied in  
 8 the world, little is known about whether their subsurface temperature  
 9 regime and hydrologic and geologic conditions are favorable for  
 10 geothermal deposits of economic potential. Only drill holes can  
 11 supply much of the necessary data.

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

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

1 Measurements of seismicity, ground tilt, elevation changes, and  
 2 horizontal ground displacements repeated regularly by the Hawaiian  
 3 Volcano Observatory show that inflation and deflation of Kilauea's  
 4 summit area is generally centered in or near the southern part of the  
 5- caldera (Mogi, 1958; Eaton, 1962; Fiske and others, 1969; Kinoshita  
 6 and others, 1974). These centers of deformation are interpreted to lie  
 7 above a complex magma reservoir system. When magma rises to fill the  
 8 reservoir system, the increased pressure inflates the summit area;  
 9 when magma drains rapidly from the reservoir complex, especially  
 10- during certain flank eruptions, internal pressure is relieved and the  
 11 volcano deflates. Analysis of deformation during these inflations and  
 12 deflations by elastic models indicates that the magma reservoir  
 13 system may be about 2 to 4 km below Kilauea's summit region (Mogi,  
 14 1958; Eaton, 1962).

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



DRILLING PROCEDURES AND OPERATIONS

1  
2 A contract for drilling the Kilauea Research Drill Hole was  
3 awarded <sup>to</sup> Water Resources International, a drilling company located at  
4 Honolulu, Hawaii, with experience in drilling water wells in the  
5- State of Hawaii. After considering drilling with air or with a  
6 stabilized foam, it was decided to drill using conventional water-base  
7 drilling mud because the company's experience showed this drilling  
8 procedure was best suited for conditions in Hawaii.

9 The entire drilling operation was carried out "blind"; that is,  
10- fluid losses into permeable zones made it impossible to maintain a  
11 return circulation of mud to the surface. During actual drilling,  
12 water consumption ranged from 38,000 to 114,000 liters per day. A  
13 total of 4,500,000 liters of water was used during, which had to be  
14 transported 30 km from the nearest water supply. This water was  
15- combined with approximately 400,000 kg of bentonite clay to form a  
16 high-viscosity, low-density drilling mud.  
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1 It had been planned to recover core from most of the interval  
 2 drilled. A heavy-wall coring barrel with a capacity for recovering  
 3 up to 20 meters of 9-cm (3.5-inch) core per run was selected on the  
 4 basis of its successful use on the Deep Sea Drilling Program. Without  
 5- mud circulation, however, it became necessary to change to a shorter  
 6 coring barrel with smaller outer diameter. Furthermore, the diamond  
 7 bits lasted for an average of only seven meters of core drilled. The  
 8 great amount of time required for coring operations and poor diamond-  
 9 bit life, led to such high cost that the plan to cut nearly complete  
 10- cores had to be abandoned. Only occasional cores were cut for a total  
 11 of 29 core runs that recovered about 47 meters of core or about 3.7  
 12 percent of the total hole depth (Table 1).

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13  
 14 Table 1 near here

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

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

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

\*Runs 1-14 used a 20-m-capacity coring barrel; runs 15-29 a shorter coring barrel; 3-m capacity.

+Depth relative to derrick floor, approximately 3 m above ground surface.

‡Schlumberger 2.5-cm (1-inch) coring plugs fired by explosive charges.

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

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

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DESCRIPTIONS OF CORE SAMPLES

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

14 Systematic petrographic and chemical studies of the cores are  
15 pending. Although the sampling is undoubtedly biased toward the more  
16 competent rocks, some generalizations can be made from megascopic  
17 observations of the available core. The entire hole is in basalt, but  
18 three broad lithologic zones appear to be represented in the depth  
19 intervals 0-300 m, 300-600 m, and 600-1,262 m.  
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1           The uppermost 300 m appears to be composed mainly of thin  
2           pahoehoe flows characterized rather uniformly by about 20-45 volume-  
3           percent vesicles and a few phenocrysts. Most of the rocks have less  
4           than 2 percent olivine phenocrysts; a few samples contain as much as  
5-          5 percent olivine, and even fewer contain 10 percent plagioclase  
6           phenocrysts. In general, the core recovered is much like the exposed  
7           prehistoric lavas of the Puna Volcanic Series in the wall of Kilauea  
8           caldera (Stearns and Macdonald, 1946, p. 193).

