A Coordinated Exploration Program for Geothermal Sources on the Island of Hawaii

AUGUSTINE S. FURUMOTO

Hawaii Institute of Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822, USA

ABSTRACT

Staff members of the Hawaii Institute of Geophysics carried out an exploration program for geothermal sources on the island of Hawaii by using all relevant geophysical and geochemical methods. Infrared scanning surveys by aircraft followed by reconnaissance-type electrical surveys and ground-noise surveys narrowed down the promising area to the east rift of Kilauea.

The surveys carried out over the east rift included magnetic, gravity, and electrical surveys by various methods; microearthquake surveillance; temperature profiling of wells; and chemical analysis of water samples. Aeromagnetic, regional gravity, and crustal seismic refraction data were available in the published literature.

A model of the thermal structure of the east rift was put together to account for the data. The dike complex through which magma from the central vent of Kilauea travels laterally occupies a zone 3 km wide extending from a depth of 1 to 5 km. On the south side of the dike complex, there may be a self-sealing geothermal reservoir where ground water heated by the dike complex is trapped. Not all of the dike complex is hot; hot sections seem to occur in patches.

INTRODUCTION

The active volcanoes of Kilauea and Mauna Loa on the island of Hawaii indicate the existence of a large amount of thermal energy. Because these volcanoes are surface manifestations of thermal processes, geologists and laymen have speculated whether that energy could be harnessed for the generation of electrical power. The high porosity and permeability of the basaltic rock that makes up the volcanoes has been the major obstacle so far. As the lateral flow of ground water is consequently rather swift, even with the existence of fumaroles and warm springs, it has been generally considered that geothermal reservoirs do not exist in the Hawaiian Islands.

Most of the world's geothermal power development is located in continental areas. Even the geothermal field in Iceland is located among acidic volcanoes which resemble continental rather than oceanic volcanoes. Because of these negative facts, it was deemed necessary to do rather comprehensive research on the volcanoes on the island of Hawaii to see whether geothermal sources do exist there.

On the other hand, there are some encouraging speculations that have been proposed since the mid-60s. The concept of a self-sealing geothermal reservoir (Facca and Tonani, 1967) could very well apply to basaltic rocks in Hawaii. Furthermore, in recent years we have seen progress in experiments attempting to utilize hot rock or magma. Because of these developments, a research program was conceived to determine whether Hawaii had a conventional type of geothermal reservoir brought about by a self-sealing mechanism or whether thermal energy was limited to hot rock and magma. If the latter were the case, then the research program should determine the utilizable energy content of the sources.

Although Hawaiian volcanoes have been investigated more than any others in the world, examination of the literature showed it would be necessary to carry out a coordinated series of surveys in order to define the thermal processes associated with the volcanoes. With this in mind, a proposal was submitted to the U.S. National Science Foundation for support of the research. The proposal was accepted and funded.

EXPLORATION PROGRAM

The coordinated exploration program as carried out is shown in schematic form in Figure 1. The actual program differed from that planned because of the funding level, and the slow delivery of equipment and instruments from manufacturers. When the program was begun in May 1973, the USA was facing an acute shortage of material, especially electronic and electrical components and parts.

The persons involved in the exploration program from the Hawaii Institute of Geophysics (HIG) were: Professors A. S. Furumoto and A. T. Abbott; Associate Professor P. F. Fan; Graduate Assistants W. Suyenaga, D. P. Klein, J. Halunen, E. Epp, G. McMurtry, and J. Kauahikaua; Research Associate R. Norris; and Electronics Technician C. Dodd.

In addition, G. V. Keller of the Colorado School of Mines was engaged to conduct an electrical resistivity survey over the summit area and east rift of Kilauea. Throughout the survey he kept in contact with the HIG group and provided timely inputs. Independent of the HIG effort, C. Zablocki of the U.S. Geological Survey was carrying out self-potential surveys in areas of mutual interest. In exchange for field assistance, Zablocki made his data available to the HIG exploration program.

The island of Hawaii is composed of five volcanoes,

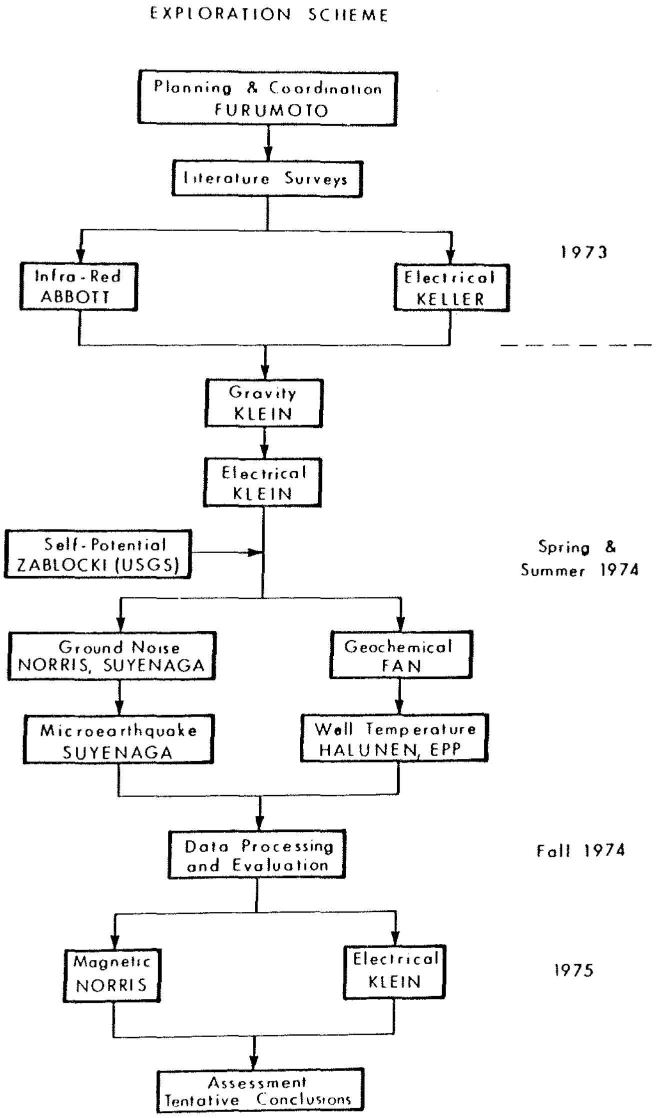

Figure 1. Exploration scheme.

namely Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea (Fig. 2). Of these, Mauna Loa and Kilauea are considered active. Associated with each volcano are rift zones that are named for the direction in which they extend. The exploration program started out with infrared scanning surveys over the rift zones. The results showed that temperatures over the east and southwest rifts of Kilauea and the southwest rift of Mauna Loa were above normal. The other rift zones of the active volcanoes as well as those of the inactive volcanoes showed no temperature anomaly.

