PRELIMINARY STUDIES FOR GEOTHERMAL
EXPLORATION IN HAWAII, 1973-1975

By

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FOREWORD AND ACKNOWLEDGEMENTS

During the world petroleum crisis of 1973-1975, the existence of surface geothermal phenomena such as volcanoes, fumaroles, and hot springs in the Hawaiian Islands suggested that Hawaii should look to geothermal sources for solutions to its energy requirements. In response, staff members and affiliate researchers of the Hawaii Institute of Geophysics, University of Hawaii, are presenting in this series of reports the knowledge and data presently available on geothermal sources throughout the Hawaiian Islands.

The geophysical exploration program on the island of Hawaii was part of the Hawaii Geothermal Project, which was funded by the National Science Foundation Grant GI-38314, State of Hawaii Grant RCUH 774, a County of Hawaii Grant RCUH 773, and by Energy Research and Development Agency Grant 03-1093. The exploration work on the island of Oahu was funded by the Office of Naval Research, Contract C-0824.

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ABSTRACT

This first volume of the series on geothermal exploration in Hawaii has attempted to gather information and data relevant to geothermal resources, which were available prior to the commencement of the exploration program. It is felt that the assembly under one cover of the vast, scattered information will be of service to students of Hawaiian volcanoes and in particular to students of Hawaiian geothermal resources.

A narrative account of the exploration program puts into perspective the various stages of the exploration program from 1973 to 1975. The value of this narrative account lies in that it shows how the conclusion was reached to concentrate the exploration program on the east rift of Kilauea volcano as that rift zone showed the most promise of all the volcanic centers and rift zones. The narrative ends at the selection of a drilling site.

The geology and hydrology of the east rift has been summarized to include data existing before the exploration program and some of the early results of the field surveys.

A literature survey of Kilauea volcano attempted to cover the information available on the volcano. The survey includes recent information published by investigators not associated with the Hawaii Institute of Geophysics.

A literature survey of the geothermal potential of the volcanoes on the island of Oahu has already been published elsewhere. A short summary and reference is included in the volume.

A NARRATIVE OF
THE GEOTHERMAL EXPLORATION PROGRAM ON
THE ISLAND OF HAWAII, 1973-1975

Augustine S. Furumoto

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INTRODUCTION

As surface manifestations of active volcanism such as eruptions, fumaroles, and hot springs are prominent on the island of Hawaii, it was natural that exploration for geothermal sources should start on that island. An exploration program by the staff members of the Hawaii Institute of Geophysics (HIG) at the University of Hawaii was begun in 1973 as part of the Hawaii Geothermal Project, which had been funded through grant GI-38319 from the National Science Foundation and through matching grants from the State of Hawaii and County of Hawaii. The Hawaii Geothermal Project consists of four programs: geophysics, engineering, socio-economics, and drilling. This narrative will deal with only the geophysics program; information on the other programs can be found in project reports (Shupe et al., 1975).

This report chronicles the steps taken in carrying out a geothermal exploration program on the island of Hawaii. First, we pose the problem of geothermal sources associated with Hawaiian volcanoes, which are basaltic volcanoes in the middle of an oceanic plate. Next we discuss the overall exploration scheme. The main part of the report, the chronological narrative, covers the period from April 1973 to June 1975.

A narrative report of this type has certain value. Technical reports appearing in this series will be limited usually to one discipline, such as seismic method or magnetic method. A narrative will show how seemingly disparate disciplines were planned to obtain a coherent scheme. Perhaps, after reading this report, future geothermal exploration workers may build upon our successes and avoid any problems we may have encountered.

THE PROBLEM OF GEOTHERMAL SOURCES IN HAWAII

At the present time, geothermal energy development, whether for electrical power generation, building heating, or other thermal uses, has been limited to certain types of tectonic provinces, as defined by contemporary plate theories of global tectonics. Most of the developments are located in volcanic belts on the continental side of subduction zones. In the subduction zones where the lithosphere of one plate plunges under the lithosphere of another plate, the compressive forces cause rocks to melt, and the resulting melt rises to the ground surface as volcanic extrusions. Associated with the

volcanic process are the geothermal reservoirs. Examples of geothermal development along subduction zones are those in Japan, New Zealand, Indonesia, Chile, Ecuador, and the Philippines.

Geothermal energy developments are also found along spreading zones, areas where new crust is being produced by upwelling from the deep mantle. A notable example of geothermal development along spreading zones is in Iceland, which is considered to be a part of the Atlantic Ridge. The geothermal sources of California and northwestern Mexico are also thought to belong to spreading zones. According to plate tectonics theory, the active spreading zone known as the East Pacific Rise has been overridden by the North American plate, so that beneath the lithosphere of California, Nevada, and northwest Mexico are the linear spreading zones of the East Pacific Rise.

The Hawaiian volcanoes, belonging neither to the subduction zones nor to the spreading zones, exist in the middle of the Pacific plate. To account for the phenomenon of mid-plate volcanism, various theories have been advanced. Some of them are: the hot spot theory, the propagating crack theory, and megashear theory. We shall not, however, discuss these theories here.

An important fact to remember is that with the technology of the present day, there must exist a very favorable geologic structure for utilization of geothermal energy for electrical power generation. The typical geothermal resource is a hydrothermal system that consists of an aquifer heated from below by hot rock or magma and sealed above by a relatively impermeable caprock (White, 1973). Such geological formations are rare, as attested by the small number of geothermal power plants in the world. Although research is being undertaken on methods of harnessing energy from other subterranean thermal sources such as hot rock or magma, a utilizable geothermal source for power generation today must nevertheless be a hydrothermal system as described.

The rocks of Hawaii are shield basalts characterized by high porosity and permeability. They differ from flood basalts as found in the Columbia Plateau, not so much in mineralogical and petrological properties, but in permeability, which seems to be an effect due to space between rock layers rather than to porosity. Because of the relative absence of sedimentary layers in the newer Hawaiian volcanoes such as Kilauea and Mauna Loa, there has been conjecture that caprocks that would form the confining layer for geothermal reservoirs are missing and that utilizable hydrothermal systems do not exist.

The quest for geothermal sources in Hawaii attempts to solve some fundamental problems: the relation of hydrothermal systems to mid-plate volcanoes, the possible existence of caprocks in the absence of sedimentary layers, and the possible existence of geothermal reservoirs without caprocks.

ORIGINAL PROPOSAL AND ACTUAL SCHEDULE

In the proposal submitted to the National Science Foundation as the Hawaii Geothermal Project, the exploration program consisted of fourteen tasks grouped in the following categories:

Aerial methods	
Photogeology	Task 2.1
Magnetic	Task 2.2
Electrical Methods	
Resistivity	Task 2.3
Electromagnetic	Task 2.4
Seismic methods	
Microearthquake and microseismic	Task 2.5
Offshore ocean bottom	Task 2.6
Refraction and reflection	Task 2.8
Thermal Measurements	
Shallow wells	Task 2.7
Deep drilling	Task 2.13
Geochemistry	
Solids	Task 2.9
Fluids	Task 2.10
Physical properties of rocks	Task 2.11
Hydrology	Task 2.12
Model Studies	Task 2.14

The intent of the proposed program was to look for geothermal sources on the island of Hawaii and in the seabed offshore from the island. The amount of funds obtained through the National Science Foundation grant GI-38319 and through matching grants from the State of Hawaii and County of Hawaii caused a curtailment of the ambitious program and limited the objective to searching for hydrothermal sources on the island. This limitation meant the elimination of the task for offshore seismic monitoring by ocean bottom seismographs and the task for seismic refraction and reflection surveys. Also, a drilling project carried out by G. Keller (1974) in the summit area of Kilauea showed that because of temperature inversion in the groundwater systems, shallow well surveys are not justified. Elimination of those tasks made possible the performance of all the other tasks.

The exploration program was carried out as shown in the schematic diagram of Figure 1. The blocks do not mean that the tasks were limited in time, but they show how data and information gathered in one task influenced the work schedule of a subsequent task. For example, from the literature survey, we

Figure 1.

decided to begin the field program with a reconnaissance survey over the whole island with aerial infrared scanning method and also simultaneously an electrical survey over the east rift and summit area of Kilauea because we had much seismic, gravity, and magnetic data over these features. The literature survey continued even as field work began, and it influenced all other tasks. The electrical surveys also proceeded, sometimes at a slow pace, sometimes intensely, for the duration of the program.

The persons involved in the exploration program (Fig. 1) are:

Agatin T. Abbott, Professor, Department of Geology and Geophysics, University of Hawaii(U.H.)
 Pow-foong Fan, Assoc. Professor, Hawaii Institute of Geophysics (HIG), U.H.
 Augustine S. Furumoto, Professor, HIG, U.H.
 George V. Keller, Professor, Colorado School of Mines
 Charles Zablocki, U.S. Geological Survey
 Roger Norris, Research Associate, HIG, U.H.
 Douglas Klein, Research Associate, HIG, U.H.
 David Epp, Graduate Assistant, HIG, U.H.
 John Halunen, Graduate Assistant, HIG, U.H.
 Wayne Suyenaga, Graduate Assistant, HIG, U.H.