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1           The side-wall-coring attempts were made in the upper 300 m of the  
2 hole at depths chosen on the basis of geophysical-log properties  
3 that might represent ash zones: large hole size where drilling had  
4 been rapid, low resistivity, high apparent hydrogen content, and low  
5- apparent bulk density. The ground surface at the drill site is under-  
6 lain by about 9 m of unconsolidated to weakly indurated ash and  
7 volcanic rubble. A plug was recovered from the surface ash at 11 m  
8 (the drill collar was about 3 m above the ground). Another plug  
9 obtained from a 2.5-m thick zone at depth of 34 m consists of  
10- fine- to medium-grained ash. Its thickness and depth suggest that it  
11 could be the Uwekahuna Ash, a unit found low on the northwest caldera  
12 wall (Powers, 1948, p. 280-284). An ash zone about 6 m thick was  
13 sampled at a depth of 178 m. It is tempting to correlate this zone  
14 with the widespread Pahala Ash that occurs at elevations as high as  
15- about 670 m above sea level at Hilina Pali, 10 km south of the drill  
16 hole. If this correlation is valid, the lavas underlying this ash  
17 in the drill hole would be expected to correlate with the Hilina  
18 Volcanic Series, which contains numerous ash interbeds (Stearns and  
19 Macdonald, 1946, p. 191). All of the other sidewall cores consist of  
20- fragmented, partly glassy vesicular lava, most of it probably  
21 representing crushed pahoehoe crusts.  
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1           The interval between 300 and 600 m, sampled in core runs 14  
2 through 21 (Table 1), is made up of basalt generally coarser grained  
3 and more crystalline than that higher in the hole. Core samples are  
4 most commonly aphyric, nearly holocrystalline, and contain slightly  
5- greater proportions of megascopic groundmass plagioclase and Fe-Ti-  
6 oxides than higher in the hole. The vesicularity of samples is highly  
7 varied, ranging from dense rock with only a few percent vesicles less  
8 than 1 mm in diameter to varieties in which vesicles as large as 3 cm  
9 make up as much as 40 percent of the rock. Some continuous cores show  
10- clear gradations from low to high vesicularity, apparently preserving  
11 chilled margins of thick, ponded pahoehoe flows or sills. In general,  
12 the rock in the 300-600 m interval is more competent than the rock  
13 above or below. Some of the core runs, most notably numbers 17 and 19,  
14 yield continuous solid core 2 m in length. All runs in this interval  
15- were characterized by core recovery not less than 92 percent. The  
16 average drilling rate for this interval was slower than that for the  
17 first 300 m.

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

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

9           The densest-appearing rocks recovered were in the bottom half;  
10- these fine-grained, essentially nonvesicular rocks may represent  
11 chilled zones of sills or thick flows. Perhaps coincidentally, the  
12 deepest core recovered (core run 29, Table 1) is also the least  
13 vesicular and the only one from below present sea level, which is  
14 1,102 m below the drilling platform. Although this core shows no  
15- obvious petrographic or other features typical of submarine lavas, we  
16 cannot entirely dismiss the possibility that this dense rock was  
17 quenched under relatively high hydrostatic pressure with little  
18 attendant degassing.

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

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### TEMPERATURE MEASUREMENTS

1  
2 Temperature measurements made both during and after drilling are  
3 essential in evaluating the possible presence of a hydrothermal  
4 system. Bottom-hole temperature measurements were made frequently  
5- during the course of the drilling, whenever operations were interrupted  
6 for a few hours so that the bottom-hole temperature could stabilize.  
7 These temperatures were recorded by 3 to 6 maximum-reading thermometers  
8 attached to a short length of drill pipe lowered to the bottom of the  
9 hole on the sand line and permitted to stabilize for 30 minutes to an  
10- hour. Coincidence of readings on a majority of the thermometers  
11 was accepted as evidence that the thermometers had not shaken down  
12 during their return trip to the surface.

