Research Proposal to the Geothermal Division
Energy Research and Development Administration

from

University of Hawaii
Honolulu, Hawaii 96822

HAWAII GEOTHERMAL PROJECT - PHASE II
EXTENSION TO CONTRACT E(04-3)-1093

addendum to proposal submitted May 17, 1976

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SUMMARY OF PROPOSAL

Now that high temperatures have been encountered in HGP-A,
additional importance is placed on a comprehensive analysis of
all of the scientific data that has been accumulated by the Project
over the last three years. Pertinent information from the USGS,
State agencies, and other University projects must also be
evaluated and related to actual subsurface conditions. This is
an essential phase of this scientific endeavor, if maximum benefit
is to be derived from the significant investment of public and
private funds that have gone into this project. The analysis and
synthesis of this information should provide valuable insight into
the understanding of potential geothermal reserves not only in
Hawaii, but for basaltic volcanic geothermal regimes in the Western
United States and throughout the world.

The purpose of the funds requested in this proposal is to
provide support with which to complete analysis and interpretation
of the data and, through comparison with actual subsurface condi-
tions, develop correlations on the reliability of the various
methods of prediction. We also propose a limited number of field
experiments designed to assist in the understanding of the
reservoir dynamics. A synthesis of all pertinent data--from
geosciences, from mathematical modeling, from drilling, from well-
testing--will contribute to a more complete understanding of the
geothermal regime associated with this well.

Tasks to be completed in this twelve-month study, and a related budget for each, are as follows:

Management and Support (Task 1.1). . . . . . . $ 32,375

Coordination (Task 2.1). 39,651

Geosciences

    Magnetics, Gravity and Thermal
      Budget Studies (Task 2.2). 28,404

    Seismic Studies (Task 2.3A). 18,638
                 (Task 2.3B). 20,910

    Geoelectric Surveys for Geothermal
      Prospects (Task 2.4) 20,955

    Petrography, Petrology and
      Geochemistry (Task 2.5). 21,471

    Hydrology and Hydrothermal
      Geochemistry (Task 2.6). 16,122

    Physical Properties of Rocks (Task 2.7) 38,374

Engineering

    Numerical Modelling (Task 3.1) 44,947

    Well Test and Analysis (Task 3.2). . . . 47,367

    Physical Modelling (Task 3.3). 23,806

Environmental Studies

    Geotoxicology (Task 4.1) 11,050

               TOTAL $364,070

Brief narrarive summaries for each task, with associated budget sheets are attached. Also attached are copies of biodata for all named investigators.

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Overview of the Geophysical Program in
the Hawaii Geothermal Project

C. E. Helsley and A. S. Furumoto

As originally proposed, the geophysical program was
aimed at selecting a drill site and at developing an under-
standing of the thermal process of a basaltic volcano and its
associated rift zones. In spite of the fact that the Kilauea
volcano in Hawaii was the most investigated active volcano in
the world there are many areas in which our understanding is
limited. Thus an important task of the geophysical program
was to obtain a picture of a volcano and its rift zones that
was as complete as possible.

The island of Hawaii is made up of five basaltic volcanoes:
Kilauea, Mauna Loa, Hualalai, Mauna Kea and Kohala. Of these
Kilauea, Mauna Loa and Hualalai are considered active. A
typical Hawaiian volcano has a recognizable summit vent or
caldera and rift zones radiating outward from the summit. At
the outset of the geothermal program we were not certain whether
the rift zones or the summit areas were better candidates for
geothermal prospects. However because the summit areas of
Kilauea and Mauna Loa were national parks, and because the
summit areas of the others were inaccessible, or nearly so, to
heavy equipment, we were limited to investigations of the rift
zones.

The present geothermal program is unique in that we attemp-
ted to find geothermal fields in an active volcano. The proven

geothermal fields in the U.S. are not in active volcanoes; in Iceland the geothermal fields are in volcanic zones and not in a specific volcano; in Japan current research is still going on to find geothermal fields in an active volcano. With the exception of the geothermal fields in Iceland, most geothermal fields of the world are in andesitic or rhyolitic volcanics or in nearby sediments. Our effort, by necessity, was concentrated on basaltic volcanoes.

As we had little help from the professional literature to guide us in our exploration program, we decided to try all geophysical techniques that seemed reasonable. There were some critics who stated that because of high permeability of basalts, temperature surveys were useless, but nevertheless, they have proved useful. Others denigrated ground noise surveys in that surf noise was expected to be too high on islands, but our initial results show a high near the present geothermal well. Our philosophy was that nothing had really been evaluated under the conditions present in Hawaii and thus we should try all available techniques in our basaltic terrain.

During the first year of the exploration program, 1973-1974, much of the effort was devoted to reconnaissance type surveys. An infrared scanning survey by airplane covered the rift zones of Kilauea, Mauna Loa and Hualalai. Electrical surveys covered parts of the east and southwest rifts of Kilauea, the southwest rift of Mauna Loa and the west rift of Hualalai. Microearthquake monitoring was done on the southwest rift of Mauna Loa, and the east and southwest rift of Kilauea. All

of these surveys concluded that the east rift of Kilauea was without any doubt the best candidate for geothermal resources.

Literature on past studies of the east rift of Kilauea was abundant, but studies relating to thermal processes were few. It was generally agreed among geologists and geophysicists that the lava erupting along the east rift came from the magma chamber under the central caldera of Kilauea. Yet, there were a few proponents of the concept that the rift zones were primary features, and that the magma for the east rift came from depths directly under the east rift. Hence it was even necessary to investigate some of the fundamental aspects of the structure of a volcano as well as to search for means to detect subsurface thermal reservoirs.

We applied every method of geophysical survey in which the Hawaii Institute of Geophysics had capability although some techniques, such as the electrical survey, had to be developed. The surveys included the following: gravity, magnetic on ground surface, electrical including galvanic and inductive, well temperature, seismic (passive and active), geochemical (isotope and analytical), and hydrology. Data from a self-potential survey by the U.S. Geological Survey was also made available to us.

The results of these surveys have already been reported in the Summary Reports of Phase I and Initial Reports of Phase II of the Hawaii Geothermal Project. But the reported results are interpretations made before the completion of the drilling

of HGP-A well and before any log or information from the well was available. Now with information from the well in hand, better insights into the geophysical data can be developed. These new insights have been included as part of the proposal. We have attempted to make it clear to the reader that the results reported are only partially complete. Not only should the investigators of the separate tasks consult the well logs, but they should consult one another or the results of other disciplines to enrich their depth of interpretation. We have been doing that, but time is necessary to fully digest the richness of cross-consultation.

With the completion of HGP-A we have asked ourselves the question "where do we go from here?". The first answer is obvious, namely complete the analysis of data in hand and synthesize it with the data coming from the well. This is the content of the present proposal and is discussed in detail as various tasks and subtasks.

One can take a broader view of the geophysical program of the geothermal project. In a sense we are at a stage of development and maturing from the experience of the past three years. We have gained a measure of understanding a geothermal field in a basaltic environment. We now look to new frontiers to take advantage of the store of acquired information and experience. Among the new challenges that loom into view are the following suggested projects:

(1) Exploration on the other rift zones of Kilauea and of Mauna Loa

(2)   Exploration on the volcanoes on the islands
of Maui and Oahu

(3)   Commencement of investigation of continental
basaltic volcanoes.

Detailed plans for these subsequent studies are currently being prepared and will form the basis for future proposals.

TASK 2.1

COORDINATION

A. S. Furumoto

Original Proposal

The original proposed responsibility for the task of coordination included: (1) scheduling the various surveys, (2) smooth functioning of logistics, (3) keeping an inventory of equipment and supplies, (4) calling meetings of the various task leaders at proper times, (5) overseeing services in terms of typing and administrative assistance, and (6) assuring the public relations are maintained with residence in which field work was being done. The above were tasks specified in the original proposal.

Besides the objectives mentioned above, there were several objectives not spelled out in the proposal, but clearly understood to be part of the coordination. These were (1) to assist in the development of land-type geophysics at the Hawaii Institute of Geophysics and (2) to nurture and develop expertise in resource geophysical exploration. The Hawaii Institute of Geophysics has had great expertise in marine geophysics, but land-based geophysical disciplines needed to be reestablished in order to do the electrical surveys, magnetic surveys, array seismology, land-type seismic reflection and refraction required for geothermal exploration. Resource exploration is a team effort that has to zero in on narrowly defined goals, and thus more effort at coordination is necessary than is normal in typical academic research.

The Results

The coordination of the ten or so geophysical surveys moved along smoothly. The originally planned schedule of surveys were not carried out because some tasks had great difficulty in getting instruments working properly. Adjustments were made depending on the circumstances and all tasks had their day in the field. A trailer was purchased for field operations, and it was used by several tasks in turn as their field office or base of operations. The use of a field office was most convenient as the closest motel or hotel was twenty or thirty miles from the field.

The cooperation among the various tasks made the work of coordination very easy. All the geophysical tasks showed fiscal responsibility as no task had any serious cost overrun.

As the project progressed, timely publications were necessary, some of them perhaps prematurely, as invitations were received to present papers at various symposia, etc. As geothermal energy became the "in" thing there were nearly a dozen conferences on geothermal energy from 1974 to 1976. As many of these conferences as reasonably possible were attended by various geophysicists as conferences are an essential means of communication in a rapidly developing field. Papers were presented whenever it was appropriate.

A list of publications which were prepared as part of the task of coordination is attached at the end of this task description. Other tasks will list their separate publications. The publications of the coordination task usually turned out to be progress reports for as new data came in, the previous publications became

obsolete and subsequent reports were quite different from the earlier ones.

Proposed Task

As there is more work to be done in the geophysical program to round out the study of the east rift of Kilauea, the task of coordination will continue for the fiscal year. Some of the tasks will carry out field projects, such as seismic monitoring, electrical surveys, sample gathering. Field projects will require processing of purchase orders, work sheets, travel allowances.