With the information provided by the infrared surveys, the three prospective rift zones were examined by reconnaissance-type electrical and ground-noise surveys. The results showed that the east rift of Kilauea was by far the best prospect as a geothermal source. In the spring of 1974 we therefore decided to concentrate on the east rift of Kilauea, which is located in the Puna district. The central vents of Kilauea and Mauna Loa volcanoes were excluded from consideration because they are within the confines of the Hawaii National Park.

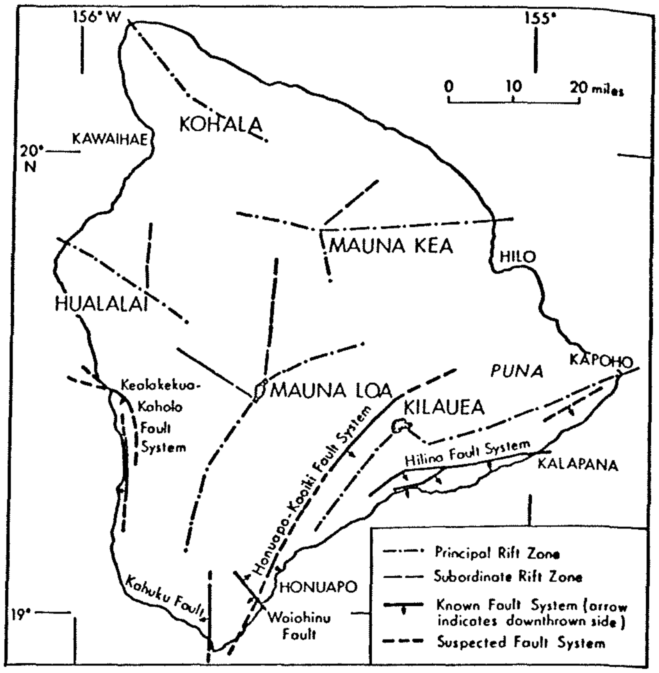

Figure 2. Map of the island of Hawaii showing volcanoes and associated rift zones.

Upon making the decision to concentrate on the east rift of Kilauea, electrical surveys were carried out in greater detail. However, after the anomalous areas of low resistivity were delineated, we found it difficult to interpret the data in terms of thermal processes because of our limited knowledge of the structure of the east rift. Hence, gravity, magnetic, and microearthquake surveys were carried out. The exploration scheme of Figure 1 shows the manner in which the results from one survey provided information or incentive for the others. From time to time, data were assessed and plans were revised.

At this writing (May 1975), the active exploration program has come to a pause, but not necessarily to completion. Although enough data have been gathered to justify a drilling program, further surveys are being planned—especially seismic refraction, gravity, and magnetic surveys—in order to better understand the hydrothermal process.

As part of the broader geothermal project for the island, a site selection committee for a drilling program was set up independent of the exploration program. Although the committee did consider input from the exploration program, it selected a drill site at an early stage before the exploration program could satisfactorily analyze the data collected. There are some misgivings concerning the site chosen.

The next section will present a brief summary of the geophysical data obtained to date.

GEOPHYSICAL DATA

Our discussion is limited to data on the east rift of Kilauea, as the east rift is the only area adequately surveyed so far.

Electrical Surveys

The electrical surveys were conducted by Keller (1973) and Klein and Kauahikaua (1975). The techniques used included dipole-bipole mapping, line-loop time-domain inductive sounding, galvanic sounding, and loop-loop fre-

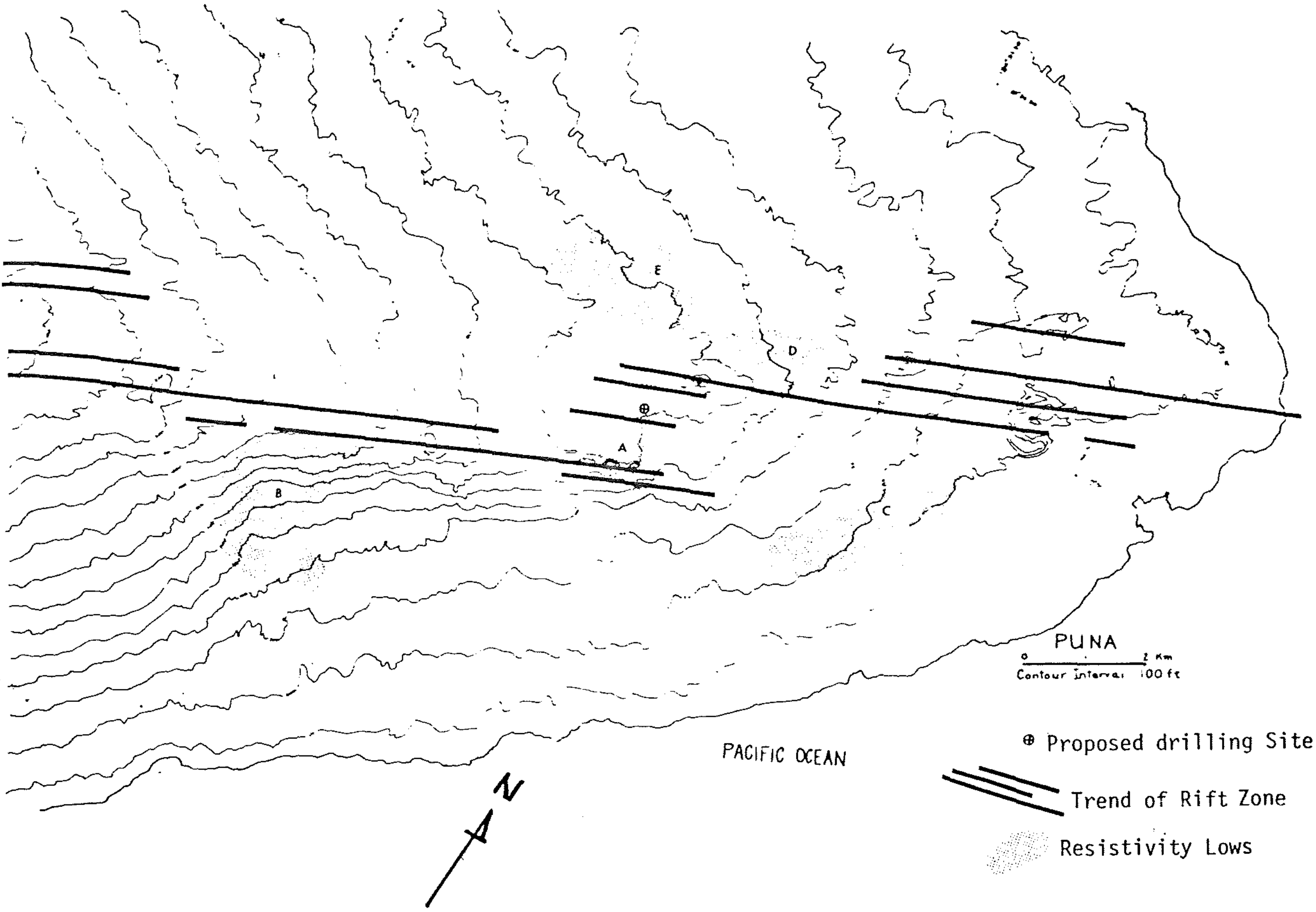

Figure 3. Contour map of Puna area showing trend of rift zone and areas of low electrical resistivity.

quency-domain sounding. The composite results of the surveys given in Figure 3 show five areas (A, B, C, D, and E) of low resistivity. Also shown is the generalized trend of the line of vents to illustrate the geographical relationship of the rift with the areas of low resistivity. Of these, area E is considered the result of cultural sources such as water pipes, sewer pipes, and cables. The low-resistivity zone in area B, which was outlined by Keller (1973), was estimated to exist from a depth of 700 to 2100 m. As outlined by Keller the original area for B was larger; in the map it has been trimmed to exclude those portions thought to be caused by salt water intrusions from the sea. Even so, area B is still much larger than area A.