13 Beginning on May 30, and continuing until August 25, continuous  
14 temperature logs were run at intervals using a wire-line logging  
15- system and a down-hole thermistor probe. Maximum values recorded  
16 simultaneously with the thermistor probe and the maximum-reading  
17 thermometers generally agreed to within  $\pm 2^{\circ}\text{C}$ . Figure 3 summarizes  
18 some of the temperature measurements made during and after drilling.  
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1           The temperature profile obtained in the Kilauea research drill  
2 hole, like those of many hydrothermal systems, is complex. The  
3 prominent features are:

- 4           (1) An essentially isothermal interval between the surface and  
5-           488 m depth;
- 6           (2) A rapid rise in temperature between 488 m and 732 m;
- 7           (3) A decline in temperature between 732 m and 976 m;
- 8           (4) An increasingly steep rise in temperature between 976 m  
9           and the bottom of the hole, 1262 m.
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1           Temperature measurements made in a single drill hole do not  
2 provide a unique determination of the heat flow in the vicinity of  
3 the hole because the horizontal component of heat flow is not  
4 determined. These temperature data do place limits on the amounts of  
5- possible heat flow. For example, the possibility that the temperature  
6 profiles shown in Figure 3 are the result of steady-state flow without  
7 convection is slight. Reversals and rapid changes in gradient almost  
8 certainly require convective transfer of heat or transient conductive  
9 transfer.

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

### GEOPHYSICAL LOGGING

1  
2       In addition to the borehole temperature measurements, other  
3 physical measurements were made in the borehole using conventional  
4 well logging methods (Table 2), which provide a relatively complete  
5- suite of information about the rock around the borehole, and make up  
6 the primary set of data from the drilling project. The cores recovered  
7 represent only a small sample of the section, and are probably  
8 biased towards the more competent rock intervals, but they provide  
9 a basis for correlating the physical properties measured with the logs  
10- with lithologic character of the rocks penetrated by the borehole.

11       The quality of the logging data was good for most sections of  
12 the hole, although large variations in hole diameter in the uppermost  
13 300 meters caused some problems with the response of the sidewall  
14 logging devices (gamma-gamma density, neutron porosity, and magnetic  
15- susceptibility).  
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1        In this brief report, only certain salient features of the logs  
2 are discussed. Figure 4 contains three 92 meter (300 ft) sections of  
3 the well logs for zones where significant changes in the average  
4 values of physical properties of the rocks are believed to take place.

5- In most logs, the parameters show large variations in value within  
6 short intervals, suggesting distinct changes in the character of the  
7 rock. Superimposed on these abrupt changes are less obvious changes  
8 in the average values.

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

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1 Values of porosity from the neutron-porosity log range from less  
2 than 2 to 35 percent. The scale shown, however, is based on a  
3 limestone matrix and may need to be revised after calibration with  
4 porosity measurements of the core samples. These data are necessary

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6 Table 2 and Figure 4 near here  
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8 for determining pore-water resistivities from the resistivity log  
9 and for studying the degree of water saturation in the section above  
10- the water table. When cross correlated with the density and sonic  
11 logs, values for average grain density and matrix velocity can be  
12 obtained.

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

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

| <u>Type of Log</u>                 | <u>Date Run</u> | <u>Logged Interval (m)</u> |
|------------------------------------|-----------------|----------------------------|
| 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                 |

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

10- A key objective of the logging program was to determine the  
 11 variation in the salinity of the pore waters with depth in the hole.  
 12 The basis for such a determination rests on an empirical relation  
 13 between the resistivity of a rock,  $\rho_r$  and the resistivity of the  
 14 contained water,  $\rho_w$ , which in turn is a function of the concentration  
 15- and mobility of the dissolved salts (Pirson, 1963)

$$16 \rightarrow \rho_r = a \rho_w \phi^{-m} \quad (1)$$

17 where  $\phi$  is the volume fraction of water in the rock (water-filled  
 18 porosity) and  $a$  and  $m$  are empirically determined parameters that depend  
 19 on the pore/interstice distribution within a given type rock.  
 20-

21 *Note to typesetter: r and w subscript; -m superscript*  
 22  
 23  
 24  
 25-