As the various tasks near completion, there will be a mountainous amount of typing to be done of manuscripts for reports and journal publications. Student help will be hired to ease the bottleneck of typing at critical times.

Several tasks propose to carry out field programs that require the services of an electronic technician to attend to proper functioning of the instruments. As the technician services several tasks, his salary has been lodged with the coordination task.

The budget for coordination includes salaries for a clerk-administrative assistant, an electronic technician and student helpers, expenses for publication of general reports and articles.

Publications

1. John L. Colp and Augustine S. Furumoto, editors, Utilization of Volcano Energy, Proceedings of a Conference held at Hilo, Hawaii. 680 pp, publ. by Sandia Corp., Albuquerque, N.M., 1974.

2. A.S. Furumoto, Geophysical Exploration on the Structure of Volcanoes: Two Case Histories, in Utilization of Volcano Energy, Proceedings of a Conference Held at Hilo. pp. 41-58, 1974.

3. W.A. Wiebenga and A.S. Furumoto, Geophysical Evidence for the Availability of Geothermal Energy in New Gritain. In Utilization of Volcano Energy, Proceedings of a Conference Held at Hilo, pp. 59-74. 1974.

4. A.S. Furumoto, Using Volcanoes. Physics Bulletin, Vol 25, p. 287, 1974.

5. A.S. Furumoto, U.S. Japan Seminar on Utilization of Volcano Energy. EOS, Trans. Am. Geophys. Un., Vol. 55, pp 895-899, 1974.

6. A.S. Furumoto, A Coordinated Exploration Program for Geotheraml Sources on the Island of Hawaii. In Proceedings of Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, in press.

7. A.S. Furumoto. Geothermal Exploration on the Island of Hawaii. Journal of the Japan Geothermal Energy Association. Vol. 12, No. 4, pp. 29-36, 1975 (in Japanese).

8. A.S. Furumoto. Prospects for Geothermal Energy on the Island of Oahu, Hawaii, Geothermal Energy, Vol. 4, no. 6, pp. 7-25, 1976.

9. A.S. Furumoto and K. Yuhara. On the Status of Research Leading toward Volcano Energy Utilization. Critical Reviews in Environmental Control. In Press.

10. A.S. Furumoto. Geothermal Exploration in the State of Hawaii. In Proceedings, Conference on Exploration for the Geothermal Reservoir. Golden, Colorado, 1976 (In press).

BUDGET

Coordination - Task 2.1

A. Salaries and Wages

    1. Support personnel

        a. Administrative assistant and
           clerical stenographer (12 mos) $10,935

        b. Electronics Technician (9 mos)   9,635

        TOTAL SALARIES AND WAGES   20,570

B. Fringe Benefits   4,756

C. Equipment   -0-

D. Travel

    1. Domestic (east coast meeting)   760

E. Supplies   800

F. Publications - 6 @ $400 each   2,400

G. Other Costs

    (communications, xerox, car rental, etc.)   800

H. Total Direct Costs 46% of Salary & Wages $30,086

I. Indirect Costs   9,565

J. Total Costs $ 39,651

TASK 2.2

MAGNETICS, GRAVITY AND THERMAL BUDGET STUDIES

R. Norris and A. S. Furumoto

Introduction

The objective of this task, together with the Seismic Studies
Task, is to determine the geological structure of the east rift
of Kilauea. In particular, the aim is to outline the structure
of the intrusive zone or dike complex which has been the source of
lava outpourings along the east rift. Well HGP-A, which was drilled
adjacent to the intrusive zone and has come across a geothermal
resource, indicates that further understanding of the origin and
properties of rift zones is essential for future development of
geothermal resources in Hawaii.

In Hawaii, it is well known that gravity methods are very
useful in outlining intrusives, because intrusive rock, whether in
a dike complex or volcanic neck, has higher density than the country
rock, which is usually extruded lava rock (e.g. Strange, Woollard
and Rose, 1965). Magnetic surveys are also useful as cooled
intrusive rocks produce more discernible dipoles than country rock.

Of the three parts to this task, the magnetic part is in the
stage of manuscript writing. The gravity part is presently incor-
porating data from the logs and core samples of HGP-A to obtain
more constrained interpretation. The third part of numerical
study of the thermal process of the dike complex is getting started
as data on thermal diffusivity is coming in from physical properties
task and as the dimensions of the dike complex are becoming clearer
by composite data from several tasks.

PUNA MAGNETICS (TASK 2.2A)

The magnetic survey is finished, and we are not at this time proposing any more work; the only funds we are requesting are publication funds. No magnetic work was proposed in the original proposal, but it was later decided that it could yield significant information if observations were made near ground level. A preliminary draft of a paper prepared for a journal article summarizes the results of our magnetic surveys and is included as the Appendix at the end of the text for Task 2.2.

GRAVITY STUDIES (TASK 2.2B)

Gravity studies were not contemplated at the inception of the geothermal project, as there were published gravity data over the Puna area (Kinoshita, 1965) and as the gravity data did not seem too informative. In April, 1974, D. Klein carried out a closely-spaced gravity traverse across the east rift zone while awaiting the weather and bureaucratic permissions to clear up before conducting an electrical survey. The resulting gravity profile suggested that with a dense set of data, the subsurface structure of the intrusive zone or dike complex can be revealed and that the sub-surface structure may be offset from the line of east rift vents as seen on the ground surface. It was then decided to initiate a gravity study in the geothermal project.

In June, 1975, a gravity survey was carried out over the Puna area by two teams, one using a La Coste Romberg meter and the other using a Worden meter. The survey was tied in with the Hawaii gravity network through the base station in the old terminal building at Hilo Airport. Over a hundred stations were occupied, with a network spacing of about 1 km wherever possible.

Bouguer corrections and terrain corrections were applied to the data with the assumption of country rock density of 2.3 g/cm^3. The resulting Bouguer gravity map is shown in Figure 1. At first glance, the gravity map resembles a topography map and objections can be raised that the choice of Bouguer density was wrong. The response is that the two maps may agree over the topographic high south of the town of Pahoa (see gravity map), but around Kapoho Crater, the two maps diverge. The value of 2.3 g/cm^3 has been arrived at by
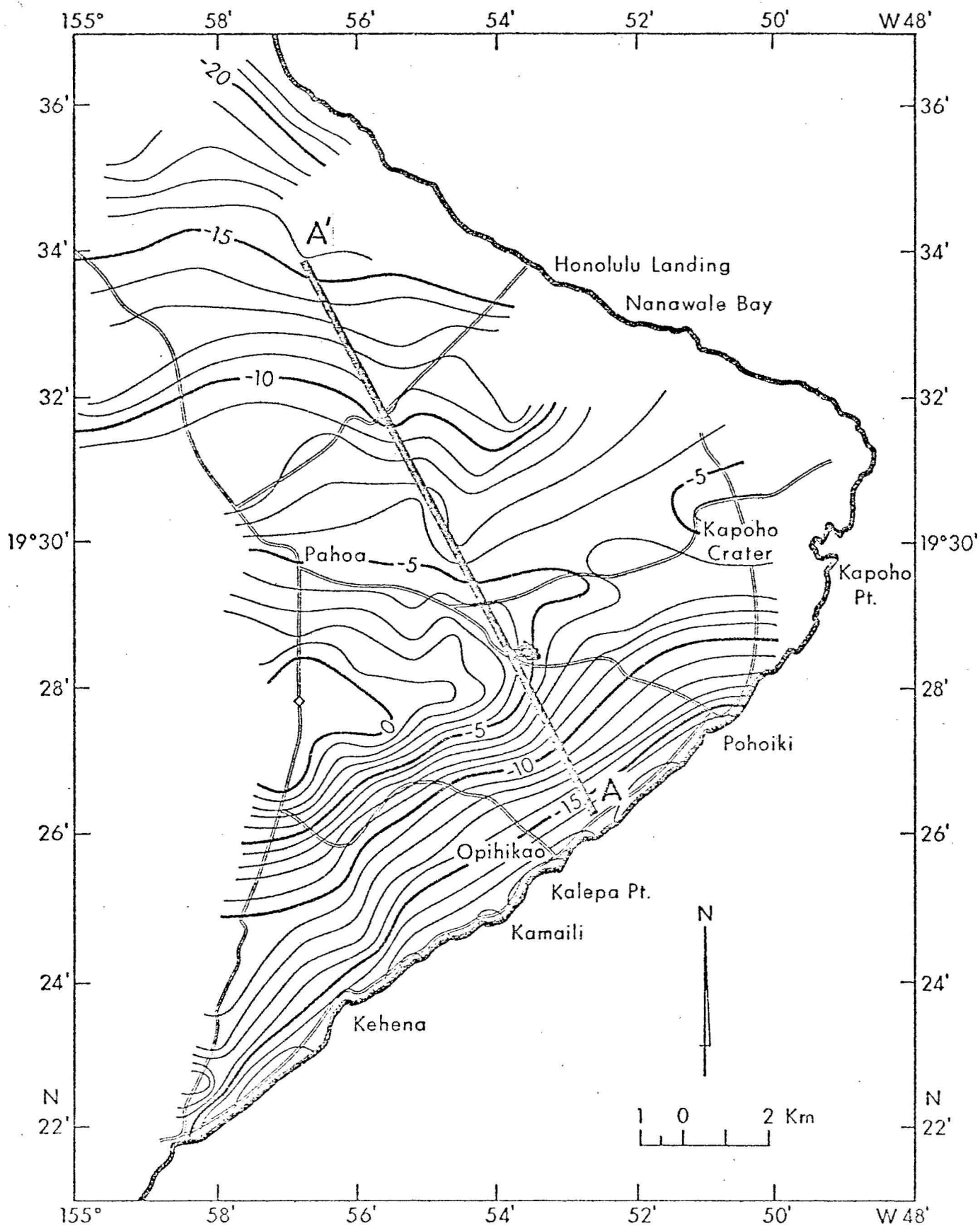
-13-

Figure 1. Bouguer gravity map of Puna area island of Hawaii.
The highest value has been arbitrarily set at zero.
Triangle shows site of HGP-A well.