Attempts have been made to interpret the resistivity data in terms of Archie's Law. The conclusion, although admittedly hazardous, is that the upper limit of the temperature of hot water in the areas under consideration is about 140°C.

Gravity Survey

The available Bouguer gravity map of the island published by Kinoshita (1965) was not particularly useful to the geothermal project because the gravity stations were confined to highways and were spaced at 2-km intervals; for this reason, a more detailed survey was carried out in April 1974 over a stretch of Highway 13 in the Puna district (Fig. 4). For analysis of the data, Bouguer corrections were added and the values were projected along a line that ran perpendicular to the line of vents along the Puna east rift. On incorporating Kinoshita's data, a gravity profile crossing the east rift was obtained, as shown in Figure 5.

To analyze the data, we assumed that the subsurface feature causing the gravity profile was a two-dimensional body. Also, in order to use simplified methods of analysis, we considered the body to cause a symmetrical profile around the maximum value which is shown as 275.3 mgal in Figure 5. We assumed the high gravity values to the right of that point to be caused by a separate body. Upon using the simplified methods as proposed by Skeels (1963) we obtained the values for the gravity anomaly shown in Table 1.

Of the density contrast values given in Table 1, we prefer the value of 0.6 g/cm^3 since this is the value Strange et al. (1965) chose for analysis of volcanic intrusives in the Hawaiian Islands. From the gravity surveys the following conclusions can be drawn:

1. The width of the anomalous body, which we identify as a dike complex, is 3.2 km. This agrees with topographic expression.
2. The vertical dimension of the anomaly is about 3 to 4 km. The anomaly extends from a depth of 1 km to about 4 km.
3. The dike complex exists below the line of vents known as the east rift of Kilauea and trends N65°E.

Magnetic Surveys

An airborne magnetic survey map published by Malahoff and Woollard (1965) showed the east rift as a magnetic low of about 100 gammas trending in an east-west direction.

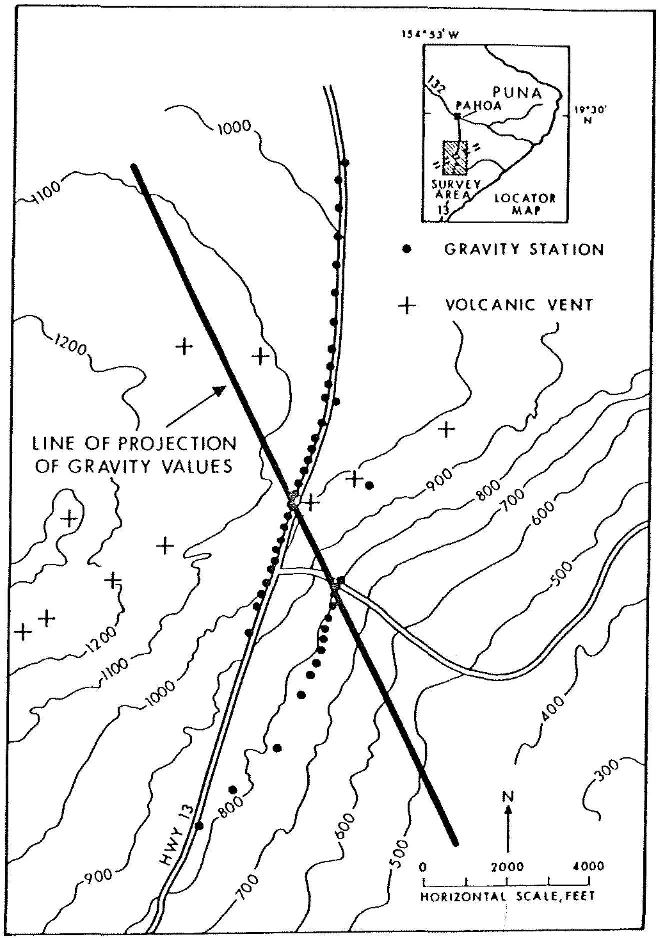

Figure 4. Survey area and gravity stations.

Table 1. Dimensions of an assumed rectangular prism anomaly.

Density contrast (g/cm³)	Depth to top (km)	Depth to bottom (km)	Width (km)	Depth to center (km)
0.6	1.0	3.4	3.2	2.2
0.5	.87	3.6	3.2	2.2
0.4	.69	4.0	3.2	2.3

As data are sparse over the Puna district, a ground survey was carried out in January 1975 (Fig. 6). Although the amount of data gathered was large, only the traverse between the areas of Pahoa and Kaimu (Fig. 6) has been processed to date. The profile is given in Figure 7, and its interpretation in Figure 8.

In the interpretation of the data, we assumed that nonmagnetic areas are regions whose temperatures are above the Curie point, and areas of intense magnetization are relatively cool regions. This meant that along the line from Pahoa to Kaimu, only the southern section of the dike complex has temperatures above the Curie point and that some of the adjacent nondike rocks are also hot. Data from other traverses also showed that not all of the dike complex is hot, and that hot sections occur in patches. Of particular concern to the project is that the spot which the drilling committee has selected for its first drill hole is in one of the relatively cool areas.

Temperature Measurements in Wells

In 1961 three wells were drilled in the Puna district in search of geothermal sources. All three, together with irrigation wells were measured with a temperature probe to obtain thermal profiles with depth. The location of the wells is shown in Figure 9 and temperature profiles of five of these wells in Figure 10. The most prominent profile is that obtained from geothermal test well No. 3. The temperature in the well rises to a high of 92°C, but the hot water layer is rather thin and the water table practically at sea level. This thinness of the hot water layer confirms the rather high permeability of the rocks in the area, which is due not so much to porosity, but to the cracks between successive layers of volcanic flows.

Microearthquake Surveys

An array of seven geophones was set up over the Puna district with signals from all seven telemetered to one central recording station, three of them by hard wire and the other four by radio. The survey covered a period of two weeks and the number of earthquakes detected was not large. Figure 11 shows epicenteral locations and Figure 12, focal depths projected onto cross section AA′ of Figure 11. On the left side of the latter figure is given the velocity structure which we have used to obtain epicenters and focal depths. Notice in Figure 12 that there is a cluster of earthquakes concentrated in the shallow depth between the surface to 5 km. Below the 5-km depth earthquakes are few. One interpretation from these data is that the dike complex, or the active part of the dike complex, is limited to a depth of 5 km. This inference is in accord with our gravity survey which determined the bottom of the dike complex at about 4 km.