Among those listed above, C. Zablocki is not actually a participant of the exploration program but has been carrying on a self-potential survey over the summit area and flanks of Kilauea as part of the U.S. Geological Survey's continuing effort in studying volcanoes. In return for assistance with fieldwork over the east rift of Kilauea, he supplied the field data to the exploration program.

The chart of Figure 2 shows time spent in field work, travel undertaken for consultation and discussions, and the general in-house meetings held by the exploration group to assess progress. As shown, field work was carried out throughout the years of 1973 to 1975 with varying degrees of intensity. As several researchers had academic responsibilities, plans were made to dovetail field work with the academic year. Although Hawaii has a stable climate without seasonal extremes, there were periods of heavy rainfall that precluded outdoor fieldwork. The electrical surveys in particular could not be done in heavy tropical storms. Figure 2, therefore, shows fieldwork concentrated during summer months because of release from academic duties and favorable weather.

	1973												1974												1975				
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
COORDINATION						T																M		M	T				
LIT. SURVEY																													
INFRARED							X																						
ELECTRICAL (Keller)							X																						
ELECTRICAL (Klein)								X	X				X						X	X					X				
GRAVITY																X													
MICROSEISMIC								X											X	X									
GROUND NOISE														X				X		X	X								
GEOCHEMICAL													X			T		X			X			X	T				
WELL TEMP																			X	X									
MAGNETIC																									X				
DRILLING PREPARATION																				T		M							

X= field work

T- travel out of state

M= general meetings

Figure 2. Time Table of Geophysical Exploration Program.

CHRONOLOGICAL PROGRESS OF THE EXPLORATION PROGRAM

Before narrating the sequence of events of the exploration program, we should point out a few geographical names, with the aid of the map of Figure 3. The island of Hawaii is composed of five volcanoes: Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea. Each volcano has two or more rift zones, which are named after the directions in which they radiate. For example, Mauna Loa has four rift zones--southwest, west, north and north-east; Kilauea has two--southwest and east. The east rift of Kilauea cuts through the Puna district, which includes the villages of Kapoho and Kalapana.

Work during 1973.

As soon as funds became available in May 1973, the exploration group began assembling and mobilizing instruments and equipment at the Hawaii Institute of Geophysics in hopes of doing some field work during the summer months. Unfortunately, the spring of 1973 was characterized by a national shortage of materials and parts, and tasks were delayed because of slow delivery (up to five months) of sundry components.

A used trailer was purchased locally to be outfitted as a field office, saving both time and the expense of shipping from the mainland U.S.

In mid-May, A. Furumoto joined ten faculty members from the engineering program of the geothermal project to travel to Stanford University for consultations and to visit the Geyser Geothermal Field. The presentations at Stanford University dealt almost exclusively with engineering aspects. At the Geyser Geothermal Field one becomes impressed with the potential for pollution by a geothermal field.

In June and July, Furumoto visited Japan and Australia, in conjunction with a project funded by the Office of Naval Research. In Tokyo, he discussed with Japanese volcanologists the Proposed U.S.-Japan Seminar on "Utilization of Volcano Energy", which was held in Hilo, Hawaii in February 1974. The Japanese principals in this discussion were Dr. Takashi Minakami and Dr. Kozo Yuhara. He then visited the University of Kyushu in Fukuoka to learn about the nearby geothermal fields of Otake. The discussions about the association of geothermal sources with faults and about discrepancies of results between geological and geophysical surveys were useful to the Hawaiian program.

The first field task was to be the electrical survey by G. Keller. As Keller was in Hawaii to supervise a drilling program in the summit area of Kilauea, he needed only a few

Figure 3. Map of the island of Hawaii showing volcanoes and associated rift zones.

days to mobilize for field work after contractual arrangements with the University of Hawaii were formalized. Because the electrical survey of the Hawaii Institute of Geophysics had to begin from the very bottom with the assembling of instruments, we decided to contract Keller to obtain rapid first-look results over the east rift of Kilauea, where thermal sources were evident from surface manifestations. Keller carried out his surveys in June-July 1973 and submitted a report at the end of July. He concluded that in the Puna district there are areas of low resistivity rock layers, as low as 5 ohm-m, and that these anomalous layers exist at depths of 600 to 2100 m.

The infrared scanning survey was subcontracted to a commercial firm, the Daedalus Corporation of Los Angeles, with A. Abbott in control of the task and responsible for the final interpretation. Flights during the period July 27 to August 4 scanned the rift zones of Kilauea, Mauna Loa, and Hualalai. The results showed what looked like thermal anomalies along the east and southwest rifts of Kilauea and the southwest rift of Mauna Loa. From this survey we decided to limit other survey tasks to these three rifts.

In August 1973 the HIG electrical survey team, with Klein as party chief, and the microearthquake monitoring team took to the field. A loop-to-loop induction method was tried for electrical surveys over the Puna area. This method was designed for shallow probing, so the surveys were done over areas where Keller's survey had shown low resistivity anomalies. The method showed that there was a thin layer of low resistivity at about sea level in addition to what Keller found. After consulting well-temperature data, the team concluded that this thin, low-resistivity layer was hydrothermal water coming off the rift zone. The temperature as measured in the wells ranged from 50°C to 92°C, not hot enough for geothermal uses but a promising indicator of possible thermal sources.

The microearthquake monitoring team set up an array of three geophones about 0.5 to 1 km apart over an area where Keller's survey indicated a low resistivity anomaly. The seismic signals from the geophones were telemetered by hard wire to a cassette tape recorder. Recording was done only during daylight hours, as there was no provision for overnight camping in a lava field. (The field office trailer was being used by the electrical team.) Two weeks of recording revealed only one earthquake in that area, a disappointing result.

Work During 1974

Taking advantage of a sabbatical leave, A. Furumoto spent December 1973 and January 1974 in Japan consulting with scientists, engineers, and industrialists involved in geothermal development, through arrangements made by the Japan Geothermal Energy Association. He also edited abstracts and formulated the program for the U.S.-Japan Science Seminar on Volcano Energy Utilization, scheduled for February 1974 in Hawaii.

In the meantime, at the beginning of 1974, D. Klein's electrical survey team was again in the field, in the Puna area, using the line-to-loop method and the Schlumberger galvanic sounding method. The line-to-loop method confirmed the low resistivity detected earlier by Keller. The galvanic sounding method determined the resistivity values of the dry rocks above the water table. The values varied from 6000 to 30,000 ohm-m.

In January, a geochemical investigation was initiated by P. F. Fan. The initial effort was confined to collecting water samples from existing wells in the Puna area and gathering information on location of wells from the U.S. Geological Survey Offices, files of the Hawaii Department of Land and Natural Resources, and the offices of the County Board of Water Supply. Because the University of Hawaii did not have the type of mass spectrometers necessary for isotope determinations, water sample analyses were performed by University of Hawaii graduate students using the laboratories of the University of California at Riverside.

During the week of February 4-8, the U.S.-Japan Science Seminar on Volcano Energy was held in Hilo. The seminar, Sponsored by the National Science Foundation and Japan Society for the Promotion of Science, was attended by 60 persons. A. Abbott presented the results of his infrared scanning survey on the first day of the seminar. Many papers relating to the thermal processes of Kilauea were given.

During the last week of February, Suyenaga and Furumoto conducted a ground noise survey over the Puna district. Because of the surf pounding on the precipitous, rocky shore, the Puna district had an overall high level of ground noise; however, a pocket of noise high in the 4- to 8-Hz range above the background level was found. This pocket could not be correlated

to any geophysical anomaly found up to that time, but later it was correlated to resistivity anomalies.

During April, the electrical survey team attempted further loop-to loop and galvanic soundings in Puna area. The work was often frustrated by torrential rains. When electrical work was not feasible, a gravity survey was done over a stretch of highway.

In May the isotope analyses of water samples from Puna were performed by G. McMurtry at the University of California at Riverside.

The summer months were marked by a variety of field work. In June, the geochemical group began to gather samples. The electrical team carried out surveys over the southwest rift of Kilauea and the southwest rift of Mauna Loa. The results of these surveys showed that the possibility of geothermal sources in these rifts was less than in the east rift of Kilauea. Also, a ground noise survey showed that microseisms in these rifts are all attributable to surf beats on the shoreline. These findings led to the decision to concentrate on the east rift of Kilauea. The Hualalai rifts were surveyed electrically at the request of the Research and Development Department of the County of Hawaii. Since infrared scanning surveys were unpromising, the negative results of the electrical surveys were not unexpected.

In August, a seven-station array of seismographs was set up in the Puna area to monitor microearthquakes. The stations were in operation night and day for three weeks. Due to absence of public utility electricity, a gasoline-driven generator was installed at the base stations, and although it was operated only to recharge batteries, its noise interfered with the monitoring.

While the seismograph array was in operation, a ground noise survey using portable seismographs was carried out. The advantage is that diurnal variation in ground noise can be checked against the recordings of the seismograph array. Because filtering, summing, and other types of operations were planned for the seismic data, the recording was done on a tape recorder.