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numerous studies of rock samples and field corrections and appears
to be applicable for all the islands of the Hawaiian Chain (Rose,
1976). In addition, if the gravity map is to be flattened out, a
density value of 4.3 g/cm^3 would be necessary, a density much
greater than that permissible for crustal material.

As a "first cut" attempt to determine the shape of the
anomalously dense body, the approximate method proposed by Skeels
(1963) was employed. The result of applying the method to the
profile along line AA' of Figure 1 is shown in Figure 2. A density
contrast of 0.6 g/cm^3 was chosen after consulting the paper by
Strange et al. (1965). Similar analyses were done for other lines.
The results show that the observed gravity can be approximated by
a tabular body 0.6 km thick at a depth of 1 km. Although the
density contrast terminates at 1.6 km, we do not think that the
intrusive zone or dike complex ends there but that the zone extends
to greater depths and that the country rock also increases in density
with depth. Thus at depths greater than 1.6 km, the density
contrast is too small to affect the gravity profile. The structural
picture obtained by these early simple analyses was used in interpret-
ing microearthquake data.

As a second step to gravity data analyses, spatial harmonic
analyses have been attempted. The two dimensional data were resolved
into components so that the general trend could be seen without being
masked by smaller variations and undulations of the data. Figure 3
shows the third order polynomial trend surface of the gravity data
contoured by the computer program known as SYMAP. Figure 4 shows
the residual of the third order polynomial trend. From Figure 3, we
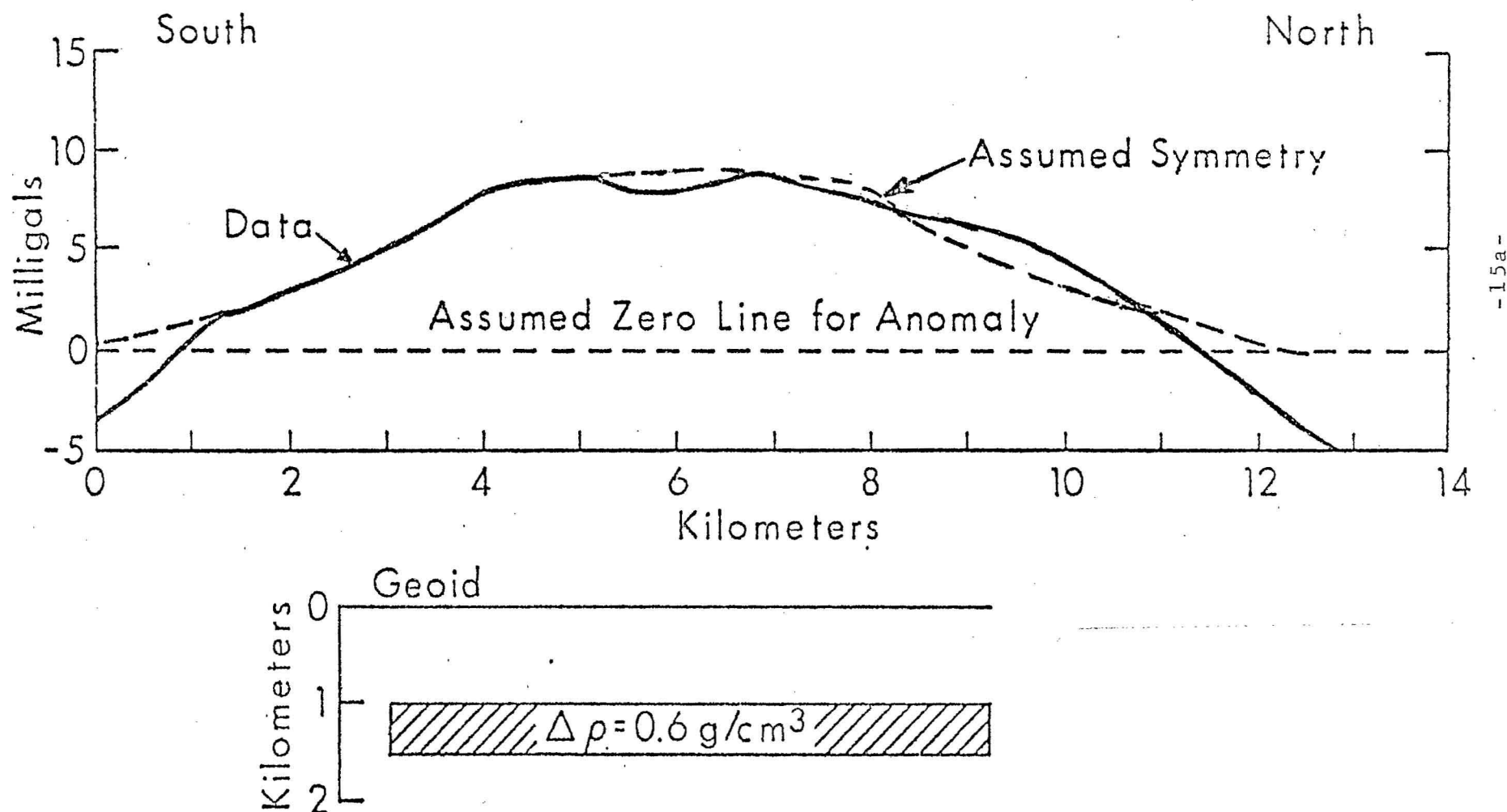
-15-

Bouguer Anomaly, Profile AA'

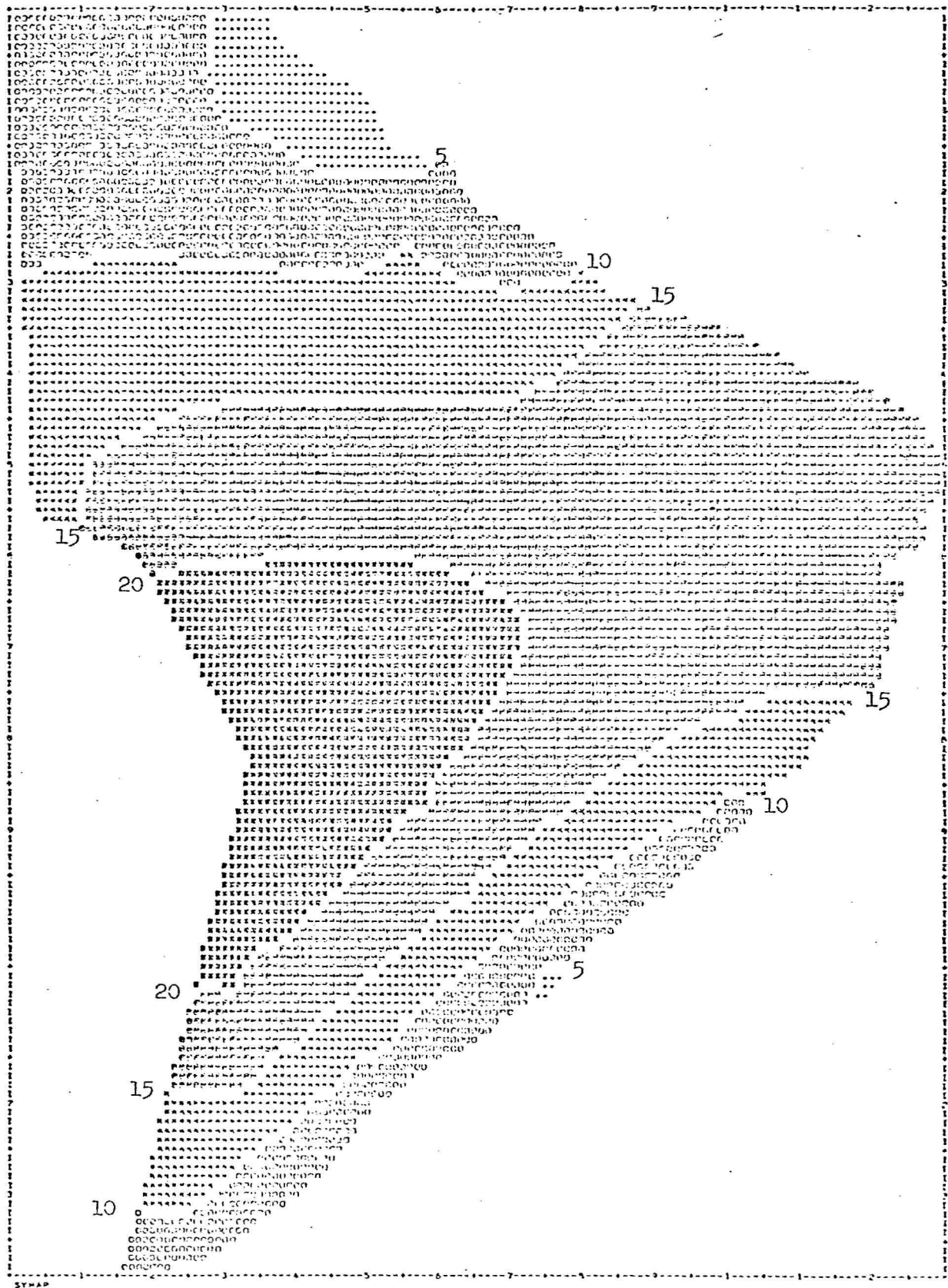Figure 2. Profile along AA' of previous figure and its associated anomaly.
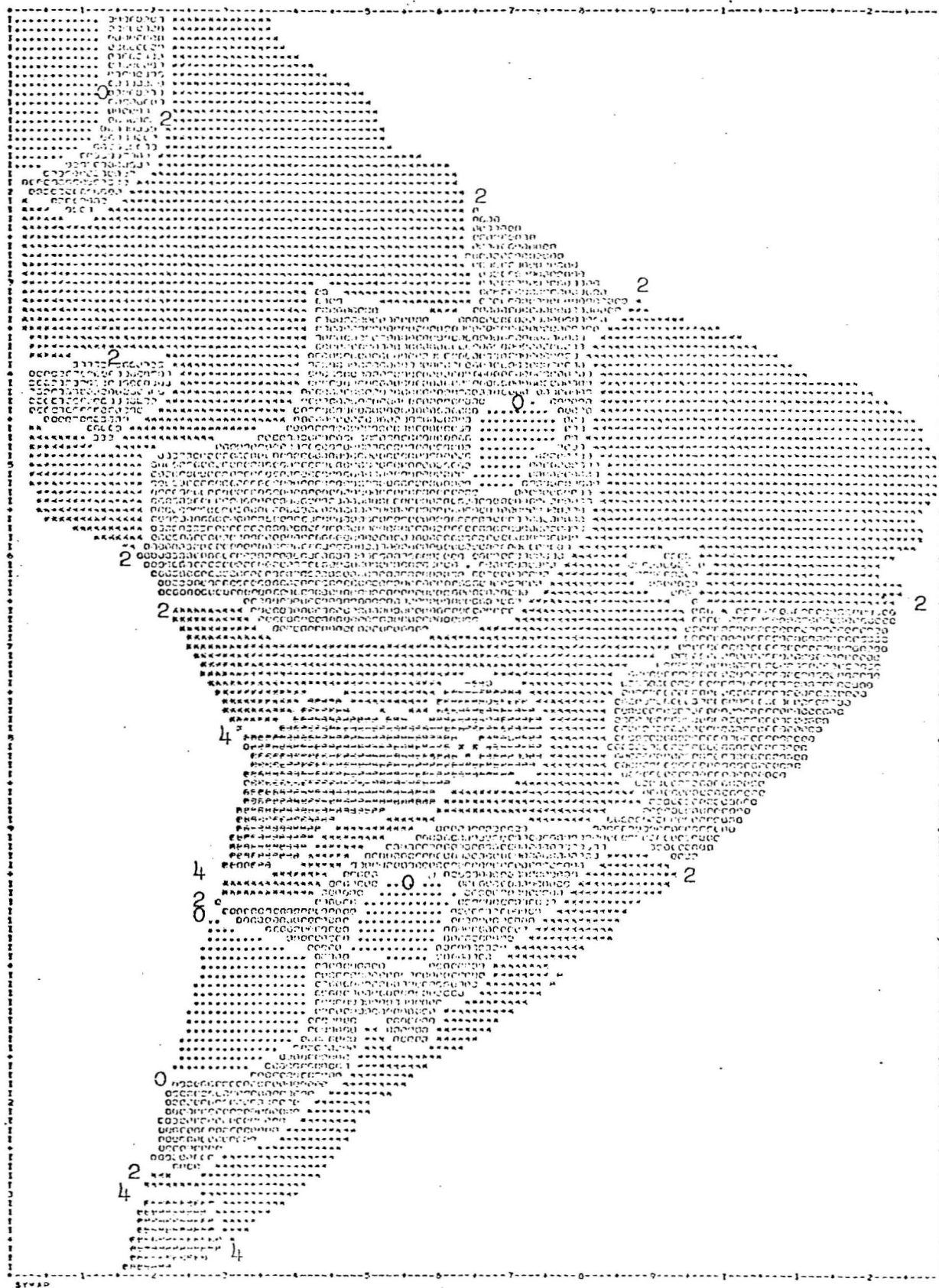
Figure 3. Contour of the third order polynomial trend surface of the Bouguer gravity data. The contours are in 5-milligal intervals.