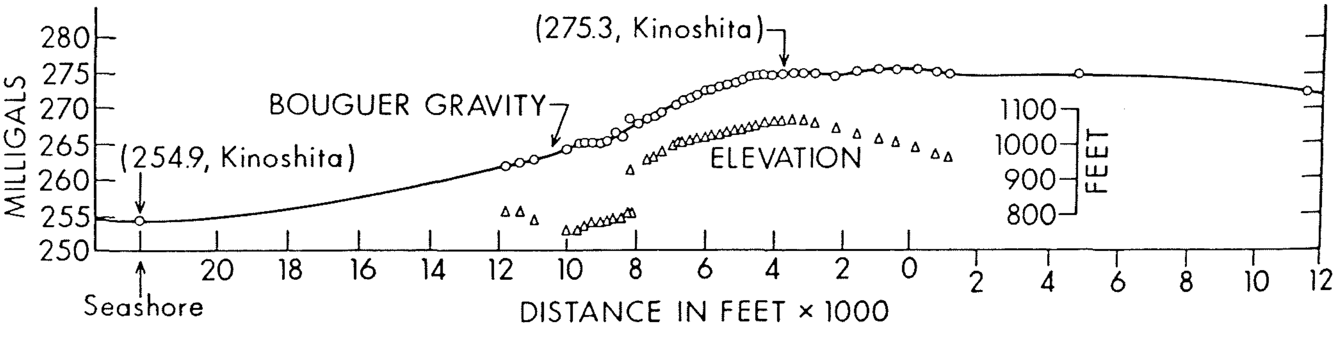

Figure 5. Gravity profile.

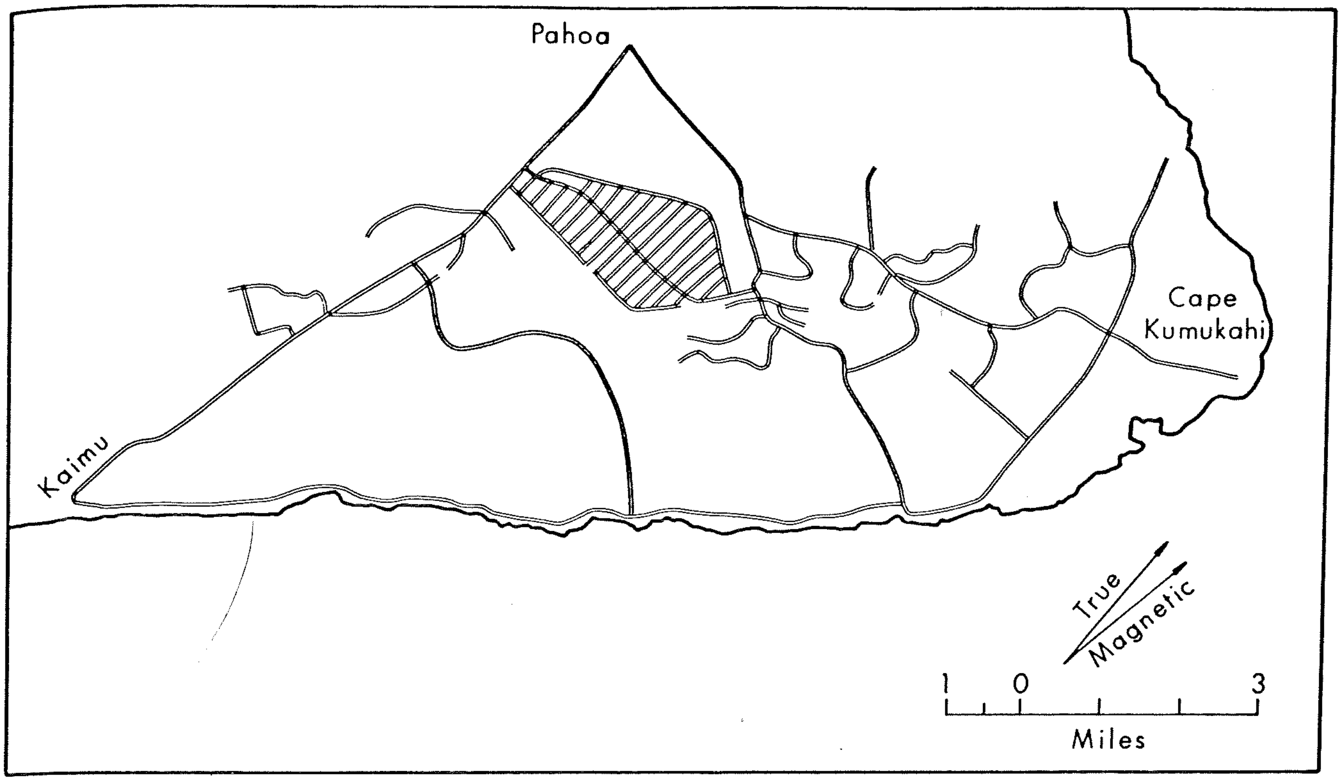

Figure 6. Tracks of magnetic measurements in Puna area.

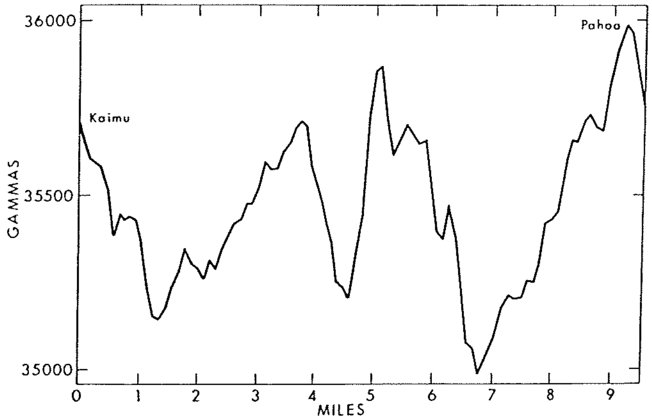

Figure 7. Space-filtered magnetic profile from Kaimu to Pahoa.

Ground-Noise Survey

A ground-noise survey using a 1-Hz geophone was carried out in August 1974. Recording was done on an FM tape recorder. After taking into consideration such things as diurnal variation, meteorological factors, and so forth, a ground-noise intensity map centering on 4 Hz was obtained as shown in Figure 13. Other frequency ranges were analyzed with similar results.

Geochemical Surveys

Water samples from the wells throughout the Puna area were collected and analyzed for oxygen isotope content. Chemical analysis showed that silica content in some of the wells was rather high although the basaltic rock is undersaturated in silica. The significance of the chemical survey is not fully understood at the present time because the use of isotope data as a geothermometer has not been worked out for basaltic rocks. We are seriously looking into this problem.