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

#### 14 PHYSICAL MEASUREMENTS ON CORES

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



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

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

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

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

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CAPTIONS

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

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

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

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

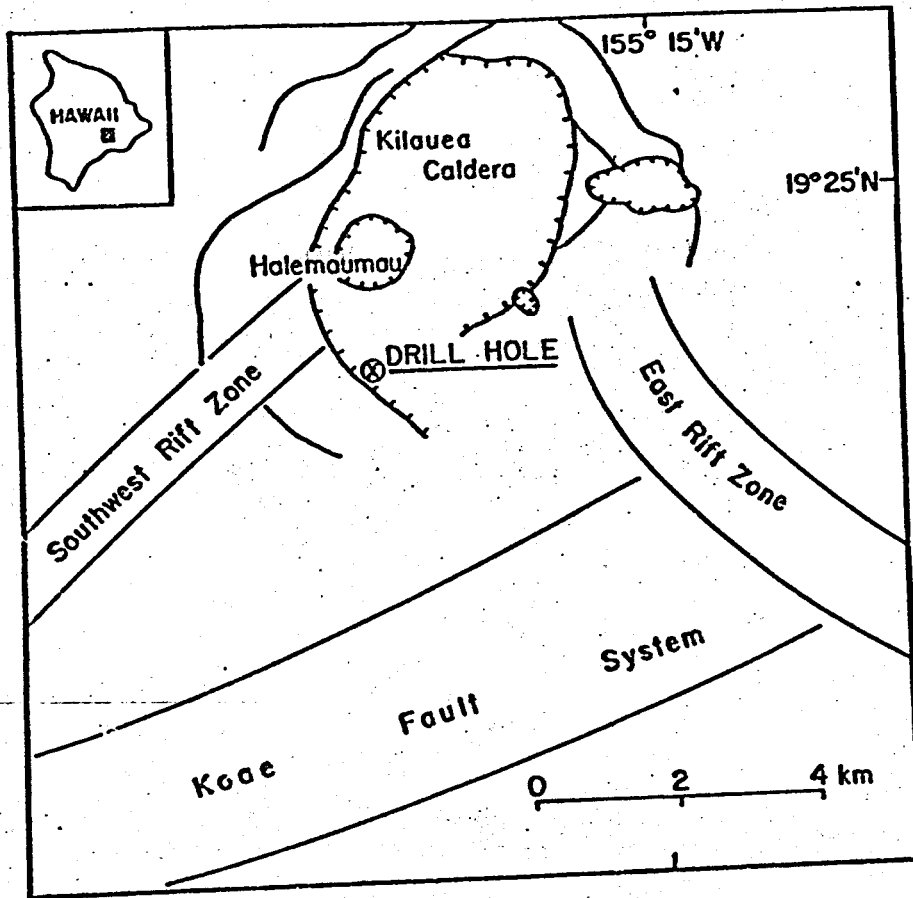


FIG. 1

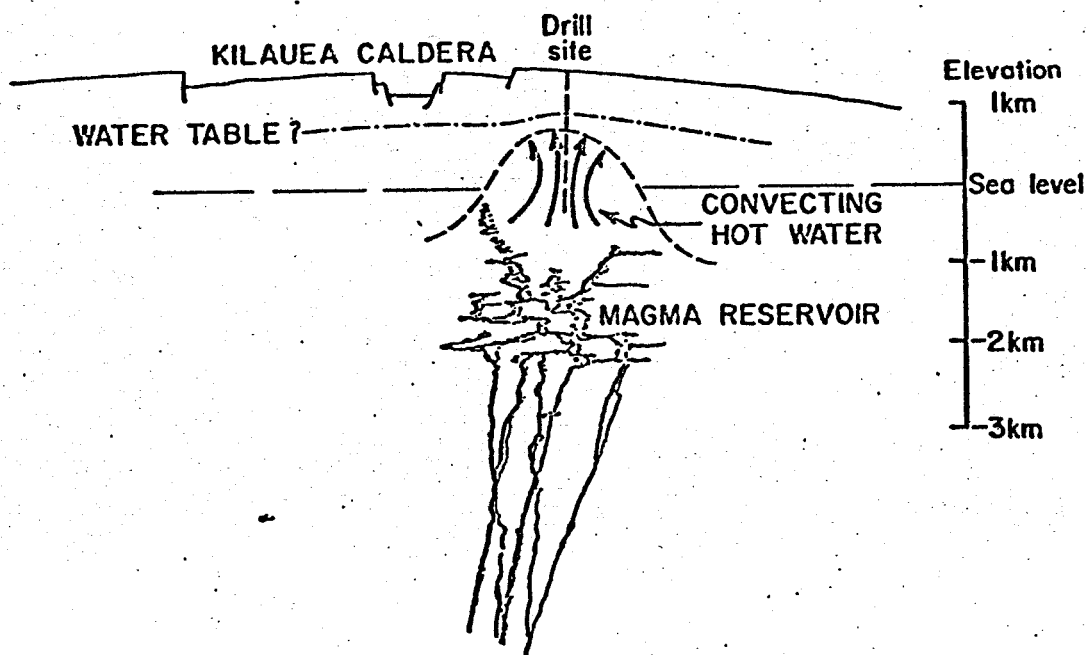


FIG. 2

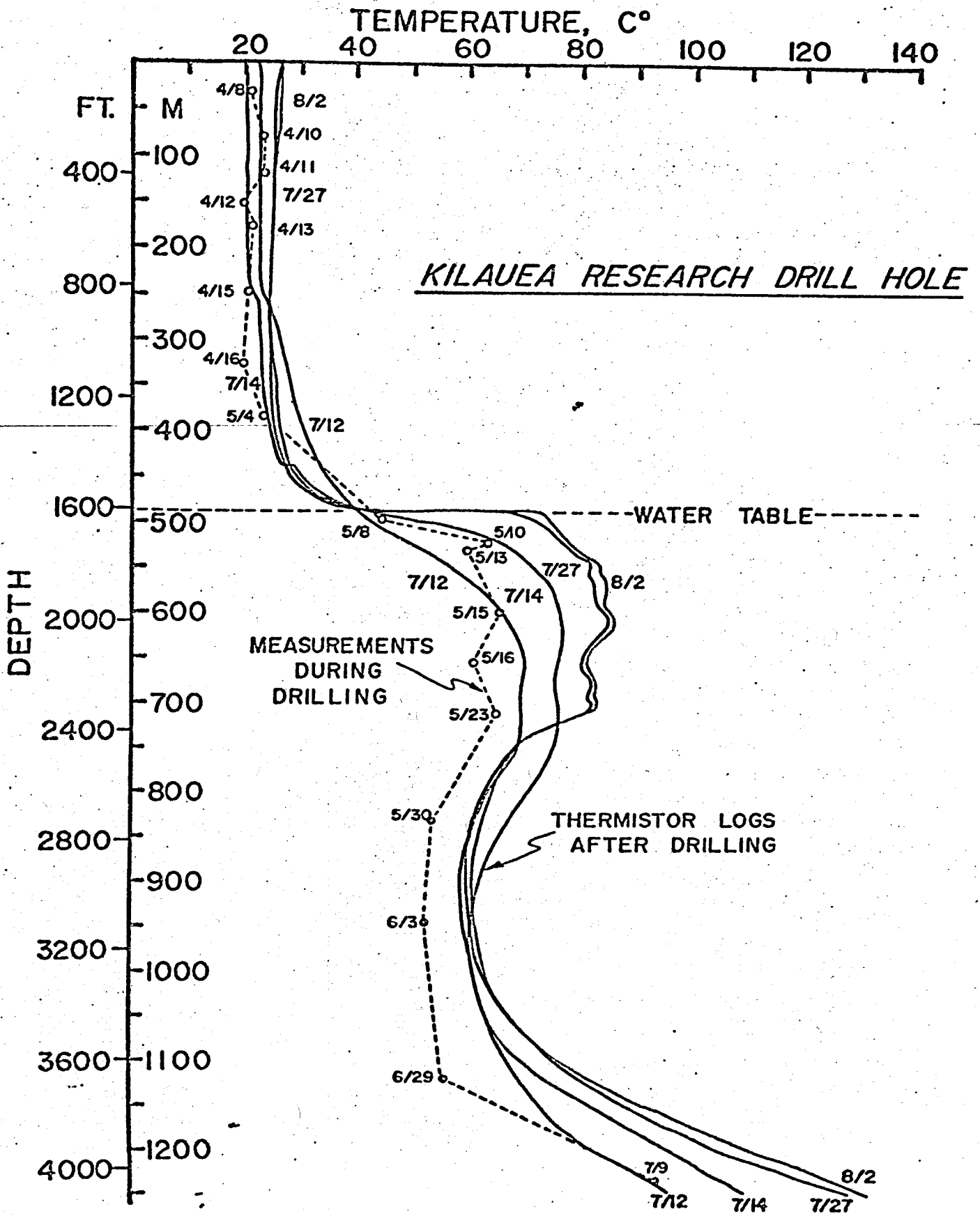


FIG. 3