Figure 4.   Contour of the residual after the third order polynomial
             trend surface has been removed from the Bouguer gravity
             data.   Contours are in 2-milligal intervals.

-15c-

can see readily the general trend of the intrusive zone.

After spatial harmonic analysis has been done, the next stop is to consider the various constraints to be introduced in interpreting gravity data. With the availability of log data and lithological analysis of cores from HGP-A, we now have useful constraints to continue our analysis and interpretation.

First, we shall discuss constraints from seismic data. From microearthquake study, we infer that the intrusive zone or dike complex decreases abruptly at a depth of 5 km, although this may in part be due to the decrease of "detectibility" of small events as distance from the station increases. From the seismic refraction survey of Hill (1969), we notice that seismic velocity changes from 3.1 km/sec to 5.1 km/sec at a depth of 1.7 km. These considerations impose the constraint that the density contrast terminates at a depth of 1.7 km. Below 1.7 km, there may be small density contrasts but they are too small to influence the surface data perceptibly. The approximate method used earlier reinforces the validity of this constraint.

Lithological logs from HGP-A tell us that at 1800 feet (540 m) below ground surface, the rocks change from subaerial extrusives to submarine extrusives (pillow lavas). Throughout the drill hole, all rocks encountered were extrusives and no rocks with textures character-istic of dikes or sills were found. These considerations introduce the constraint that the density contrast starts at 540 m depth and that the density contrast will be less than 0.6 g/cm^3. The neutron log from well logging show a decrease of water content in rocks at about 2400 feet (731 m) depth. This introduces another constraint relative to density changes at depth.

By taking into account the resolution of the gravity data into spatial harmonics and the various constraints from seismic data and well logs, we shall use the Talwani method (Talwani, et al., 1959) to obtain models that account for the gravity data. We expect that the incorporation of these constraints for density contrast with depth will allow more definitive models to be developed. Hopefully, we can use these models to constrain the lateral extent of the intrusive zone or dike complex. An early result shows that the width of the dike complex may be about 12 km.

Although no dike rock was encountered by the well, this does not lead to the conclusion that dikes are absent from the east rift zone. Lava outpourings along the east rift must have come from the central magma chamber through conduits. In Hawaii, ancient exposed intrusive zones show that these conduits are nearly vertical dikes. Hence, it can be safely stated that even under the east rift the conduits are dikes. Along the east rift, it could be that the dikes are not closely spaced, but that they occur at intervals among the pillow lavas.

Completion of the gravity study using constraints from the well log and seismic data should outline the lateral extent of the intrusive zone or dike complex. Although gravity methods alone have measure of ambiguity, their use with seismic refraction data greatly reduces these ambiguities and thus a combined gravity-seismic analysis of the East Rift should assist greatly in the delineation of the dike systems present beneath the rift. Since we believe that the source of the heat for the geothermal system observed in HGPA is to be

associated with these intrusive rocks, further exploration efforts will be greatly enhanced by a more complete understanding of the gravity field.

NUMERICAL STUDY OF THE THERMAL BUDGET
OF THE EAST RIFT (TASK 2.2C)

In this study, we plan to examine the thermal budget of the east rift by numerical methods. We are considering the structure of the east rift as a whole, rather than any one geothermal reservoir. The study we propose is one of thermal conduction, in which we take into consideration the intrusive zone or dike complex, the flanks to the south and north of the east rift, and the structure of the island in Puna area.

The source of heat for all thermal activities in the east rift, including lava eruptions and formations of hydrothermal systems, is the magma periodically injected into the east rift. From historical data, it seems that magma travels down as far as the Puna area once in a hundred years. The dissipation of heat from the magma is, on the whole, by conduction. Circulation of ground water above and around the intrusive zone removes a large part of the heat, but what we are concerned is the transport of heat to the boundary where convection then removes the heat.

Fiske and Jackson (1972) have proposed that magma is forcefully injected into the east rift from the central magma chamber. From physical model studies using gelatin molds and ink, they reasoned that the magma travels through nearly vertical dikes. If we assume that their conclusions are correct, then we must place these dikes at depth, since in an eruption on the rift, linear lava vents appear at intervals instead of continuously. The main dike is deep, and along the way some of the magma rises up through cracks to erupt as lava. In our study we will place the hot dike at depths deeper than 2.5 km.

The drilling of HGP-A did not encounter any dike rock. Below 1800 feet (540 m) the rocks were submarine lava, such as pillow lava. We will extrapolate from this information and assume that down to a depth of 2 km, the greater part of the rocks in the intrusive zone are pillow lavas, and dikes or sills occurs infrequently. The thermal conductivity and diffusivity values will be obtained from the task on physical properties.

The dimensions of the intrusive zone or dike complex will be obtained from gravity and seismic studies. At the present, we can say that the intrusive zone or dike complex extends to a depth of 5 km, but the lateral dimensions are still subject to discussion. The density of the structure will be obtained from core samples of HGP-A, but the core extends only to a depth of 2 km. Density values below that will have to depend on the seismic refraction task.

In our study, we shall start off with calculating the temperature distribution of a two dimensional structure after a hot dike-like body has been emplaced into it. We shall calculate the temperature decay with time.

After we have obtained the temperature profile over a period that is equivalent to a hundred years, we shall then inject another hot dike into the structure. The temperature profile at the hundred year time will be the boundary condition of the next set of computation. In the calculations, we will emplace the hot dikes randomly within a broadly confined zone, since we notice historically that lava erupts from different vents at different eruptions.

The first models for calculation will assume that the intrusive zone or dike complex is impermeable to water. Convection takes place on the boundaries but not within. After we have solved the

impermeable cases, we shall proceed to the more complicated cases where water circulates through parts of the structure. Mathematically we shall represent this as a heat sink.

Boundary conditions will have to be given serious consideration. On one side of the east rift is the sea and this can have a simple boundary condition of constant temperature. At other places, the temperature rises slowly due to heat from the dike. Perhaps a boundary condition of constant temperature gradient may be more proper. The boundary condition at interfaces with convecting water can be simplified to fixed temperatures.

In this task, after collecting all the information available on the structure, we shall proceed to calculate the thermal budget of the east rift. Specifically, we want to answer the following questions:

(1) At the rate magma is being injected into the east rift, is the east rift heating up or not? Or is the east rift in thermal equilibrium such that heat coming in equals heat dissipated.

(2) At what rate can we safely remove heat from the east rift so as not to allow the rift to cool down?

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Pacific Science, v. 19, p. 339-340.

Skeels, D.C. 1963, An Approximate Solution of the Problem of
Maximum Depth in Gravity Interpretation, Geophysics, Vol. 28,
p. 724-735.