INTEGRATION OF GEOPHYSICAL DATA

Each of the geophysical tasks provides, in its own way, part of the structure of the east rift of Kilauea and the hydrothermal processes associated with it. When the parts are assembled, a composite picture of the thermal processes emerges. However, the picture obtained is not entirely clear.

The location, shape, and size of the dike complex were determined by gravity and seismic data. Interpretation of magnetic data led to the conclusion that only parts of the dike complex are hot enough to be above the Curie point, but a hot section can heat up adjacent nondike rocks to temperatures above the Curie point. The dike complex in Figure 14 is shown in its geographical relation to the line of vents of the east rift and to the electrically anomalous areas. One of the hot sections inferred from magnetic data is also shown in the figure.

The map of Figure 15 shows that although the dike complex and the line of vents trend N65°E, the magnetic lineaments trend east-west. The magnetic data are from the aeromagnetic surveys of Malahoff and Woollard (1965). The east-west trends are probably ancient remnants of the Molokai fracture zone, as mapped by Malahoff and Woollard (1968). These lineaments are disturbed by hot intrusives, a good example of which is the summit area of Kilauea (Fig. 2). The hot area which we have found by surface surveys also disturbs the lineaments.

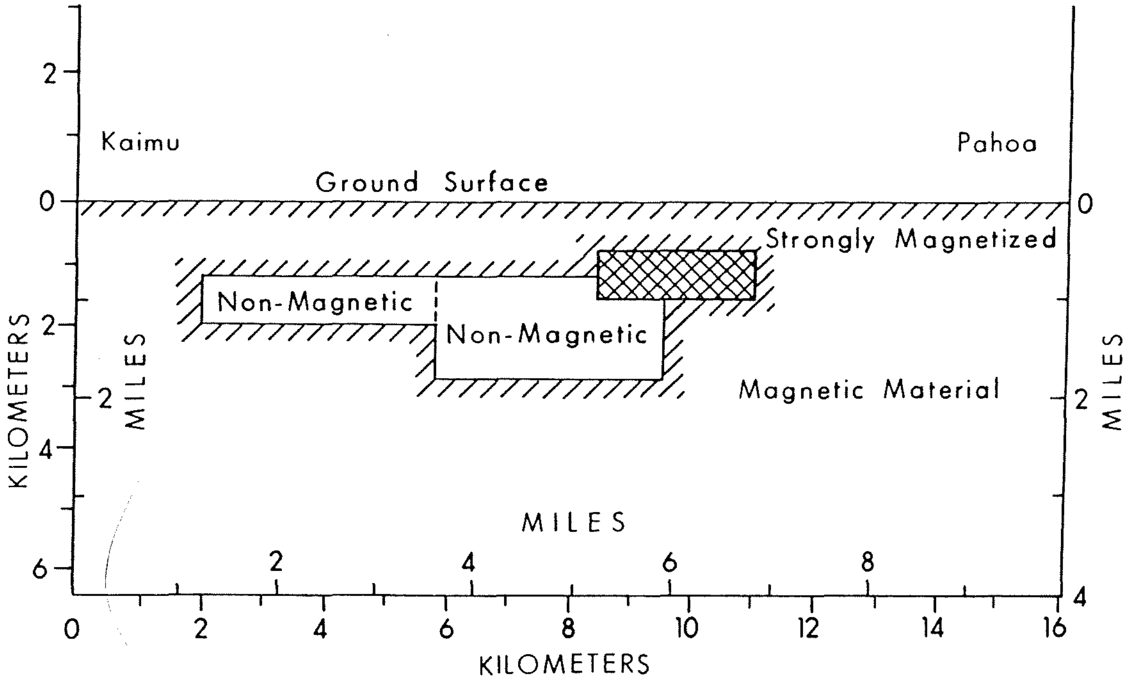

Figure 8. Magnetic anomalies inferred from magnetic profile.

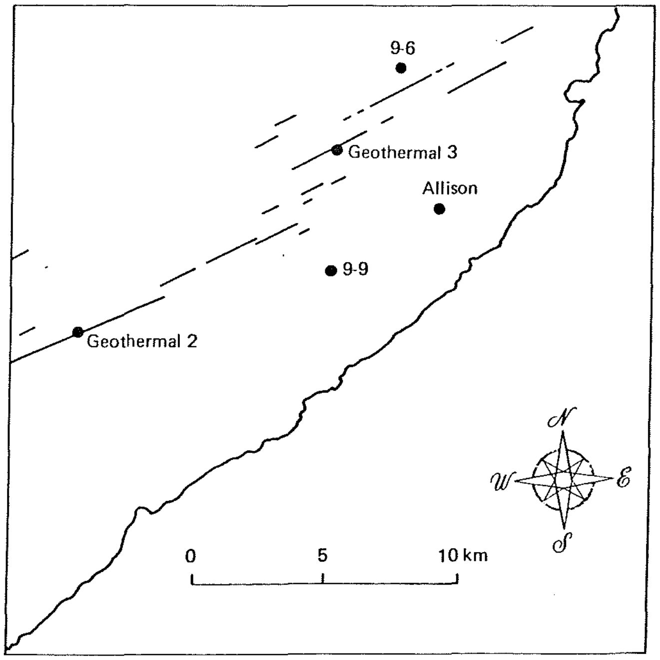

Figure 9. Location in Puna area of wells discussed in the text.

Let us consider first the hot area of Figures 14 and 15 which also corresponds to area B of low electrical resistivity. Keller (1973) calculated that the low-resistivity zone here extends from a depth of 700 m to a depth of 2100 m. Keller (personal commun., 1975) also found from earthquake data that rocks in this area have high Poisson's ratio, about 0.4, and also that small earthquakes here have fault plane solutions which dip southward at angles from 45 to 70 degrees. A high Poisson's ratio is indicative of fractured rocks. Another bit of geophysical data for this area is that of Hill (1969) who, using seismic refraction methods, found a layer with a seismic velocity of 3.1 km/sec at a depth of 700 m, coinciding with the low-resistivity layer of Keller.

We shall now attempt to assemble these seemingly disparate bits of geophysical parameters into a coherent model, which is shown in Figure 16. The source of heat for the rift zone is the dike complex, but hot material whether magma or hot water leaks off into the southern flank of the rift zone. The fractured rocks have cracks dipping south 45 to 70 degrees, as the fault plane solutions indicate. The hot material heats up brine seeping in from the sea, in the manner of the Ghyben-Herzberg hypothesis. Now if the brine is heated, how are we to account for the low resistivity at 700 m depth? We account for it by saying that the 3.1-km/sec seismic velocity represents a pore-filled rock layer. The 3.1-km/sec velocity is peculiar in that it cannot be produced by compressing low-velocity surface basalts with pressures equivalent to 700 m depth. Since some other mechanism is needed, we propose that filling of rock pores and crevices by precipitates from the hot brine changed the seismic velocity to 3.1 in analogy to the self-sealing theory of Facca and Tonani (1967). The pore-filled layer then acts as a caprock to confine the hot brine below 700 m. The pore-filled layer is not very thick, perhaps just thick enough to be a wave guide for seismic waves. In brief, we propose a self-sealing geothermal reservoir for area B.