In November the geophysics group met to evaluate the results of the geophysical surveys. Each task presented its up-to-date results, but the tasks had not progressed to the stage of definitive conclusions. Only the self-potential data from Zablocki could show a contour map with

recognizable bull's-eye. (Self-potential data require only simple processing to show recognizable contours, while other types of data, such as seismic, require weeks or months of processing. But self-potential data can have several possible source mechanisms--chemical, thermal, or mechanical.) After much debate, the geophysics group concluded that geophysical evidence then available did not justify a program of drilling to search for a geothermal source. More time would be needed to analyze the data and to fit pieces of the puzzle together. Plans were laid for more field work.

Although the consensus of the geophysics group was made known to the other programs in the Hawaii Geothermal Project, the desire to start drilling in 1975 overrode their misgivings. So the geophysics coordinator agreed to an exploratory drill hole to test geophysical data. This fine distinction, exploratory hole to test data versus exploratory hole for geothermal source, was lost in the writing of the renewal proposal.

The site selection committee for the drilling program, which is independent in organization from the geophysics program, met in November to select a drilling site for the renewal proposal. As far as the geophysics program was concerned, no site could be recommended for geothermal exploration, but a hole could be recommended to check geophysical data. The committee chose a site based on self-potential data and geological formation. The geophysical program agreed, as a hole at the site could have value in verifying gravity and magnetic data.

A lengthy renewal proposal for 1975, including drilling funds, was submitted to the National Science Foundation by the participants in the geothermal project in the early part of December.

In December, more water samples were gathered for geochemical analyses at Riverside in January 1975.

At the annual fall meeting of the American Geophysical Union in December at San Francisco, Furumoto presented a paper, "A Systematic Exploration Program for Geothermal Sources in the Island of Hawaii," which included data from the photogeologic, electrical, gravity, and seismic surveys. In informal discussions following the presentations, Chevron Research geophysicists pointed out the problems of applying Archie's law in an attempt to infer subsurface temperature from electrical resistivity data.

Figure 4. Location of electrical anomalies (shaded area) and preliminary determination of dense subsurface body (corcles).

Work During 1975

The site chosen by the drilling committee was based on self-potential data and on the surface manifestations of an offset in vents along the east rift. Keller's survey seemed to indicate that this area was characterized by higher resistivity than background, but his data were sparse. To check resistivity, a dipole-bipole survey was done over the proposed drill site in January. Fortunately, a small area, less than 2 km² of low resistivity, was found near the proposed drill site.

Aeromagnetic surveys had been done over the entire island of Hawaii in 1965 (Malahoff and Woollard, 1968), but the coverage over Puna was not dense. The difficulty is that the absence of navigational markers made close-spaced flights meaningless. To augment data coverage, a magnetic survey on the ground was carried out in January with a rented magnetometer. Although many magnetic materials near ground surface tended to obscure deeper sources, proper spatial filtering and averaging revealed the deeper anomalies.

In March, a critique of the proposal submitted by the Hawaii Geothermal Project in December was received. The critics singled out the lack of geophysical evidence to justify a drilling program. This reaction was not unexpected, as the proposal had been submitted before geophysical data could be properly analyzed and interpreted. By March, the data collected in 1974 was processed to a stage where early attempts at interpretation could be made.

From analyses and interpretation of gravity, magnetic, and microearthquake data, the intrusive zone or dike complex under the east rift of Kilauea was tentatively outlined. The magnetic data seemed to show that only patches of the rift zone were hot enough to be above the Curie temperature.

In April, a few definable areas began to emerge as possible geothermal reservoirs. These areas are denoted by A and B in Figure 4, which also shows areas of anomalous low resistivity. As there were doubts about the previously selected drilling site, in May the drilling site selection committee chairman called another meeting for discussions. George Keller flew in from Colorado to attend.

The meeting revolved around which of the areas, A or B, should be the site for drilling. As drilling funds were limited, it was important to choose the site with the most probability of success. Keller explained his preference for site B because of indications by seismic data of highly fractured rocks and by electrical data indicating low resistivity. Furumoto also advocated area B because seismic and electrical data seemed to suggest a confined reservoir

with a caprock, perhaps formed by a self-sealing process. The area of anomalously low resistivity is larger at B than at A. At the end of the discussions, Keller and Furumoto, the two senior geophysicists in the program, favored area B; Norris was noncommittal, and others favored area A. The decision of the committee to stick to area A as the drilling site was based on a numerical count of votes.

At the United Nations Geothermal Symposium in May at San Francisco, a written report of the geophysical exploration program was submitted for publication in the symposium proceedings (Furumoto, 1976).

CONCLUDING REMARKS

At present, June 1975, most of the Puna field work has been completed, and other areas of the island of Hawaii have also been examined. Unpromising results from the other parts of the island encouraged us to concentrate on the Puna district.

In evaluating the results, we find that gravity and magnetic data became very significant, more than had been anticipated at the start of the exploration program. The microearthquake monitoring task should have calibrated the instruments so that source mechanisms could be determined. The electrical data cannot stand by themselves to provide sufficient evidence for drilling site selection. The salinity of seawater percolating into the island rock mass can cause misinterpretation of data unless gravity and magnetic data are available to show the original thermal sources.

It should be emphasized that the exploration program was initiated without any previous experience to go by, without much help from scientific literature. Nowhere else have geothermal sources been sought on an active volcano in an oceanic basaltic province. Exploration among basaltic rocks was being carried out in Iceland, but literature from Iceland was scarce at the time our program took to the field. Even if Icelandic data had been available, there would have been only a slight similarity, as Iceland sits on a spreading zone between plates, while Hawaii is a case of mid-plate volcanism.

Although this program was one of applied research, i.e. to find a geothermal source, it is felt that future results will contribute substantially to the basic knowledge of volcanoes in a mid-plate setting.

REFERENCES

- Furumoto, A.S., 1976. A coordinated exploration program for geothermal sources on the island of Hawai. In Proceedings of the Second United Nations Geothermal Symposium, Vol. 2, p. 993-1001.
- Keller, G.V., 1974. Drilling at the summit of Kilauea volcano. Reported submitted to the National Science Foundation by the Colorado School of Mines, 45 pp.
- Macdonald, G.A., 1956. Structure of Hawaiian volcanoes. Verhandelingen van het Koninklijk Nederlandsch Geologisch Mijnbouwkundig Genootschap, Vol. 16, 1-22.
- Malahoff, A., and G.P. Woollard, 1968. Magnetic and tectonic trends over the Hawaiian Ridge. In The Crust and Upper Mantle of the Pacific Area, . Geophys. Monogr. Ser., Vol. 12, pp. 241-276, Am. Geophys. Un., Washington, D.C.
- Shupe, J.W., A.S. Furumoto, P.C. Yuen, R.M. Kamins, and A.T. Abbott, 1975. Hawaii Geothermal Project, Summary Report for Phase I. Univ. of Hawaii, Honolulu, Hawaii 160 pp.
- White, D.E., 1973. Characteristics of geothermal resources. In Geothermal Energy, Resources, Production, Stimulation, Stanford Univ. Press, p. 69-94.

GEOLOGY AND GROUND-WATER HYDROLOGY

Gordon A. Macdonald

INTRODUCTION

The island of Hawaii was formed by five major volcanoes. Kohala, at the north end, and Mauna Kea, next to the south, have not been active in recorded history; the last eruptions occurred several thousand years ago. On the west side of the island, Hualalai erupted last in the years 1800-1801. Since the advent of European and American visitors to Hawaii and the beginning of written records, Mauna Loa and Kilauea have been among the world's most active volcanoes. Mauna Loa erupted last in 1950. Kilauea has erupted repeatedly since 1952 and has been in eruption almost continuously since 1969.

Both Kilauea and Mauna Loa are indented by summit calderas whose floors are as much as 180 m below the rims. The calderas were formerly somewhat deeper but have been partly filled by lava flows. As exposed in the dissected calderas of older volcanoes on other Hawaiian islands, the lavas filling the caldera tend to be considerably denser, more massive, and less permeable than those on the flanks of the volcano outside the caldera. In some of them, such as the Koolau caldera on Oahu and the East Molokai caldera, further reduction in permeability has resulted from alteration of the rocks by gases rising through them, with transformation of pyroxene to chlorite and epidote, and deposition of secondary quartz, calcite, and zeolites in vesicles and other openings. Similar changes can be presumed to have occurred, at least to some extent, beneath the caldera depressions of Kilauea and Mauna Loa.

Extending outward from the calderas are rift zones-- zones of innumerable open or filled fissures that have served as pathways for the rise of the magma that produced most of the eruptions. (A few eruptions take place away from the rift zones.) Kilauea and Mauna Loa each have two major rift zones. At the surface the rift zones are marked not only by fissures but also by many spatter cones and ramparts and cinder cones built at the site of eruptions, and by a few pit craters. Parts of the rift zones are bordered by faults, between which the intervening area has sunk to form a shallow graben. Similar rift zones exposed by erosion on older Hawaiian volcanoes contain thousands of dikes, formed by consolidation of the magma

in the fissures. Individual dikes may reach as much as 15 m in thickness, but most of them are less than 5 feet. Transects of the dissected rift zones typically give counts of several hundred dikes per kilometer, and more than 350 per kilometer of width of rift zone is not uncommon. The attitude of the dikes varies considerably, but most of them strike more or less parallel to the rift zone and dip in one or the other direction at angles greater than 70° .

