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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 of 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 three to 10 kilometers deep, the manner in which heat can be transferred to shallower depths is still poorly understood. If heat is transferred

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Keller

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 nonexplosive 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 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.

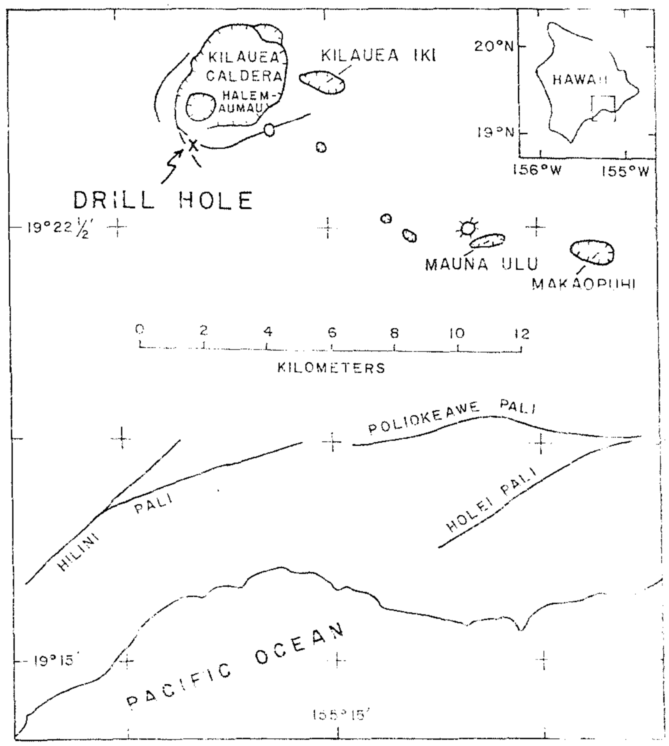


*Figure 1. Index map showing location of drill hole in relation to major features of Kilauea Volcano.*

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 two to four kilometers below the surface (Eaton and others, 1971).

An electromagnetic sounding survey by Jackson and Keller (1972) had defined a strong resistivity anomaly directly above the center of inflation associated with deformation during recent volcanic activity. This anomaly consists of a region of low resistivity with a top surface lying approximately one 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 one 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 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

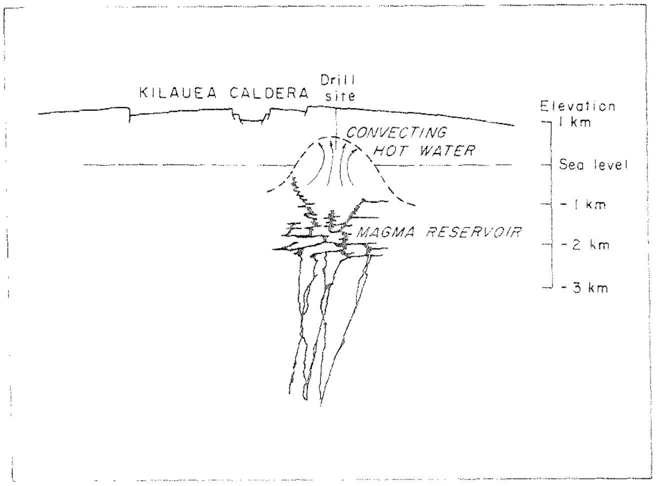


*Figure 2. Hypothetical cross section through Kilauea Volcano and its near-surface magma chamber, based on information available prior to drilling.*

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. 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. 2**) 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 model lies about one 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.

## 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.

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 9,000 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 three meters of core per run. In addition, the endurance of the diamond bits proved to be very limted, 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 one 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 six 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.

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 $\pm 2°C$. **Figure 3** summarizes 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:

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;

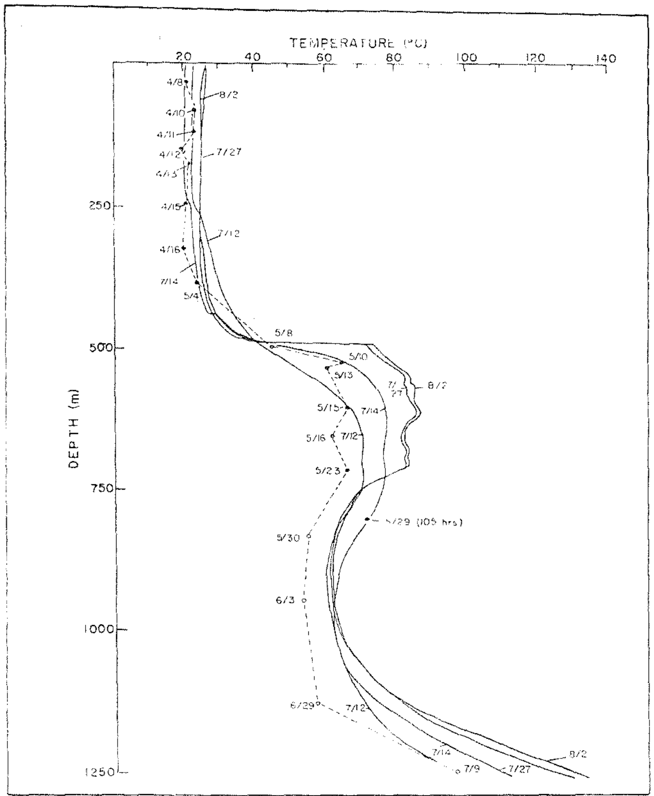


*Figure 3. Depth-temperature profiles for different times in the Kilauea drill hole. Dashes cover links bottom-hole temperatures measured between drilling shifts (generally about eight hours after drilling unless otherwise indicated); dots indicate readings by maximum-reading thermometers and circles indicate readings by thermistor probe. Solid curves are selected post-drilling temperature profiles obtained with continuously recorded thermistor probe.*

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 3.** 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.

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 3** 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.

## 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.

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.


## ACKNOWLEDGMENTS

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