The model proposed here then accounts for electrical, seismic, magnetic, and gravity data. Admittedly it is highly speculative; the association of the 3.1-km/sec velocity with a pore-filled layer is the weakest link in the series of arguments. But the self-sealing geothermal reservoir model is compatible with all the data that we have so far gathered over this area.

One hazy point in this model is that we do not know how far we can extend it laterally, since electrical data become diffused because of the proximity of this section to the sea.

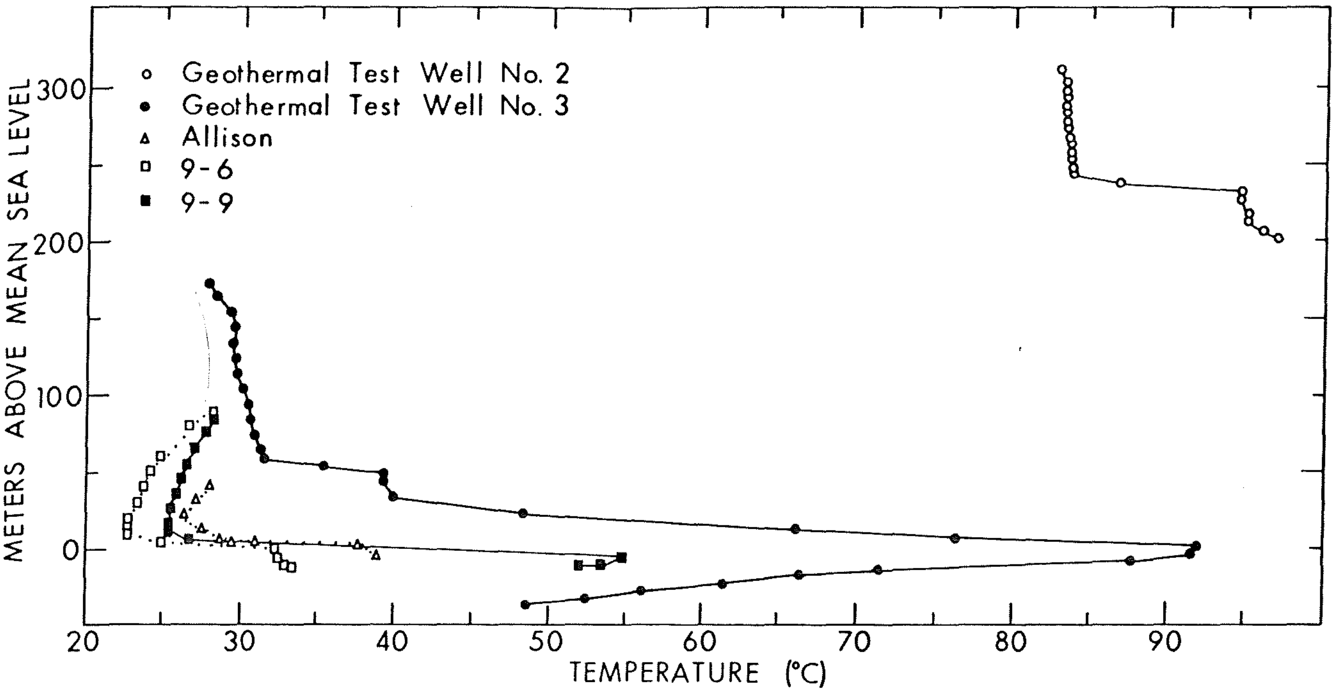

Figure 10. Temperature profiles of the five wells in Puna area.

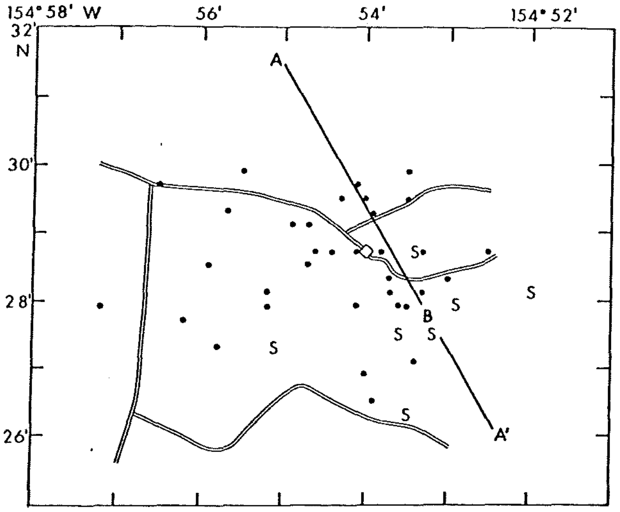

Figure 11. Epicenters of observed earthquakes, S: seismograph stations; B: base station.

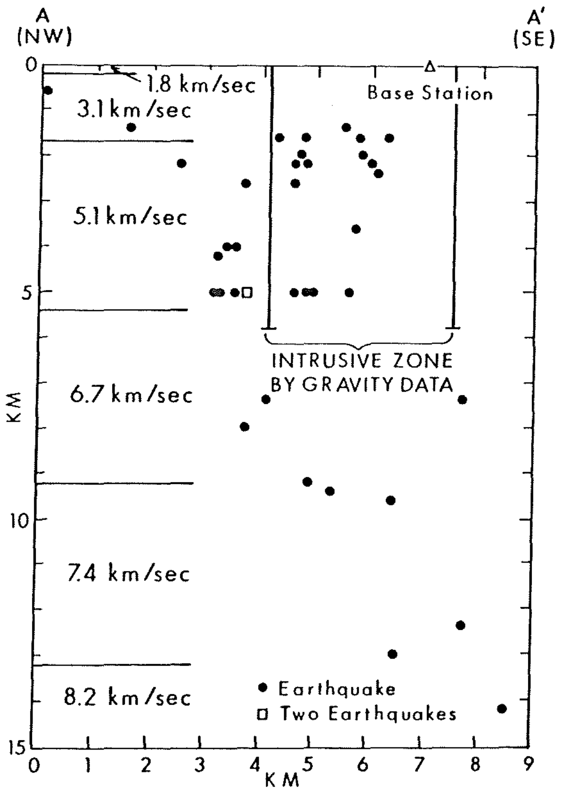

Figure 12. Depth of foci of earthquakes as projected onto plane A–A′ shown in Figure 11.

There are other low-resistivity areas in Figure 14, such as areas A, C, D, and E. Area E can be explained by cultural sources such as sewer pipes and cables; area C is quite similar to area B and may be an extension of area B; area A and C are on the dike complex. Area A has been chosen for a drill site by the site selection committee of the geothermal project. It has the following favorable geophysical data: a self-potential anomaly, a low-resistivity area, a ground-noise high, and hot water (92°C) in a nearby well. But the drawbacks are several: aeromagnetic and surface magnetic surveys do not indicate hot intrusions; the low resistivity occupies relatively a small area so that even if a hot water or vapor system were present, the volume would not be commercially viable; the hot water in the nearby well is limited to a thin layer of about 7 m, and below that the water temperature drops off considerably. The motivation of the site selection committee seems to be the hope of hitting hot rock or magma, but even this hope may turn out to be in vain, as magnetic data would appear to forecast.