Between the dikes there remain many slices of basalt lava flows. The inter-dike lava-flow masses consist of both pahoehoe and aa flows, generally thin-bedded, and identical to those on the flanks of the volcano away from the rift zones. For the most part they are moderately to highly permeable. The openings primarily responsible for the permeability are joints, inter-flow spaces, openings between the fragments in aa clinker layers, and lava tubes. Vesicles are too poorly interconnected to contribute importantly to the permeability. Alteration and secondary mineralization like that described in the caldera-filling rocks is essentially absent in the dissected rift zones, extending at the most only a few hundred feet beyond the caldera boundary.

Information on the geology and hydrology pertinent to the possible occurrence and entrapment of geothermal resources is given in the following sections for each of the areas thought to be most promising for geothermal exploration.

EAST RIFT ZONE OF KILAUEA

The east rift zone extends southeastward from the Kilauea caldera for about six km, then bends abruptly east-northeastward and extends through Cape Kumukahi, the eastern point of the island. Beyond the cape it forms a broad east-northeast-trending ridge on the ocean floor for another 65 km (Malahoff and McCoy, 1967). Northwest of the bend the rift zone is marked by a row of pit craters (the Chain of Craters) and a few spatter-and-cinder cones. East-northeast of the bend more than 60 spatter and cinder cones mark the sites of pre-historic, but geologically recent, eruptions along the rift zone. Just before the beginning of written history, eruptions took place on the eastern part of the rift zone in about 1750 and 1790. Historic eruptions along it have occurred in 1840, 1922, 1923, 1955, 1960, 1961, 1962, 1963, 1965, 1968, and 1969 to the present.

The area known as East Puna consists of the part of the Kilauea volcano east of about 155°W latitude. It is a broad, gently sloping ridge built by lava flows from the east rift zone, and the rift zone extends along its crest. It is situated more or less midway between Kilauea caldera and the termination of the rift-zone ridge at the ocean floor. Within it, between the 500-m contour and sea level, eruptions have occurred in about 1750 and 1790, and in 1840, 1955, and 1960. In 1924, numerous earthquakes and volcanic tremor accompanied the disappearance of the lava lake in Kilauea caldera and the sinking of the floor of a graben along the rift zone close to sea level in East Puna; although no molten lava appeared at the surface above sea level it is virtually certain that a large volume of magma moved eastward through the rift zone. The surface expression of the rift zone is about 3 km wide.

East of Cape Kumukahi the submarine cones along the rift zone appear very fresh in photographs. A submarine eruption occurred a few kilometers off shore in 1884.

Lava flows from vents along the rift zone have poured downslope, building a broad structural arch that plunges east-northeastward at an angle of 1° to 2°. North of the rift zone the lava beds dip 2° or 3° northeastward. South of it the dips are 2° to 4° southeastward. Locally on the south side of the ridge, dips of more than 6° probably are the result of lava flows mantling a southeast-facing fault scarp (Stearns and Macdonald, 1946, plate 1). The lava flows are of both pahoehoe and aa types. No specific determinations of permeability are available, but similar lavas yield water freely to wells, and overall permeability is unquestionably high. Large amounts of groundwater move through the area, producing many brackish basal springs along the shoreline.

Beneath sea level, divers have observed what appear to be pillow lavas, and similar lavas are shown in deeper water by photographs (Moore and Fiske, 1969).

Warm (33°C) brackish water issues in the beach at Pohoiki, 7.6 km south-southwest of Cape Kumukahi. Previous to 1960, warm (29°C) brackish basal water was present in a crack on the rift zone 2.4 km west of the Cape, and similar water at 32°C was present in another crack 1 km to the northwest. The cracks lay close to the borders of the graben that sank in 1924; both were buried by lava in 1960. A well 6 km west of Cape Kumukahi contained brackish water at 34°C. A well 4 km S80°W of

Pohoiki contains brackish water at 53°C. Many steaming vents are present along the rift zone west of 300-m altitude, but east of that altitude only minor wisps of steam issue, especially in Pawai crater, a small pit crater 10 km southwest of Cape Kumukahi. At Pahoa, and 8 km to the south along the Pahoa-Kalapana road, wells produce cold basal water of good quality.

The warm-water wells are distinctly more saline than would be expected (Macdonald, 1973) on the basis of normal Hawaiian basal groundwater conditions in other areas of similarly high rainfall and rocks of approximately the same permeability. The well nearly west of Pohoiki had, on completion, a chloride content of 6,500 mg/l (approximately 6,000 ppm), and the well 6 km west of Cape Kumukahi had a chloride content of 320 ppm. Thus there are distinct anomalies in groundwater conditions in East Puna, and the most probable cause is heating of the sea water saturating the underlying rocks, probably by hot intrusive masses along the rift zone, decreasing the density of the water to the point where it can no longer support the normal Ghyben-Herzberg lens of fresh water.

Although all of the exposed rocks are moderately to highly permeable, it is possible that less permeable material may exist at depth. Along part of the contact where Kilauea overlaps the slope of Mauna Loa, 35 km west of Cape Kumukahi, Kilauea lavas overlap several feet of relatively impermeable weathered volcanic ash (Stearns and Macdonald, 1946, plate 1). This ash layer lies on the crest of a broad constructional arch built along an ancient east-trending rift zone of Mauna Loa. Magnetic measurements (Malahoff and Woollard, 1966) suggest that this old rift zone of Mauna Loa continues eastward beneath the cover of Kilauea lavas and merges with the east rift zone of Kilauea approximately at Cape Kumukahi. If so, the ash layer may continue beneath Kilauea lavas to or beyond Cape Kumukahi at some depth below sea level. If present, the ash layer might conceivably form a tight cap over permeable lavas beneath in such a structural arrangement as to trap or concentrate steam or hot water.

Another possibility for the formation of a zone of less permeable material is related to the presumed history of the submarine growth of the volcano. It is believed that in deep water the eruptions were non-explosive, because of the restraining hydrostatic pressure of the overlying water; but as the volcano grew into shallow water the explosive liberation of magmatic gas became possible, and contact of the erupting magma with water probably caused numerous moderately violent steam explosions like those during the

recent eruptions of Surtsey volcano in Iceland and Capelinhos in the Azores. These would form large amounts of glassy ash that would rapidly become palagonitized. If the ash stayed in place it may constitute an extensive, poorly permeable layer or layers intercalated in the lava flows, possibly forming a relatively tight caprock. Still another possibility is that hyaloclastite, formed in association with pillow lavas and altered to palagonite, may form relatively tight layers in the lava sequence.

Sinking of the island may have carried any of these impermeable layers to considerable depths below the level at which they formed. Thus there is a possibility of stratigraphic and structural traps for several hundred of meters below sea level.

SOUTHWEST RIFT ZONE OF KILAUEA

The second principal rift zone of Kilauea volcano extends from the caldera southwestward to the coast and beyond. Little is known about it below sea level. Above sea level it is dotted with about 30 spatter and cinder cones at the vents of prehistoric eruptions. During historic time, eruptions occurred along it in 1823, 1968, 1919-1920, 1971, and 1974. Vents of the latter two eruptions, along the upper (northeast) part of the rift zone, were still steaming in January 1975.

The rift zone is as much as 4 km wide, and near the caldera is bordered by inward-facing fault scarps. Farther southwest the graben structure is less clear, although locally the rift zone is bordered on the northwest by southeast-facing fault scarps. The rift zone lies parallel to, and about 2 to 5 km southeast of, the Kaoiki fault zone, along which the lower slope of Mauna Loa has moved downward in relation to the upper part of the mountain.

The constructional ridge along the southwest rift zone is asymmetrical. Northwestward, the Kilauea lavas abut against the slope of Mauna Loa, usually within 2 km of the rift zone. Dips between the rift zone and the Mauna Loa contact are generally about 2° to 3° southwestward, nearly parallel to the rift zone. Southeast of the rift zone dips range from 4° to 6° southeastward. The lava flows are pahoehoe and aa, similar to those of East Puna. The rift is uninterrupted for almost 25 km along the lower part of the rift zone, and served as the near-surface conduit for the 1823 lava flow.

Warm water has long been known in a crack in Waiwelawela ("hot water") Point, at the coast 4 km southeast of the Great Crack. It is brackish, but its salinity has not been measured. Its temperature is 32°C. Anomalous groundwater conditions exist in the area west of the Great Crack, around Pahala, and between there and the ocean. Fresh groundwater, apparently part of the basal zone of saturation, stands about 70 m above sea level in the Pahala well. It is not known whether this high level of groundwater is in any way related to the southwest rift zone of Kilauea. It could result from obstruction of seaward movement of the groundwater by faults of the Kaoiki system and/or numerous relatively impermeable dikes in the rift zone, possibly combined with unexposed poorly permeable tephra and/or hyaloclastite below present sea level. The Pahala ash, which is largely palagonitized, reaches thicknesses of as much as 17 m near Pahala, and is presumably down-dropped along the Kaoiki fault system and buried by later lavas farther seaward.