Strange, W.E., G.P. Woollard, and J.C. Rose, 1965, An Analysis of the
Gravity Field Over the Hawaiian Islands in Terms of Crustal
Structure, Pac. Sci., v. 19, no. 3, p. 381-389.

Talwani, M., J.L. Worzel and M. Landisman, 1959, Rapid Gravitation
Computations for Two-dimensional Bodies with Applications to the
Mendocino Submarine Fracture Zone, Jour. Geophys. Res., v. 64,
p. 49-59.

BUDGET

A. Salaries and Wages

    1. R. Norris, Research Associate
       (9 mos @ $1329/mo) $11,961

    2. 1 Grad. Assistant
       (9 mos., 50% at $820/mo)   3,690

      TOTAL SALARIES AND WAGES   15,651

B. Fringe Benefits   2,936

C. Equipment   -0-

D. Travel

    1. Domestic: West Coast meeting   380

E. Other Costs

    1. Supplies and materials   200

    2. Publication, page charge 640

    3. Computer   1200

    4. Communications   120

      TOTAL OTHER COSTS   2,160

F. Total Direct Costs   21,127

G. Indirect Costs   7,277

H. Total Costs $ 28,404

APPENDIX TO TASK 2.2

A Ground-level Magnetic Survey on the East Rift Zone of Kilauea Volcano, Hawaii

R.A. Norris, J. Kasahara and A.S. Furumoto

INTRODUCTION

This paper concerns a ground-level magnetic survey on Hawaii Island near the seaward end of the east rift of Kilauea Volcano. The survey was done as part of an exploration program for geothermal resources on the island.

The east rift zone of Kilauea Volcano is one of the zones of fissures that extend outward from the summit of shield volcanoes and provide passageway for magma to erupt far down the flanks from the summit. The intrusive rock in the fissures has nearly twice the magnetization of the surrounding extruded rock (Malahoff and Woollard, 1966) which makes up the bulk of the volcano.

The difference in bulk magnetic properties may be because the extruded rock is made of thin layers, full of voids and pores, subject to weathering and alteration by ground water, while the intrusive rock is relatively dense and less readily weathered. The magnetic contrast between extrusive and intrusive rock is great enough that subsurface intrusives can be detected by measurements over the surface of the ground.

One would expect a complicated magnetic anomaly pattern over the intrusive complex of the rift zone. However, the aeromagnetic map by Malahoff and Woollard (1966) shows a very simple pattern seemingly unrelated to the rift zone. Because the airborne survey was flown at altitudes of 10,000 and 12,000 feet, the effects of a feature as narrow as the rift zone cannot be well resolved. Since financial limitations precluded a low-level airborne survey we decided to do a ground-surface survey.

BACKGROUND

Figure 1 is a topographic map of Hawaii Island showing the volcanic rift zones and major faults. This paper is concerned with the survey area at the east corner of the island and its environs. Figure 2 shows the total magnetic intensity at 12,000 feet over the island. Normally polarized dipole anomalies are located over each volcanic mountain and over two other spots: one south of Kilauea Volcano and the other over the Puna submarine ridge where the Kilauea east rift goes out to sea (Malahoff and McCoy, 1967). Figure 3 is a geologic map of Kilauea Volcano and its east rift zone. The rocks are Holocene basalts and olivine basalts. Numerous pit craters and cones mark the surface of the rift zone. Figure 4 is a detailed magnetic map of the same region.

The magnetic contours define a low east-west ridge in the northern part of the survey area and a parallel shallow trough in the southern part. The total relief is barely 100 gammas. The recent vents of the east rift zone are not parallel to the magnetic trend but cut across it. The difference in strike and the low relief and smoothness of the magnetic intensity leads one to suspect that this magnetic feature is unrelated to the recent surface expression of the rift zone and is related to older deeper structure. Since the recent and relatively shallow intrusive rocks of the east rift are a likely source of heat with possible utility and since these rocks are expected to have magnetic expression, a ground-level survey was undertaken in an attempt to define their structure.

GROUND-LEVEL MAGNETIC SURVEY

The problems of surface surveying over magnetic terrain (discussed by Malahoff and Woollard, 1966) are the enhanced effects of

-25-

nearby topographic irregularities and the occurrence of ferromagnetic minerals in basaltic soils. However if the topography is sufficiently smooth, as it was in the survey area, close-spaced sampling allows the surface effects to be accounted for.

The measurements were made 8 feet above the surface with a total-field magnetometer. Exploratory traverses on foot showed hundred-gamma anomaly roughness at wavelengths of a few paces and thousand-gamma roughness found at wavelengths greater than a half-mile. Considering the order-of-magnitude difference in anomalies, the short-wavelength roughness may be regarded as local fine-scale noise. The effect of the deeper features of interest appears as long-wave modulations on the shorter wavelength background noise.

After gaining familiarity with the nature of the anomaly field, the survey was made mobile by attaching the magnetometer sensor to the end of a stout bamboo pole mounted on the front bumper of a small car. To measure the effect of the vehicle, magnetometer readings were taken at eight headings around the compass with the position of the sensor held constant. The survey traversed a hundred miles of roads and jeep trails (shown in Fig. 5) at a speed of 5 miles/ hour and a rate of 1 measurement/ 8 seconds. The sampling density was thus 90 samples/mile (spacing about 59 feet). The measurements were plotted underway upon readout from the magnetometer. The plotted graphs, like the one in Fig. 6, gave feedback during the survey and were later digitized onto cards. The heading error (inset in Fig. 6) was represented by a 4th-order Fourier series and applied as a correction. No corrections were made for diurnal variation since 2 days of continuous monitoring prior to the survey showed that the total-field diurnal component was less than 50 gammas, which is negligible in comparison to the 4000 gamma range of the observed anomalies.

DATA PROCESSING

The 9000 magnetometer readings were reduced to average intensity values for each 0.1 mile of track to match the resolution of the car's odometer and to filter out the shorter wavelength fluctuations. The survey track map (1:24000 USGS) was digitized and heading corrections applied to the mean intensity values. These data were contoured by computer using SYMAP, a program developed by the Laboratory for Computer Graphics and Spatial Analysis, Harvard University. The contouring is on a smooth surface which passes through the data points. The method of calculation (Shepard, 1970) is a weighted average of slopes and values of nearby data points, developed from a gravity type model. Directional isolation of data points is also accounted for by weighting.

GROUND-LEVEL MAGNETIC MAP

Fig. 7 is the map of the total magnetic intensity at ground-level contoured at 500 gamma intervals with local interpolation within a 1-kilometer-diameter circle. The 1-kilometer limit was chosen to avoid meaningless extrapolation far off of the survey tracks, yet give interpolation between nearby tracks.

The anomaly pattern is complex, but there is a normally polarized dipole feature, roughly 2 miles across, and 2000 gammas peak-to-peak, discernable south of Leilani Estates. A prominent magnetic high is located at the northern side of Kapoho crater-the southern side was not surveyed because of difficult access. The remaining areas are either very complicated or inadequately covered. One might have expected the more highly magnetic intrusives of the rift zone to produce a ridge-and-trough anomaly like a line of dipoles, but this effect is not evident.

MODELS FOR LEILANI ANOMALY

A generalized cross-section by the Leilani anomaly based on the ground-level magnetic map (Fig. 7), was compared with Gay's (1963) curves for interpretation of anomalies over long tabular bodies. The resulting model of the magnetic body had a depth-to-top of 1000 feet, width 4000 feet, a north dip of 68°, and a magnetization excess of .01 oersted, a value consistent with the laboratory measurements on Hawaiian rocks given in Malahoff and Woollard (1966). The curve could have fit a vertical body as well, if one chose to ascribe the height of the north end of the curve to an adjacent feature. Two other kinds of models were also fit: Vacquier's (1951) vertical prism and Gay's (1965) long horizontal cylinder. All three models are shown in Fig. 8. The vertical prism model gave a maximum depth-to-top between 1000 and 2000 feet, a width of 4000 feet, and a magnetization excess of .02 Oersted. This greater magnetization contrast gives a cylinder with the smaller radius shown by the darker circle. Were the contrast as low as .006 Oersted (still consistent with the measurements cited), the cylinder would have to touch the surface of the ground. We can take the union of all model body volumes as a rough indicator of the distribution of highly magnetized material. Fig. 9 shows the theoretical magnetic anomaly for the vertical prism (from Vacquier's [1951] catalog), which best fits the Leilani anomaly. It is to be compared with the Leilani anomaly shown in Fig. 7. Admittedly, nature's anomaly is more complicated than Vacquier's, but there is essential similarity.

UPWARD CONTINUATION MAP

If the region of excess magnetization outlined by the Leilani anomaly models is a dense network of dikes extruded from magma below,

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then the effect of the deeper non-magnetic hot material might better

be seen by looking at the mathematical upward continuation of the

field--in effect, transforming the ground survey into an "airborne"

one at the desired altitude. A square portion of the ground level

magnetic map (Fig. 7) was therefore digitized on a 25 x 25 grid with

grid-spacing about 2000 feet (interpolating into data gaps where

necessary), for upward continuation using Rudman and Blakely's (1975)

computer program. The upward-continued magnetic maps (the 2000 foot

altitude map is Fig. 10) show no effects attributable to a deep

 nonmagnetic body i.e., no sign of a large volume of magma in this

part of the rift zone. The low near the center of the map (southeast

of the Leilani anomaly) is the result of little data and much interpo-

lation and therefore nothing will be said of it. The Kapoho anomaly

is still evident in the upper right corner. The small extent of the

survey area did not allow upward continuation to 10,000 feet for

direct comparison with Malahoff and Woollard's (1966) magnetic maps

(Figs. 2 and 4).

DISCUSSION AND CONCLUSION

The ground-level magnetic survey yields a complicated anomaly

pattern in which two features are prominent. One is the intense

local high near the north side of Kapoho Crater and south of the 1960

eruption vents. No magnetic low was found to correspond with the

high. If one exists, it is near the south side of the crater where

no survey track was close enough to record it. And if that is the

case, the anomaly has reversed polarity. This would indicate an ano-

malously low magnetization or, less likely, reversed magnetization.