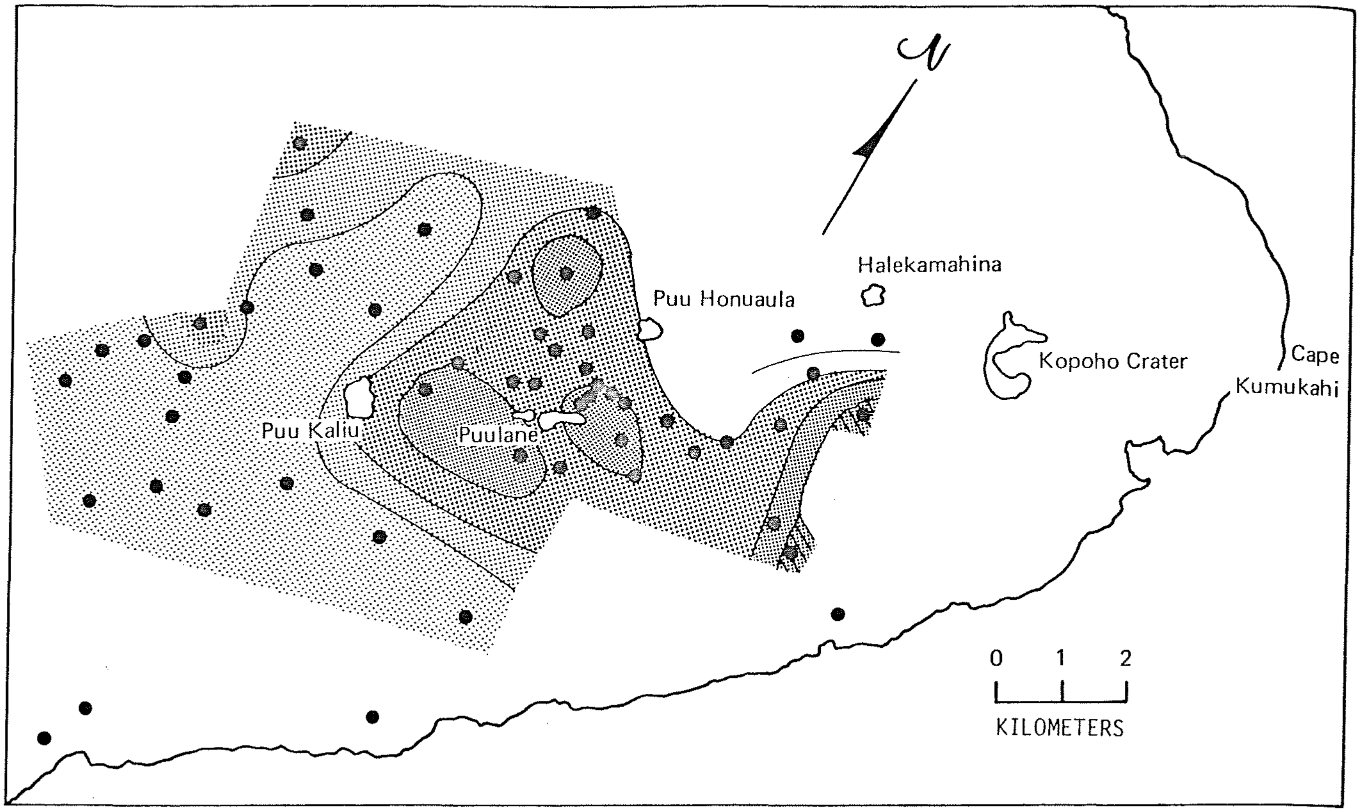

Figure 13. Three db interval contours of 4 Hz noise. The darker the area, the higher the amplitude.

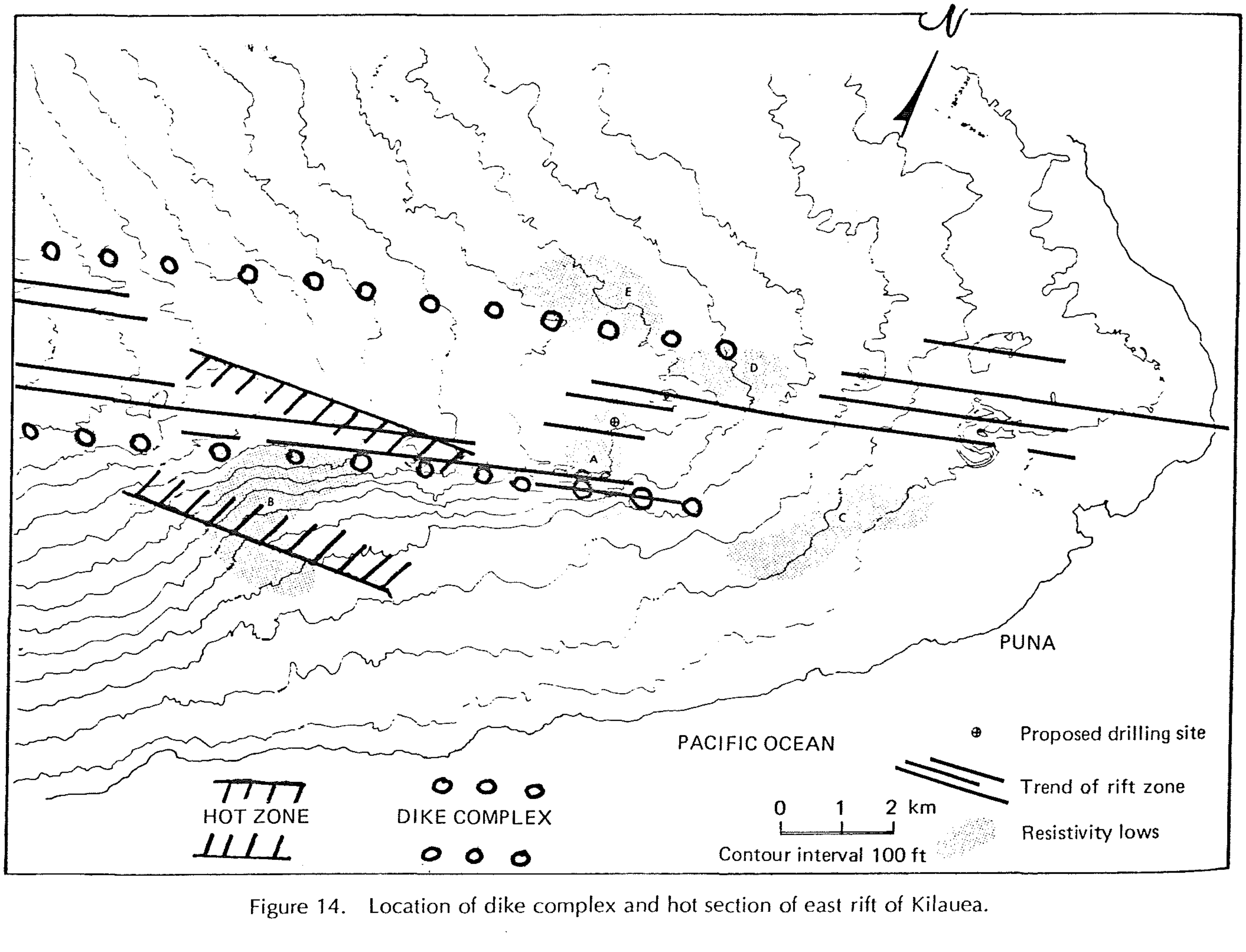

Figure 14. Location of dike complex and hot section of east rift of Kilauea.