SOUTHWEST RIFT ZONE OF MAUNA LOA

One of the two principal rift zones of Mauna Loa extends southwestward from the summit caldera to an altitude of about 2,300 m, then broadens and turns southward to Ka Lae (South Point). Above 2,300 m altitude the rift zone is approximately 3 km wide and is studded with many spatter-and-cinder cones, spatter ramparts, and open fissures. Just south of the caldera are three pit craters. Below 2,300 m the rift zone broadens to about 6 km, but at about 1,100 m the western part of the zone dies out and the eastern part continues southward. This southward extension is only about 2 km wide. Along its western edge, the north-trending Kahuku fault has formed a westward-facing scarp 180 m high near the coast, gradually decreasing in height inland and disappearing near the highway at 600-m altitude. Between 760 and 975 m altitude, the Pali o ka Eo is probably a buried west-facing scarp en echelon with, and slightly east of, the Kahuku fault. The rift-zone ridge and the Kahuku fault scarp can be traced southward on the ocean floor for about 35 km beyond South Point.

A pit crater lies near the eastern edge of the rift zone at 1,370-m altitude, and three other small ones lie close to the top of the Kahuku fault scarp between 530- and 565-m altitude. These pit craters are partly buried by Pahala ash, showing that the rift zone has been active at least since the latter part of the eruption of the Kahuku Volcanic Series (Stearns and Macdonald, 1946).

Most of the lavas along the southwest rift zone of Mauna Loa belong to the Kau Volcanic Series (Stearns and Macdonald, 1946). They are tholeiitic basalts of both pahoehoe and aa type, similar to those of Kilauea. East of the rift zone and along the top of the Kahuku fault scarp the Kau lavas rest on Pahala ash, which in this region ranges from about 2 to 8 m in thickness. The ash is largely palagonitized. Beneath the ash, in the Kahuku scarp 180 m of thin-bedded tholeiitic pahoehoe and aa flows of the Kahuku Volcanic Series are exposed. No ash beds are intercalated with the lavas below the Pahala ash.

Since 1832, seven eruptions have taken place along the southwest rift zone. Most were from vents above 2,300 m altitude, but in 1868 an eruption took place from fissures near the eastern edge of the rift zone between 600- and 1,100-m altitude. Lava from the fissures flowed into the ocean west of the Kahuku fault scarps, the more easterly of the two major flows lying directly against the base of the scarp. One of the two largest known eruptions of Mauna Loa took place in 1950, pouring out more than 460,000,000 m³ of lava from vents between 2,400- and 3,800-m altitude on the southwest rift zone (Finch and Macdonald, 1953).

No historic movement is known to have occurred on the Kahuku fault. During a strong (intensity X mM) earthquake in 1868, movement occurred on the Waiohinu fault, 8 km east of the Kahuku fault. It is inferred that other movement occurred at the same time beneath the ocean, because a big local tsunami was generated, but no movement was observed on the Kahuku fault above sea level.

REFERENCES

- Finch, R. H., and G. A., Macdonald, 1953. Hawaiian volcanoes during 1950. U.S. Geol. Surv. Bull. 996-B, p. 27-89.
- Macdonald, G. A., 1973. Geological prospects for the development of geothermal energy in Hawaii. Pac. Sci. v. 27, p. 209-219.
- Malahoff, A., and F. McCoy, 1967. The geologic structure of the Puna submarine ridge, Hawaii. J. Geophys. Res. v. 72, p. 541-548.
- Malahoff, A., and G.P., Woollard, 1966. Magnetic surveys over the Hawaiian Islands and their geologic implications. Pac. Sci., v. 20, p. 265-311.
- Moore, J. G., and R. S. Riske, 1969. Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii. Geol. Soc. Am. Bull., v. 80, p. 1191-1202.
- Stearns, H. T., and G. A. Macdonald, 1946. Geology and ground-water resources of the island of Hawaii. Hawaii Div. Hydrogr. Bull. 9, 363 pp.

LITERATURE SURVEY OF GEOPHYSICAL STUDIES
ON KILAUEA AS RELATED
TO GEOTHERMAL POTENTIAL

Augustine S. Furumoto

INTRODUCTION

The purpose of this paper is to collate geophysical and geological information and data on Kilauea volcano, that may relate to the geothermal potential of that volcano. Kilauea is one of the most intensively investigated volcanoes in the world, and from the voluminous amount of published literature concerning it, an attempt is made here to collect information that may be significant in understanding the thermal process of Kilauea and helpful in assessing its geothermal potential. The east rift zone of Kilauea is emphasized, as that area seems to have the best potential for geothermal development. Although the summit area of Kilauea is precluded from geothermal development since it is part of the Hawaii Volcanoes National Park, we shall nevertheless include a short discussion of the summit area to complete the topic.

This paper excludes results of surveys during 1973-1975 by staff members of the Hawaii Institute of Geophysics, since they are subject matter of the various articles in this series of reports. Work during that period by persons not associated with Hawaii Institute of Geophysics will be discussed.

This literature survey concerning Kilauea is intended to aid in preliminary studies of the Hawaii Geothermal Project. Details should be sought in the original publications.

GENERAL GEOLOGY OF KILAUEA VOLCANO

Kilauea, the youngest of five volcanoes on the island of Hawaii, comprises the southeastern portion of the island (Fig. 1). Kilauea is a shield volcano formed by series of lava flows of tholeiitic basalt. Interspersed among the lava flows are cinder and spatter cones and ash deposits. A good description of the geology of Kilauea can be found in Stearns and Macdonald (1946) and Macdonald and Abbott (1970).

Kilauea, like other Hawaiian volcanoes, first erupted as a submarine volcano on the ocean floor, which was probably about 5 km deep, a figure inferred from the topography of ocean floor around the Hawaiian Islands. From lineations of magnetic anomalies and by deductions from sea-floor spreading hypothesis, the oceanic crust around Hawaii and

Figure 1. Map of the island of Hawaii showing volcanoes and associated rift zones.

under the island has been estimated to be a little over 80 m.y. old (Heirtzler et al., 1968), which would date the oceanic crust as Cretaceous. The rocks of Kilauea shield range from Pleistocene to present. As Kilauea is in the shield-building stage, numerous eruptions have occurred in recent years, most recent in 1975.

At the summit of Kilauea is a well-defined caldera, about 4.5 km long and 3 km wide. Inside the caldera is a lava crater known as Halemaumau, which has been the site of recent molten lava activity. Numerous other craters and pits are found on Kilauea.

There are two rift zones associated with Kilauea--the southwest rift zone and the east rift zone. The southwest rift zone trends from the summit in the direction indicated by its name, but the east rift starts off in the southeast direction, then bends nearly 90° to trend in the east-northeast direction.

Between Kilauea and its neighboring volcano, Mauna Loa, is the Honuapo-Kaoiki fault system (Fig. 1), which trends northeast-southwest. The fault has a downthrow on the southeast side. Analysis of seismograms from an earthquake of magnitude 6.1 along the fault in 1962 indicates that the motion of the earthquake was right-lateral (Koyanagi et al., 1966).

Source of Magma

Many hypotheses have been advanced concerning the source and origin of magma for Hawaiian volcanoes, including Kilauea, but hard and fast data relevant to this topic are scarce. Among the available data are the focal depths of deep earthquakes associated with magmatic activity of Kilauea. Eaton and Murata (1960) determined that the depths of these earthquakes range from 34 to 60 km. Below 60 km, they reasoned that the mantle material is soft. As to the depth to asthenosphere, or low velocity layer, under Hawaii, data are conflicting. By analysis of Rayleigh wave dispersion, Leeds et al. (1974) proposed a depth of 80 km to the asthenosphere, while Odegard (1975) proposed a model, based on body wave data from Amchitka nuclear explosions, where the depth is at least 200 km.

Lately, "hot spots" have been proposed to explain oceanic volcanoes. As the name "hot spot" is a vague description, which can mean any small area that is relatively hot, we shall avoid it. We prefer to separate the various hypotheses proposed to explain Hawaiian volcanism into two classes: progressive crack theories and convective plume theories.

To explain the line of volcanoes from Kure Island to Hawaii, a distance of about 3000 km, along which volcanoes become progressively younger to the southeast, Daly (1933) theorized that through-going cracks extended from the surface down into the softer parts of the mantle. Injection of hot material from abyssal depths into these cracks produced volcanoes. From petrological data, Jackson and Wright (1970) proposed that a propagating crack tapped new mantle material. Otherwise, they reasoned, the uniform composition of huge shields cannot be explained. Green (1971) also argued for the crack theory. Turcotte and Oxburgh (1973) showed that thermal stresses from cooling can fracture the lithosphere and also that change of radius of curvature of the lithosphere can produce stresses of sufficient magnitude to fracture it. Turcotte (1974) calculated that several kilobars of stress can be produced by the changing radius of curvature. Anderson and Grew (1977) applied recent theories in stress corrosion theory to fracturing of the lithosphere, and they proposed a mechanism for magmatic transport through these cracks.

Wilson (1963) proposed a convective plume in the mantle, which he called a hot spot, as the source of Hawaiian volcanism and magma. As the lithosphere moved over the hot upwelling plume, successive volcanoes broke out on the earth's surface. Morgan (1971) proposed that the convective motion is a mantle-thick cell, with plumes originating at the core-mantle boundary. Dalrymple et al. (1973) has generalized the various proposed theories and said there is a melting spot under the active volcanoes.