Low magnetization may be a result of high temperature. Basalt is non-

magnetic above 600°C and well magnetized when the temperature goes

below 400°C (Nagata, 1961). Reverse magnetization is a result of

cooling in a reversed geomagnetic field and only one example of this has been observed in the Hawaiian chain, at the Koolau caldera on the older island of Oahu (Malahoff and Woollard, 1966). Kapoho crater is younger than the last geomagnetic field reversal (Macdonald and Abbott, 1970), therefore (if further measurements were to confirm reverse polarity) we may infer the existence of a hot mass beneath it. The sharpness of the anomaly would indicate a shallow source perhaps less than a mile in diameter.

The other significant feature is the Leilani anomaly. It lies over the still-steaming 1955 eruption vents, the steaming old geothermal well on the west side of highway 13, and where sulfur can be smelled when winds have stopped. This anomaly is probably caused by a network of intrusions which when viewed in bulk have a magnetization excess of .01 Oersted, a depth-to-top of 1 or 2 thousand feet, a width of 4 thousand feet or more, and an east-west length of at least 2 miles. This material, though magnetized, could still have a temperature of up to 400°C.

The Leilani magnetic anomaly is located where gravity shows a dense mass below, and where low electrical resistivity is seaward of it. This can indicate a mass with hot water flowing from it.

We conclude that the magnetics indicate that the place to drill for a geothermal resource is at the Leilani anomaly. Further investigation might show a small hot spot below Kapoho crater.
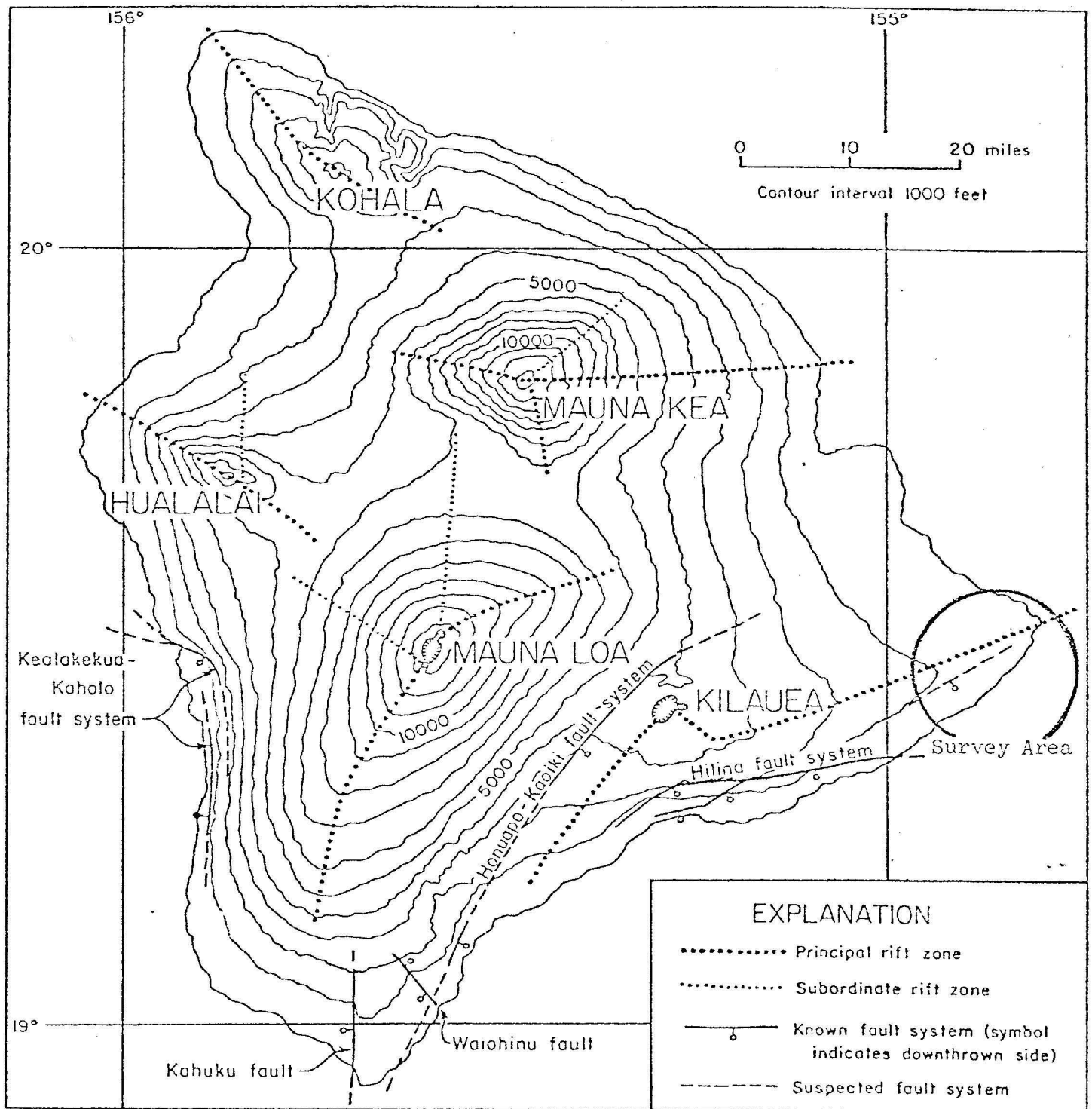
Figure 1. Map showing volcanic rift zones and major faults on the island of Hawaii (from Macdonald and Abbott, 1970).
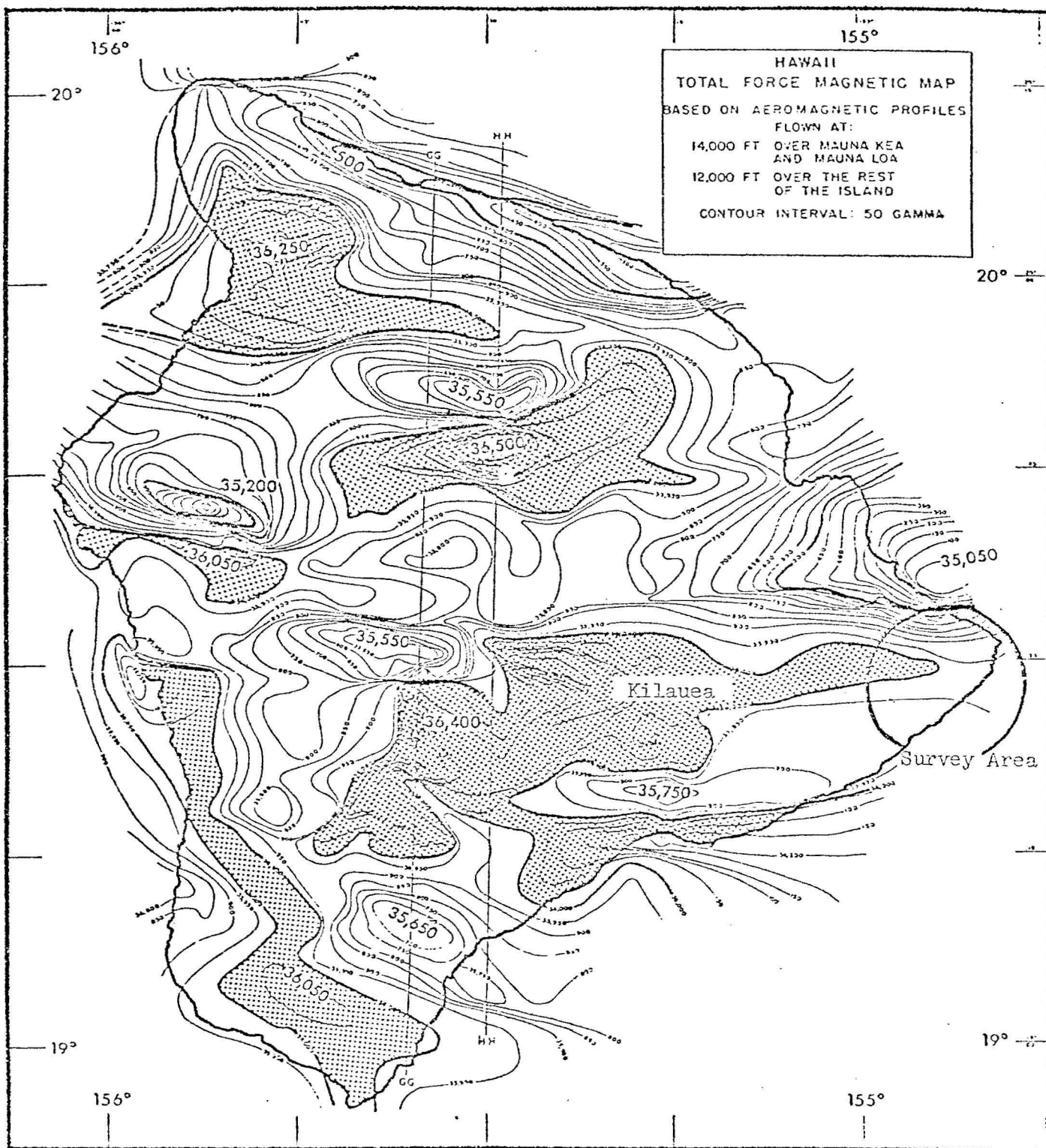
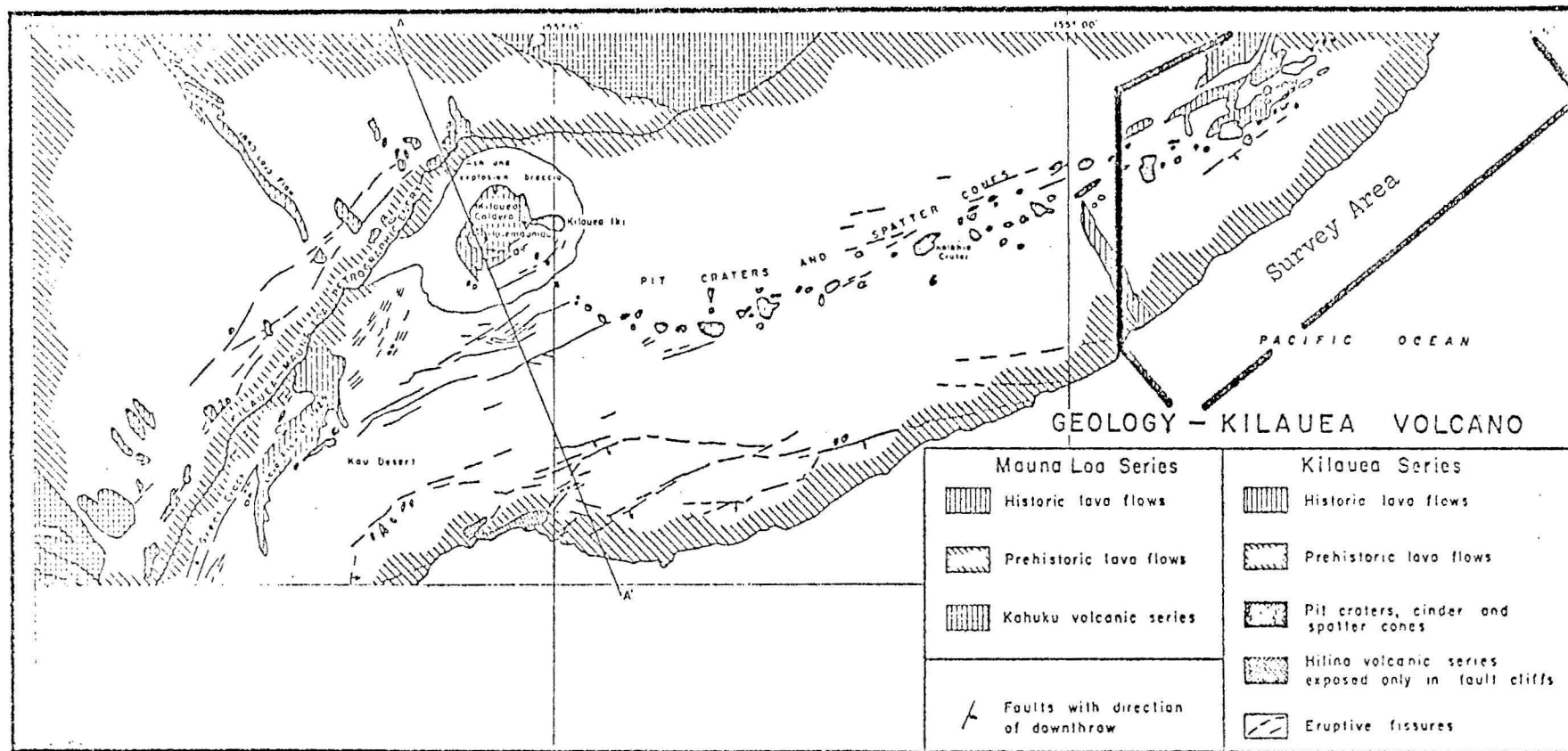Figure 2.   Total magnetic intensity map modified from Malahoff and Woollard, 1966.