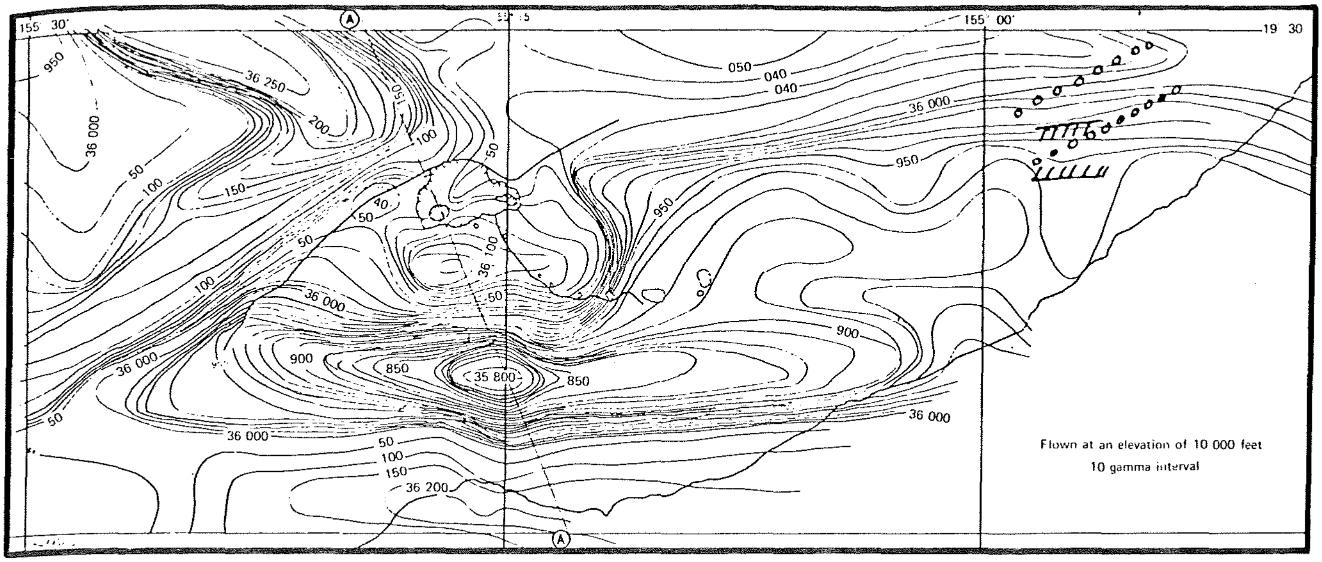

Figure 15. Magnetic map of Kilauea and Puna areas with dike complex and hot area of Figure 14 superimposed.

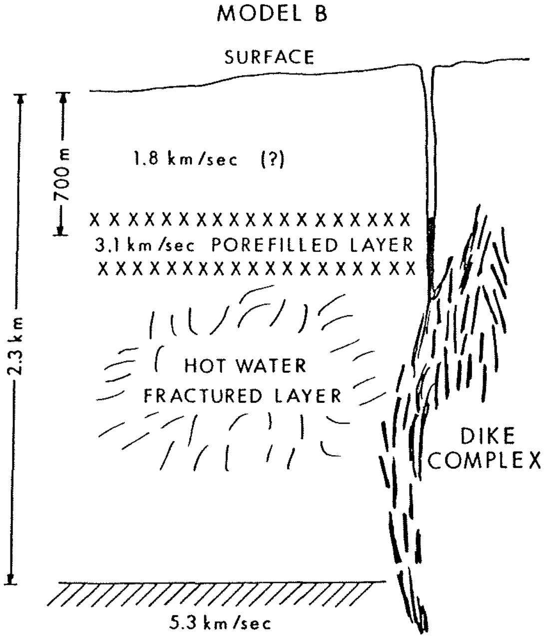

Figure 16. Hydrothermal process of area B. The model is very conjectural.

CONCLUSIONS

Electrical methods are generally considered the most powerful tool for geothermal exploration. But for basaltic rocks with high permeability, the nature of low resistivity areas found by electrical methods cannot be determined unless the ultimate source of heat is found. Usually the source is a dike complex or plug, which can be clearly outlined by gravity and seismic methods. The dike complex is not uniformly hot; hot areas occur in patches which can be found by magnetic methods. Surface magnetic surveys are more effective than aeromagnetic surveys.

We are still assessing the value of geochemical data for resource location.

ACKNOWLEDGEMENTS

Gratitude is hereby expressed to the project participants P. F. Fan, D. P. Klein, J. Kauahikaua, W. Suyenaga, R. Norris, and G. McMurtry, who made their data available for this paper. All of the illustrations used in this paper, except Figure 15, have appeared in a final report to the National Science Foundation under Grant GI 38319. This grant is gratefully acknowledged. This paper constitutes Hawaii Institute of Geophysics Contribution No. 673.

REFERENCES CITED

Facca, G., and Tonani, F., 1967, Self-sealing geothermal field: Bull. Volcano., v. 30, p. 271-273.

Hill, D., 1969, Crustal structure of the island of Hawaii from seismic refraction measurements: Seismol. Soc. America Bull. v. 50, p. 101-130.

Keller, G. V., 1973, An electrical resistivity survey of the Puna and Kau districts: Report submitted by Group 7 to the Research Corporation of the University of Hawaii.

Kinoshita, W. T., 1965, A gravity survey of the island of Hawaii: Pacific Sci., v. 19, p. 339-340.

Klein, D. P., and Kauahikaua, J., 1975, Geothermal-geoelectric exploration on Hawaii Island, preliminary report: Hawaii Inst. Geophysics Report, HIG 75-6.

Malahoff, A., and Woollard, G. P., 1965, Magnetic surveys over the Hawaiian ridge: Hawaii Inst. Geophysics Report, HIG-65-11.

Malahoff, A., and Woollard, G. P., 1968, Magnetic and tectonic trends over the Hawaiian ridge: Am. Geophys. Union Geophys. Mon. 12, p. 241-276.

Skeels, D. C., 1963, An approximate solution of the island of Hawaii: Pacific Sci., v. 19, p. 339-340.

Strange, W. E., Woollard, G. P., and Rose, R. C., 1965, An analysis of gravity field over the Hawaiian Islands in terms of crustal structure: Pacific Sci., v. 19, p. 381-389.