Upward Transport of Magma from the Deep Mantle

In addition to estimating the depth of magma source, Eaton and Murata (1960) proposed that magma came up from the deep source through conduits to enter a magma reservoir a few kilometers below ground surface. A plot by Koyanagi and Endo (1971) of earthquakes under Kilauea showed that the earthquakes outlined a column about 10 km in diameter. The column is nearly vertical but it trends to the southeast, at a dip angle of 80°.

Swanson (1972) estimated the magma supply rate to be $9 \times 10^6 \text{ m}^3/\text{month}$.

Magma Reservoir

From the earliest days of volcanological observation at Kilauea, the bulging and deflation around the summit area were noticed, and tilts and strains were measured. From deformation data, Mogi (1958) calculated that the magma chamber was 4 km deep. Fiske and Kinoshita (1969a) assumed that the reservoir took the form of an aggregate of a large number of dense sills and feeder dikes and calculated from deformation data that the reservoir was 2 to 3 km deep. Eaton (1962) proposed that the magma chamber was under the south end of the caldera, at a depth of 4 km, with a diameter much smaller than its depth. Bulging of the volcanic edifice as measured by tilts and strains is attributed to behavior of the magma chamber (Decker et al., 1966).

In studying earthquake data, Minakami (1974) noticed that the earthquakes were not located in a zone from 1 to 10 km, but that surrounding the zone were a large number of earthquakes. Minakami proposed that this non-seismic zone was composed of molten or nearly molten material that cannot contain shear stresses. From Minakami's plot of earthquakes, one can infer that the horizontal dimension of the magma reservoir is about 6 km.

Structure of Kilauea Edifice by Seismic, Gravity, Magnetic Data

Using earthquake P-wave arrivals, Eaton (1962) determined the depth to the Mohorovicic discontinuity under Kilauea to be 14.8 km. Other crustal layers determined by Eaton were a 3.9 km/sec P velocity layer from surface to 3.1 km; a second layer of 5.0 km/sec with a thickness of 8.1 km, and a third layer of 6.8 km/sec with a thickness of 3.6 km. The mantle velocity was 8.25 km/sec.

Ryall and Bennett (1968) carried out a 120-km-long seismic refraction traverse in a northeast-southwest direction from Hilo Bay to the southern point of the island, cutting across the summit of Kilauea. The analysis of data showed a structural discontinuity about the summit area. Northeast of the summit the crust was 15 km thick, whereas the crust to the southwest was only 12 km thick. Three crustal layers were detected with P velocities of 3.0 km/sec, 5.3 km/sec, and 7.0 km/sec. The mantle velocity was 8.2 km/sec. The layers varied in thickness along the traverse.

Hill (1969) carried out seismic refraction traverses along the coasts of the island. Around Kilauea, he found the depth to the Mohorovicic discontinuity to be 14 km. P velocities of the three crustal layers were 3.1, 5.1, and 7.1 km/sec. Along the southeastern shore of the island, which corresponds to the east rift of Kilauea, the 7.1 km/sec layer abruptly thickened from 4 km on the western part to 7-8 km on the eastern part.

Gravity surveys over the island showed a positive high of about 315 mgal coinciding with the topographic high of Kilauea (Kinoshita, 1965). Over the other volcanoes, gravity anomaly highs were somewhat south of the topographic highs and eruptive centers. As the Bouguer value along the island seashore is about 250 mgal, we can assume an anomalous dense body within the edifice giving rise to 65 mgal. For a density contrast of 0.7 g/cm^3 this anomalous body would roughly be a sphere of 14-km diameter with its center at a depth of 11 km.

An aeromagnetic survey by Malahoff and Woollard (1966) showed a reversely polarized field over the Kilauea summit, which is interpreted as due to the volcanic plug having a temperature above Curie point. A simple analysis of the magnetic contours using nomograms and figures provided by Vacquier et al. (1951) shows that the nonmagnetic, hot part of the plug has a diameter of 13 km.

Over the east rift the magnetic field is flat, without undulation or variation.

Summit Thermal Fields

Of the many reports narrating the chronological events of eruptions, we shall discuss only the 1959 and 1960 eruptions (Richter and Eaton, 1960; Richter et al., 1970). Tiltmeters showed that before an eruption the ground bulged upward; after the eruption the bulge deflated. Eruptions can be predicted by correct interpretation of ground tilts.

Lava temperature ranged from 1000°C to 1100°C and its viscosity from 10^3 to 10^5 cgs (Macdonald, 1963). Viscosity varies with temperature.

Lava accumulating in craters forms lava pools (Wright et al., 1968). In a short time a solid crust forms over the molten lava, sufficiently strong to support men standing on it. The molten lava has been studied by sending probes through the crust into the melt (Ault and Richter, 1962;

Shaw et al., 1968). The temperature of the melt is about 1100°C . Monitoring of the increasing thickness of the solid crust over the melt has shown that the rate of thickening is proportional to the square root of time. In five years the crust will be 16 m (50 ft) thick (Peck, 1974). At this rapid rate of cooling, generation of power using heat from liquid lava is out of the question, with today's technology.

Using data obtained from electrical resistivity surveys (Jackson and Keller, 1972) and also seismic data, Keller (1974) selected a drill site in the summit area and drilled an exploratory hole to a depth of 1200 m. At 500-m depth, a water table of 80°C was encountered. The bottom of the hole had a temperature of 136°C (Zablocki et al., 1974). The data was interpreted by Murray (1974) as a convective-conductive system where a convective section of 700-m thickness was underlain by a conducting layer with a gradient of 410°C/km . In the summit area, then, a low-temperature hydrothermal system with a base temperature of 80°C was found.

Lateral Motion of Magma into the East Rift

Magma rising from the deep interior of the earth is temporarily lodged in the magma reservoir beneath the summit caldera. Although much of the magma erupts through the summit vents, some is injected laterally into the east rift zone and southwest rift zone. From analysis of erupted rock samples, Eaton and Murata (1960) concluded that the lava erupting along the east rift zone came from the summit reservoir. The east rift zone is underlain by a conduit from the summit.

Swanson et al. (1976) concluded from surface deformation data from the east rift that magma is forcefully injected into the rift. Fiske and Jackson (1972), who studied the mechanism of magma injection into a mountainside by using gelatin models, found that vertical cracks develop parallel to the trend of the mountain ridge. The cracks are readily formed due to gravity causing sides of the mountain to sag.

GEOLOGY OF THE EAST RIFT

The east rift passes through the Puna district of the island of Hawaii. The flanks of the rift practically coincide with Puna district.

Along the east rift, most of the rocks are tholeiitic basalt in the form of thin flows, interspersed with ash beds (Macdonald and Abbott, 1970). Faults run parallel to the trend of the rift and indicate normal dip slip with downthrow on the southside. These faults are surface manifestations of the process of subsidence of the south flank of Kilauea.

Because the rocks observed on the ground surface along the east rift had been erupted and deposited subaerially, they are vesicular with high porosity. Lava rocks from submarine extrusions, however, may be different. Rocks dredged by Moore and Fiske (1969) offshore from a submarine ridge thought to be the extension of the east rift had low porosity. Porosity decreased with water depth; at 700 m the porosity was down to 1 to 4 percent. Pillow lavas are the common form of submarine extrusions.

The hooked shape of the line of vents of the east rift has been explained as due to formation of the rift against the preexisting flanks of the older Mauna Loa volcano.

Photogeologic Surveys

Infrared aerial surveys by Fischer et al. (1964) confirmed the thermal areas of Kilauea, already known by surface observations. Along the east rift, linear thermal anomalies were found to cross highways, leading to the concern that eventually the highways will be damaged by the heat. Along the seashore, infrared surveys revealed both cold springs and springs with temperatures above normal. Adams and Lepley (1968) surveyed the temperature variations of the shore water by airborne infrared methods.

Alae Crater on the east rift was measured for infrared radiation with radiometers placed on the crust that had formed over the lava pool (Decker and Peck, 1967). Decker and Peck's analysis showed that radiative emission accounted for 10 percent of the thermal dissipation or loss, while the rest of the heat was dissipated by evaporation, escaping gases, and convection of the contacted air layer immediately above the crust.

From ordinary stereoscopic aerial photographs, Duffield and Nakamura (1973) determined that Koae fault, south of Kilauea caldera, is a tensional feature with horizontal dilation in the direction of $N30^{\circ}W$ to $S60^{\circ}E$.

Geodetic Data and Surface Deformation

Fiske and Kinoshita (1969b) reported that comparison of transit surveying data in Puna district between 1914 and 1965 revealed a 4.5-m dilation of the east rift between the two time periods. As the eruptions of 1955 and 1960 occurred in that time interval, the dilation is probably associated with dike intrusions of magma. Swanson, Jackson, Duffield, and Peterson (1971) reported that the displacement associated with the dilation was in the direction of $S20^{\circ}-30^{\circ}E$, perpendicular to the general trend of the east rift. The rate of movement was several centimeters per year. Swanson, Duffield, and Okamura (1971) attributed the movement to gravity slumping of the flank.

Decker and Dietrich (1974) proposed that linear elastic theory was inadequate to account for the data and suggested that a mountain of sand is a better model. They proposed that the dike zone or intrusive plane dipped 45° to the south.