Figure 3. Ground-level survey area, within dark boundary, shown in geological context (modified from Stearns and Macdonald, 1946).

Figure 4. Aeromagnetic map for Kilauea and Puna. Ground survey area is at upper right, within dark boundary. Shaded stripe represents the east rift zone (modified from Malahoff and Woollard, 1966).
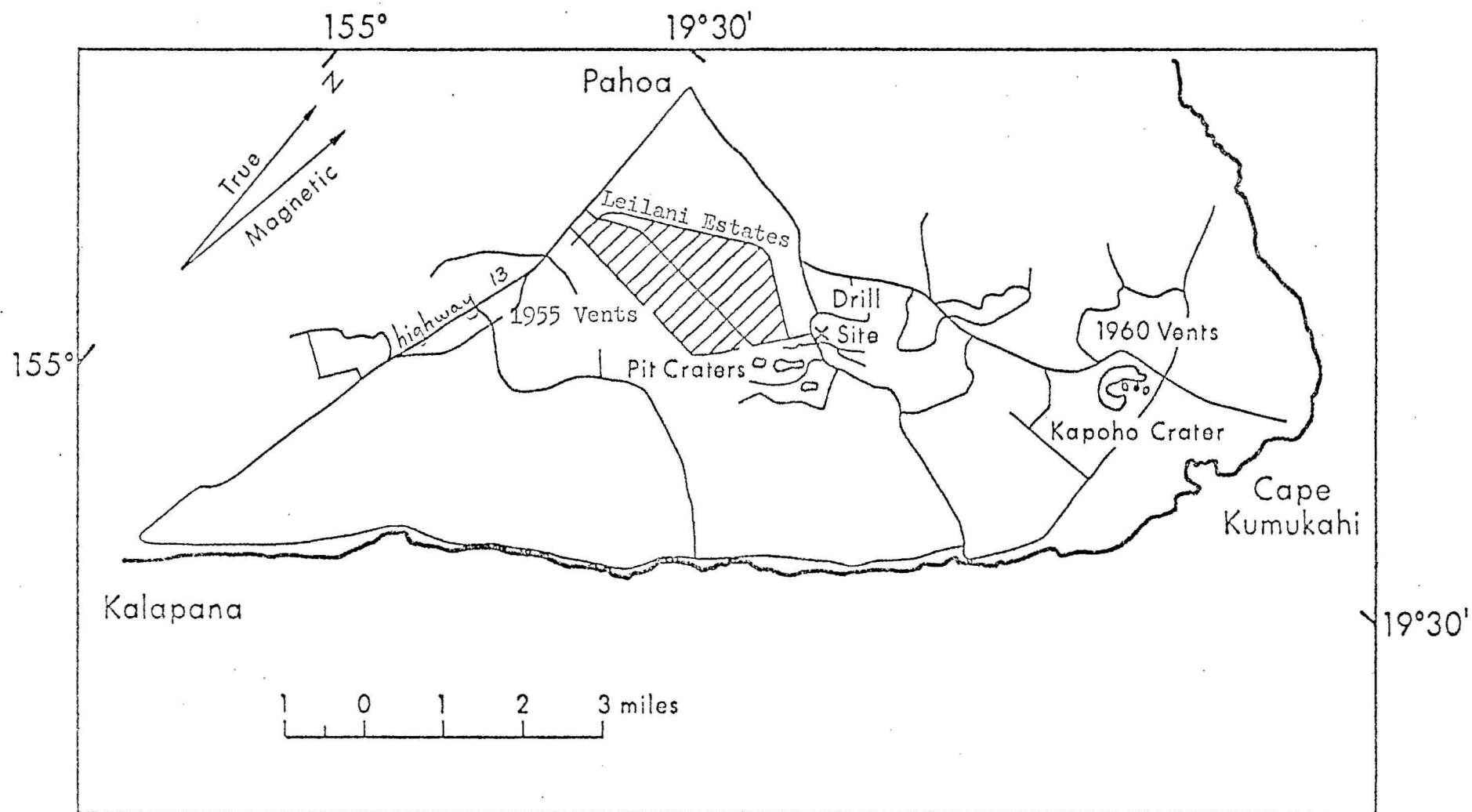
Figure 5. Map of measured tracks done by ground survey.