Gravity Data

The data coverage of the Puna district gravity survey published by Kinoshita (1965) is sparse. Gravity measurements were made at 2-km intervals along paved roads, of which there were few during the early 1960's. Kinoshita had applied Bouguer corrections with an assumed surface density of 2.3 g/cm^3 .

Along the seashore where Bouguer values were the lowest, the values were around 245 mgal. Along the topographic high of the east rift, the Bouguer values were about 260 mgal. In general, one can say that there was a ridge of Bouguer high of 15 mgal following the trend of the east rift.

Passive Seismic Observations

A statistical study of earthquakes in the Puna district showed that the coefficient m in the Ishimoto-Iida equation for local earthquakes

$$N A^m = k,$$

(where N is number of earthquakes, A is amplitude of ground motion, and k is a constant), has a value of 1.9 (Furumoto, 1957). The coefficient m usually ranges in the interval 1.7-2.0 (Asada, 1957), and it is related to b of the more familiar magnitude-occurrence relation $\log N = C - bM$ (where M is magnitude and C is a constant) by $b = m - 1$ (Asada et al., 1951). Hence, statistically the magnitudes of the earthquakes are normally distributed.

A plot of epicenters along the east rift showed that earthquakes tend to cluster around a small area just south of the bend in the rift zone. The earthquakes in the area tend to be concentrated at a depth of 10 km (Koyanagi and Endo, 1971).

More earthquakes occur south of the rift zone; the difference in numbers is so disparate that the rift zones appear to be the boundary between a seismically active area to the south and an aseismic area to the north. Earthquakes occur usually at shallow depths, <15 km deep. Focal mechanism studies suggest that maximum stress axes are oriented to the southeast generally normal to the east rift, and plunge gently downward (Koyanagi et al., 1972).

The earthquakes tend to be related in space and time to magmatic events, either intrusive or extrusive. At the early stage of a magmatic event, earthquakes occur at shallow depths, <5 km, and at later stages they occur deeper and more seaward of earlier epicenters (Koyanagi et al., 1972).

From comparison of arrival times of many earthquakes, Ward and Gregerson (1973) concluded that travel paths of seismic waves along the east rift and southwest rift have higher velocities than those along other paths. Underlying the east rift are high velocity layers whose thickness, depth, and velocity values are not yet determined.

Active Seismic Measurements

Among the half dozen or so crustal seismic refraction traverses by Hill (1969) along the coastline of the island of Hawaii, one was along the Puna coast, paralleling the east rift to the south. In these traverses, seven large shots were fired at sea and recorded by several stations on land. From the data, Hill detected four crustal layers. The first layer was 0.7 km thick with an assumed P-wave velocity of 1.8 km/sec; the second layer was about 1.5 km thick with a velocity of 3.1 km/sec; the third layer had a velocity of 5.1 km/sec; and the fourth layer 7.1 km/sec. The Mohorovicic discontinuity had a velocity of 8.1 km/sec at a depth of 13 km.

The boundary between the 5.1-km/sec and 7.1-km/sec layers had a ramplike discontinuity, under the Kalapana area. To the southwest of Kalapana the 5.1-km/sec and the 7.1-km/sec layers were each 5 km thick; to the northeast of Kalapana the 7.1-km/sec layer thickened at the expense of the 5.1-km/sec layer, so that the 5.1-km/sec layer was between 1 and 2 km thick.

The assumption of 1.8 km/sec for the first layer is subject to question. Hill (1969) had obtained the value of 1.8 by drawing a line through the first arrival and the origin of his travel time plot. A highly vesicular, surficial lava layer may have low velocity, even as low as 1 km/sec, but at depth of a few hundred meters the velocity values will rise to 2.2 to 2.5 km/sec.

Well Data

In the Puna district, several wells have been drilled for irrigation purposes and in 1961 four wells were drilled for geothermal prospecting purposes. A tabulation of the temperature in these wells was given by Macdonald (1973). The geothermal wells varied in temperature from 43°C to 100°C; one produced steam but of insufficient pressure to be of geothermal use. Warm water up to 52°C has been found in other wells and warm springs. The distribution of temperature does not form any discernible geographic pattern.

CONCLUSION

Although Kilauea volcano may be the best studied volcano in the world, for the purpose of geothermal exploration there are many gaps in our knowledge. Some of these gaps are listed here, as these are the questions we undertook to investigate in our geophysical program of the Hawaii geothermal project.

1. Does a high temperature hydrothermal system exist on Kilauea? If so, where?
2. What is the mechanism of heat transfer from magma to a hydrothermal system?
3. What is the geophysical signature of a hydrothermal system? Is it low resistivity, temperature gradient, or certain frequencies of ground noise?
4. What are the dimensions of the magma conduit under the east rift? Are there any ponded chambers?

5. How is the ground water system related to the magma conduit, if at all?
6. What is the nature of the magma conduit? Is it molten, a shallow tube, hot rock, or really non-existent between eruptions?
7. Is the ground deformation and slumping any indication of magmatic motion?

REFERENCES

- Adams, W.M., and L.K. Lepley, 1968. Infrared images of the Kau and Puna coastlines of Hawaii. Tech. Rep. No. 26, Water Res. Res. Cntr., Univ. Hawaii, 51 pp.
- Anderson, O.L., and P.C. Grew, 1977. Stress corrosion theory of crack propagation with application to geophysics. Rev. Geophys. Space Phys., v. 15, p. 77-104.
- Asada, T., 1957. Frequency distribution of earthquake magnitude, seismicity, and related problems, J. Seismol. Soc. Jpn., Ser. 2, v. 10, p. 24-34.
- Asada, T., J. Suzuki, and Y. Tomoda, 1951. Notes on the energy and frequency of earthquakes. Bull. Earthquake Res. Inst., v. 29, p. 289-293.
- Ault, W.U., and D.H. Richter, 1962. A temperature measurement probe into the melt of the Kilauea Iki lava lake in Hawaii, J. Geophys. Res. v. 67, p. 2809-2812.
- Dalrymple, G.B., E.A. Silver, and E.D. Jackson, 1973. Origin of the Hawaiian Islands, Am. Sci., v. 61, p. 294-308.
- Daly, R.A., 1933. Igneous Rocks and the Depths of the Earth. Hafner Publ. Co. (reprinted 1968), New York, 598 pp.
- Decker, R.H. and J. Dietrich, 1974. Limitations of elasticity theory in interpretation of ground surface deformation. In The Utilization of Volcano Energy, J. Colp and A. Furumoto (eds.), p. 227, N.M.
- Decker, R.W., and D.L. Peck, 1967. Infrared radiation from Alae lava lake, Hawaii. U.S. Geol. Surv. Prof. Pap. 575-D, p. 169-175.
- Decker, R.W., D.P. Hill, and T.L. Wright, 1966. Deformation measurements on Kilauea volcano, Hawaii. Bull. Volcanol., Tome 29, p. 721-732.
- Duffield, W.A., and K. Nakamura, 1973. A photogeologic method for determining the direction of horizontal dilation from patterns of en echelon fracturing. J. Res., U.S. Geol. Survey, v. 1, no. 3, p. 283-287.
- Eaton, J.P., 1962. Crustal structure and volcanism in Hawaii. In The Crust of the Pacific Basin, Am. Geophys. Monogr. Ser. 1077, v. 6, p. 13-29, Am. Geophys. Un. Washington, D.C.

- Eaton, J.P., and K.J. Murata, 1960. How volcanoes grow, Science, v. 132, no. 3432, p. 925-938.
- Fischer, W.A., R.M. Moxham, F. Polcyn, and G.H. Landis, 1964. Infrared surveys of Hawaiian volcanoes. Science, v. 146, p. 733-742.
- Fiske, R.S. and E.D. Jackson, 1972. Orientation and growth of Hawaiian volcanic rifts: the effect of regional structure and gravitational stresses. Proc. R. Soc. London, Ser. A, v. 329, p. 299-326.
- Fiske, R.S. and W.T. Kinoshita, 1969a. Inflation of Kilauea volcano prior to 1967-1968 eruption. Science, v. 165, p. 341-349.
- Fiske, R.W. and W.T. Kinoshita, 1969b. Rift dilation and seaward displacement of the south flank of Kilauea volcano, Hawaii. Proc. Symposium on Volcanoes and their Roots, Oxford, England, Int. Assoc. Volcanology and Chemistry of the Earth's Interior, p. 53-54.
- Furumoto, A.S., 1957. Some statistical investigations of Hawaiian volcanic eruptions and earthquakes. Bull. Volcanol. Soc. Jpn., Ser. 2, v. 2, p. 26-36.
- Green, D.H., 1971. Composition of basaltic magmas as indicators of condition of origin: application to oceanic volcanism, Philos. Trans. R. Soc. London, Ser. A, v. 268, p. 707-725.
- Heirtzler, J.R., G.O. Dickson, E.M. Herron, and W.C. Pitman III, X. Le Pichon, 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. J. Geophys. Res., v. 73, no. 6, p. 2119-2136.
- Hill, David P., 1969. Crustal structure of the island of Hawaii from seismic-refraction measurements, Bull Seismol. Soc. Am., v. 59, no. 1, p. 101-130.
- Jackson, D.B., and G.V. Keller, 1972. An electromagnetic sounding survey of the summit of Kilauea volcano, Hawaii, J. Geophys. Res., v. 77, p. 4957-4965.
- Jackson, E.D., and T.L. Wright, 1970. Xenoliths in the Honolulu Volcanic Series, Hawaii. J. Petrol., v. 11, pt. 2, p. 405-430.
- Keller, G.V., 1974. Drilling at the Summit of Kilauea Volcano, Colorado School of Mines, Golden, Colorado, 45 pp.

- Kinoshita, W.T., 1965. A gravity survey of the island of Hawaii, Pac. Sci., v. 29, no. 3, p. 339-340.
- Koyanagi, R.Y. and E.T. Endo, 1971. Hawaiian seismic events during 1969. U.S. Geol. Surv. Prof. Pap. 750-C. p. C158-C164.
- Koyanagi, R.Y., H.L. Krivoy, and A.T. Okamura, 1966. The 1962 Katoiki, Hawaii earthquake and its aftershocks. Bull. Seismol. Soc. Am. v. 56, no. 6, p. 1317-1335.
- Koyanagi, R.Y., Swanson, D.A., and E.T. Endo, 1972. Distribution of earthquakes related to mobility of the south flank of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. 800-D, p. D89-D97.
- Leeds, A.R., L. Knopoff, and E.G. Kausel, 1974. Variations of upper mantle structure under the Pacific Ocean. Science v. 186, p. 141-143.
- Macdonald, G.A., 1963. Physical properties of erupting Hawaiian magmas. Geol. Soc. Am. Bull., v. 74, p. 1071-1078.
- Macdonald, G.A., 1973. Geological prospects for development of geothermal energy in Hawaii. Pac. Sci. v. 27, no. 3, p. 209-219.
- Macdonald, G.A., and A.T. Abbott, 1970. Volcanoes in the Sea. Univ. Hawaii Press, Honolulu, 441 pp.
- Malahoff, A., and G.P. Woollard, 1966. Magnetic surveys over the Hawaiian Islands and their geological implications. Pac. Sci., v. 20, no. 3, p. 285-311.
- Malahoff, A. and G.P. Woollard, 1968. Magnetic and tectonic trends over the Hawaiian Ridge. In The Crust and Upper Mantle of the Pacific Area, Geophys. Monogr. Ser., v. 12, pp. 241-276, Amer. Geophys. Union, Washington, D.C.
- Minakami, Takeshi, 1974, Physical nature of source parameters of volcanic earthquakes. In The Utilization of Volcano Energy, J. Colp and A. Furumoto(eds.), pp. 191-204. Sandia Labs, Albuquerque, N.M.
- Mogi, K., 1958. Relations between the eruptions of various volcanoes and the deformation of ground surfaces around them. Bull. Earthquake Res. Inst., v. 36, p. 94-134.

- Moore, J.G. and R.S. Fiske, 1969. Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii. Geol. Soc. Am. Bull., v. 80, p. 1191-1202.
- Morgan, W.J., 1971. Convection plumes in the lower mantle, Nature, v. 230, p. 42-43.
- Murray, J.C., 1974. The geothermal system at Kilauea volcano, Hawaii. Ph.D. dissertation, Colorado School of Mines, Golden, Colorado.
- Odegard, M.E., 1975. Upper mantle structure of the north Pacific. Ph.D. Dissertation, Univ. Hawaii, Honolulu, Hawaii, 284 pp.
- Peck, D.L., 1974, Thermal properties of basaltic magma: Results and practical experience from study of Hawaiian lava lakes. In The Utilization of Volcano Energy, J.L. Colp and A.S. Furumoto (eds.), pp. 287-298, Sandia Labs, Albuquerque, N.M.
- Richter, D.H., and J.P. Eaton, 1960. The 1959-1960 eruption of Kilauea volcano. New Sci., v. 7, p. 994-997.
- Richter, D.H., J.P. Eaton, K.J. Murata, W.U. Ault, and H.L. Krivoy, 1970. Chronological narrative of the 1959-1960 eruption of Kilauea volcano, Hawaii. U.S. Geol. Surv. Prof. Pap. 537-E, 73 pp.
- Ryall, A., and D.L. Bennett, 1968. Crustal structure of southern Hawaii related to volcanic process in the upper mantle. J. Geophys. Res., v. 73, p. 4561-4582.
- Shaw, H.R., T.L. Wright, D.L. Peck, and R. Okamura, 1968. The viscosity of basaltic magma: An analysis of field measurements in Makaopuhi lava lake, Hawaii. Am. J. Sci., v. 266, p. 225-264.
- Stearns, H.T., and G.A. Macdonald, 1946. Geology and ground-water resources of the island of Hawaii, Hawaii Div. Hydrog. Bull. 9, 363 pp.
- Swanson, D.A., 1972, Magma supply rate at Kilauea volcano, 1952-1971. Science, v. 1975, p. 169-170.
- Swanson, D.A., W.A., Duffield, and R.S. Fiske, 1976. Displacement of the south flank of Kilauea volcano: The result of forceful intrusion of magma into rift zones. Geol. Surv. Prof. Pap. 963, 39 pp.

- Swanson, D.A., W.A. Duffield, R.T. Okamura, 1971, Seaward displacement of the south flank of Kilauea. (Abstract) EOS. Trans. Am. Geophys. Union., v. 52, no. 4, p. 372.
- Swanson, D.A., D.B. Jackson, W.A. Duffield and D.W. Peterson, 1971. Mauna Ulu eruption, Kilauea volcano. Geotimes, v. 16, no. 5, p. 12-16.
- Turcotte, D.L., 1974. Membrane tectonics. Geophys. J. R. Astron. Soc., v. 36, p. 33-42.
- Turcotte, D.L., and E.R. Oxburgh, 1973. Mid-plate tectonics. Nature, v. 244, p. 337-339.
- Vacquier, V., N.C. Steenland, R.G. Henerson, and I. Zietz, 1951. Interpretation of aeromagnetic maps, Mem. 47, Geol. Soc. Am., 151 pp.
- Ward, Peter L., and S. Gregersen, 1973. Comparison of earthquake locations determined with data from a network of stations and small tripartite arrays on Kilauea volcano, Hawaii. Bull. Seismol. Soc. Am., v. 63, no. 3, p. 679-711.
- Wilson, J.T., 1963. Possible origin of the Hawaiian Islands. Can. J. Phys., v. 41, p. 863-870.
- Wright, T.L., W.T. Kinoshita, and D.L. Peck, 1968. March 1965 eruption of Kilauea volcano and the formation of Makaopuhi lava lake. J. Geophys. Res., v. 73, p. 3181-3205.
- Zablocki, C.J., R.I. Tilling, D.W. Peterson, R.L. Christiansen, G.V. Keller, and J.C. Murray, 1974. A deep research drill hole at the summit of an active volcano, Kilauea, Hawaii. Geophys. Res. Lett., v. 1, no. 7, p. 323-326.

HYDROLOGY AND CHEMISTRY OF GROUND WATER
IN PUNA, HAWAII

(Abstract)

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ABSTRACT

Presented is an analysis of the hydrology and chemistry of the ground water of the Puna District, Hawaii, based on data from 16 drilled wells, ten test wells, two shafts, and four exploratory thermal wells. Ground water occurs as (1) perched water located north of Mountain View; (2) dike water located along the east rift zone of Kilauea; and (3) basal water occurring throughout most of the district, except where dike water is present. The east rift zone serves as a barrier to ground-water movement, as demonstrated by the difference in basal water-table levels on the two sides of the rift zone. Salinity and temperature of the basal ground water varies greatly north and south of the rift zone due to differences in precipitation, sea-water intrusion, volcanic activity, flow rates, permeability, and discharge.

Basal ground-water type is predominantly sodium chloride. Water samples taken from thermal test well no. 3 showed the dissolved silica values two to three times higher than the 49 mg/l average for the rest of the island. Hydrologic and geologic conditions in and around Kilauea's east rift zone support the possibility of accumulations of superheated ground water. The mixing of waters of different composition at depth proved to be the most difficult problem encountered in estimating deep ground-water temperatures.

PROSPECTS OF GEOTHERMAL ENERGY ON
THE ISLAND OF OAHU, HAWAII

(Summary)

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SUMMARY

With peak load of 845 megawatts in 1975 for electrical power generation dependent on petroleum, it is necessary to diversify the energy base to other sources, geothermal energy for example.

There are two ancient volcanoes on the island of Oahu, namely Koolau and Waianae. These volcanoes have been examined by various geophysical methods for over a decade. The internal structure of these volcanoes are now well documented.

Under Koolau volcano is a dense, ancient magma chamber with a diameter of 16 km. The top of the chamber is at a depth of 2 km, and is covered by marine and alluvial deposits. Indications of geothermal potential are warm water in shallow wells. Another consideration is that age dating established the latest lava flow from the Honolulu series to be only 31,000 years old.

Similar things can be said of the Waianae volcano. In addition Waianae volcano has electrical resistivity anomalies and groundwater with above average dissolved silica content.

Further exploration on Oahu is suggested.