Figure 6. An example of one mile of plotted magnetometer readings made on the ground survey. Inset shows heading error due to vehicle. Data in circles show tenths of mile.
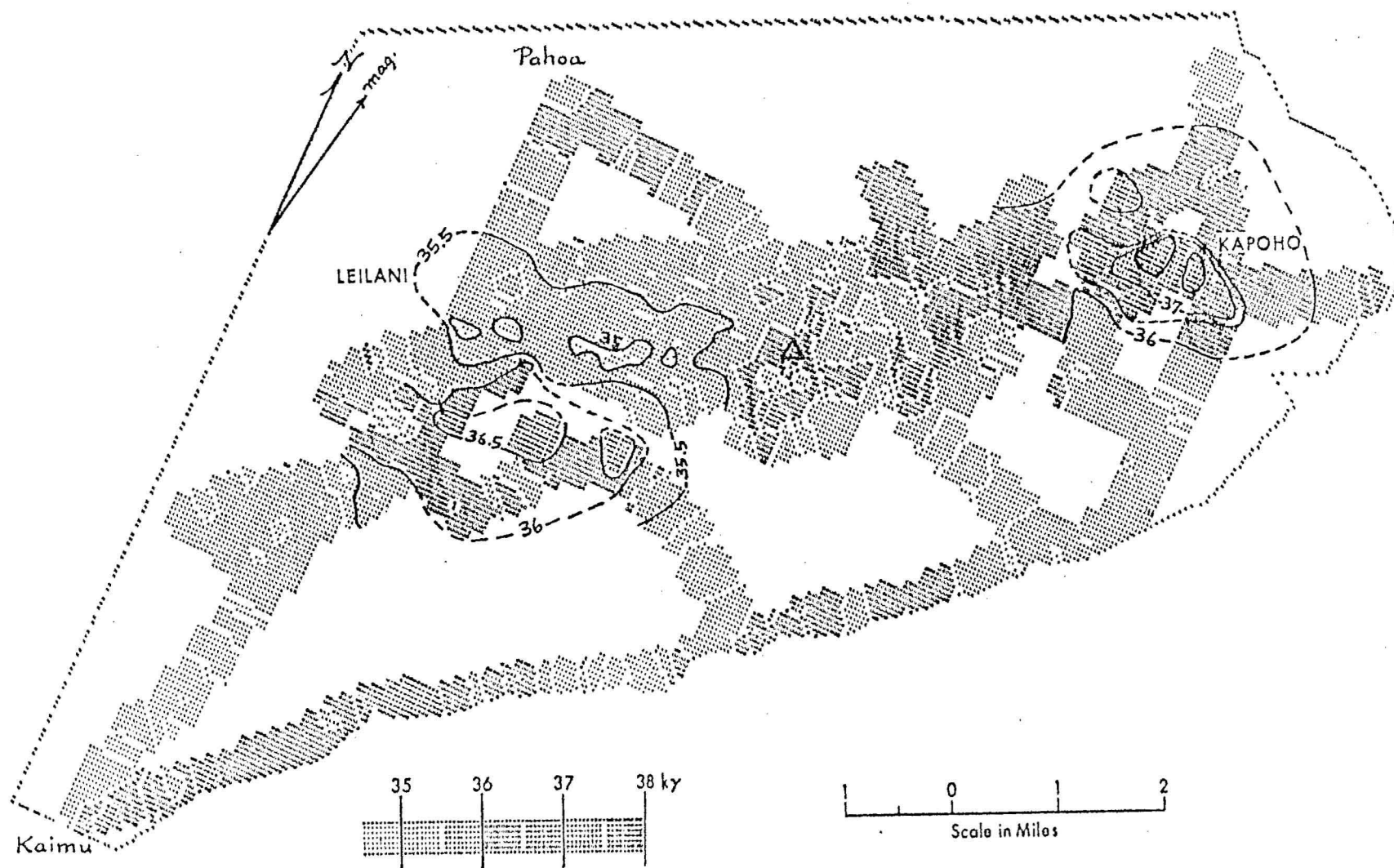
Figure 7. Total magnetic intensity at ground level contoured at 500 gamma intervals with local interpolation within a 1-kilometer-diameter circle. Inked contours clarify Leilani and Kapoho anomalies. Drill site shown by triangle.
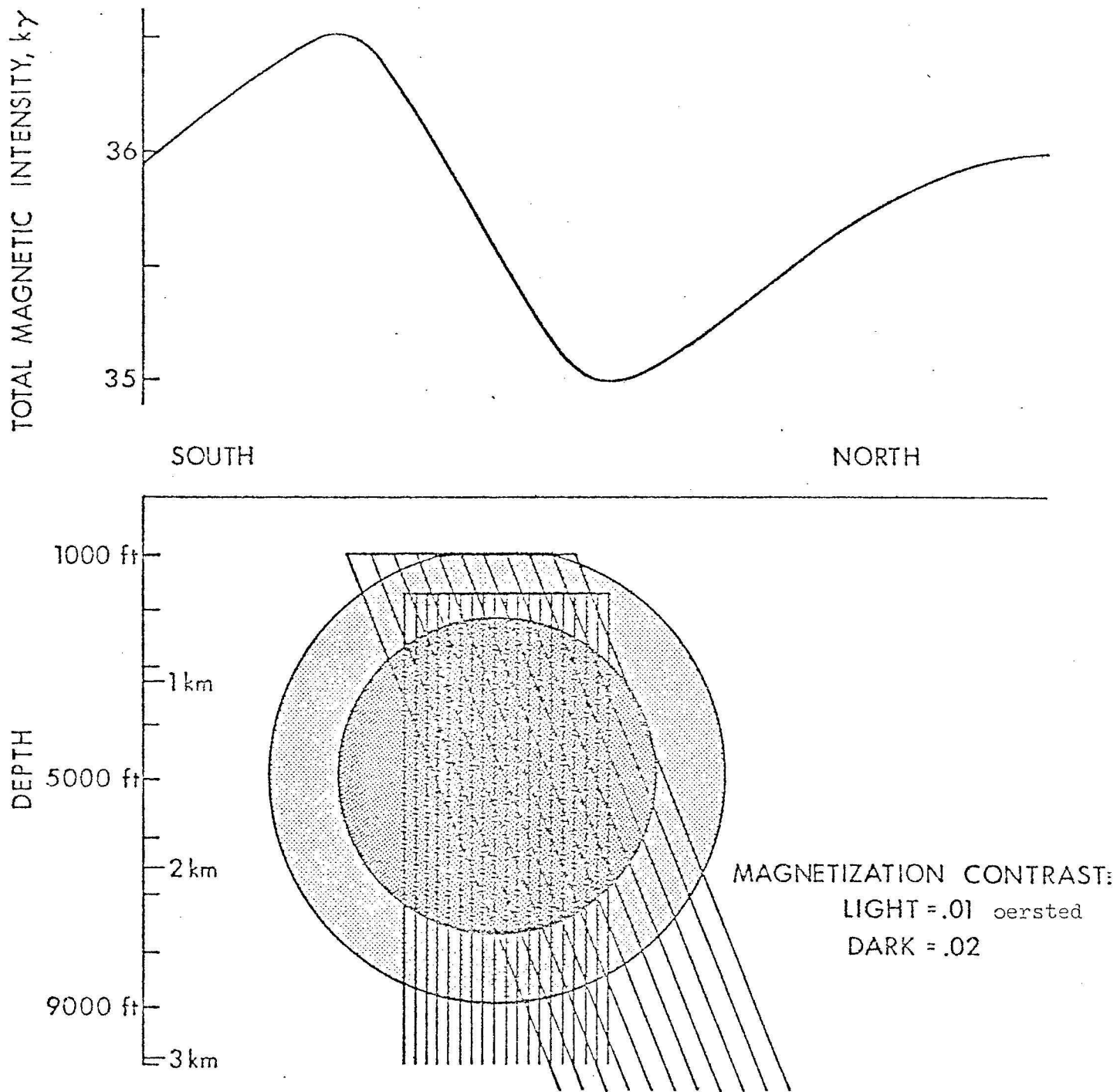
Figure 8. Generalized cross-section of Leilani anomaly (top) and some model bodies which could cause it (bottom). Horizontal and vertical scales are the same.
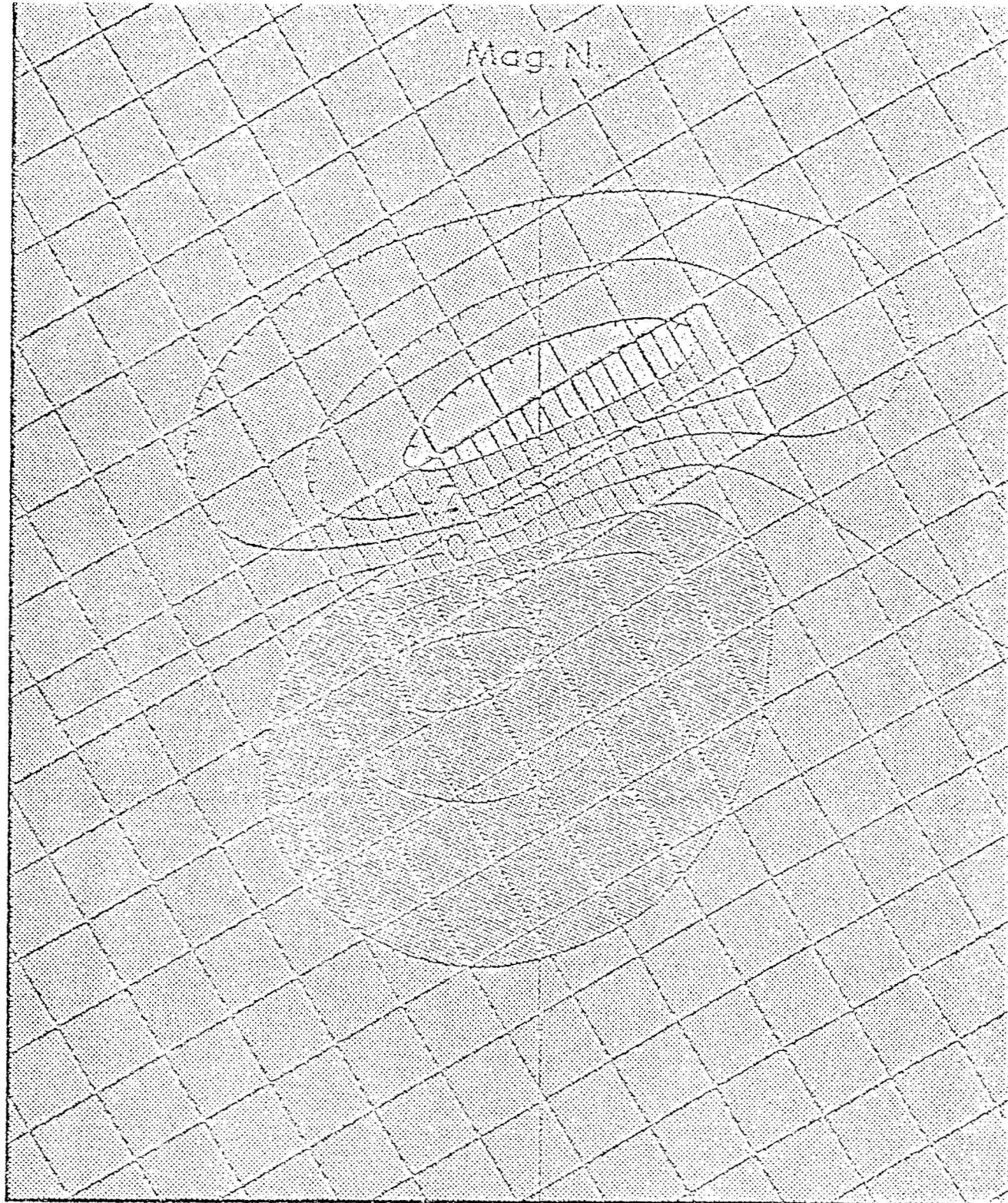
TOTAL INTENSITY, $\Delta T / I$ (C.G.S.)

Inclination 30°   Grid Interval = Depth of Burial

Strike = N. 60° E. (Mag.)

Figure 9.   Theoretical vertical prism anomaly from
Vacquier, et al, 1951, which approximates the Leilani
anomaly, grid interval is 2000 ft. (shading added)

Figure 10. Upward continuation to about 2000 feet of the ground-level magnetic field in Figure 7 (vertical scale compressed 8:6 by change in printer line-spacing). Done with program of Rudman and Blakely, 1975. Heavy line shows coast.

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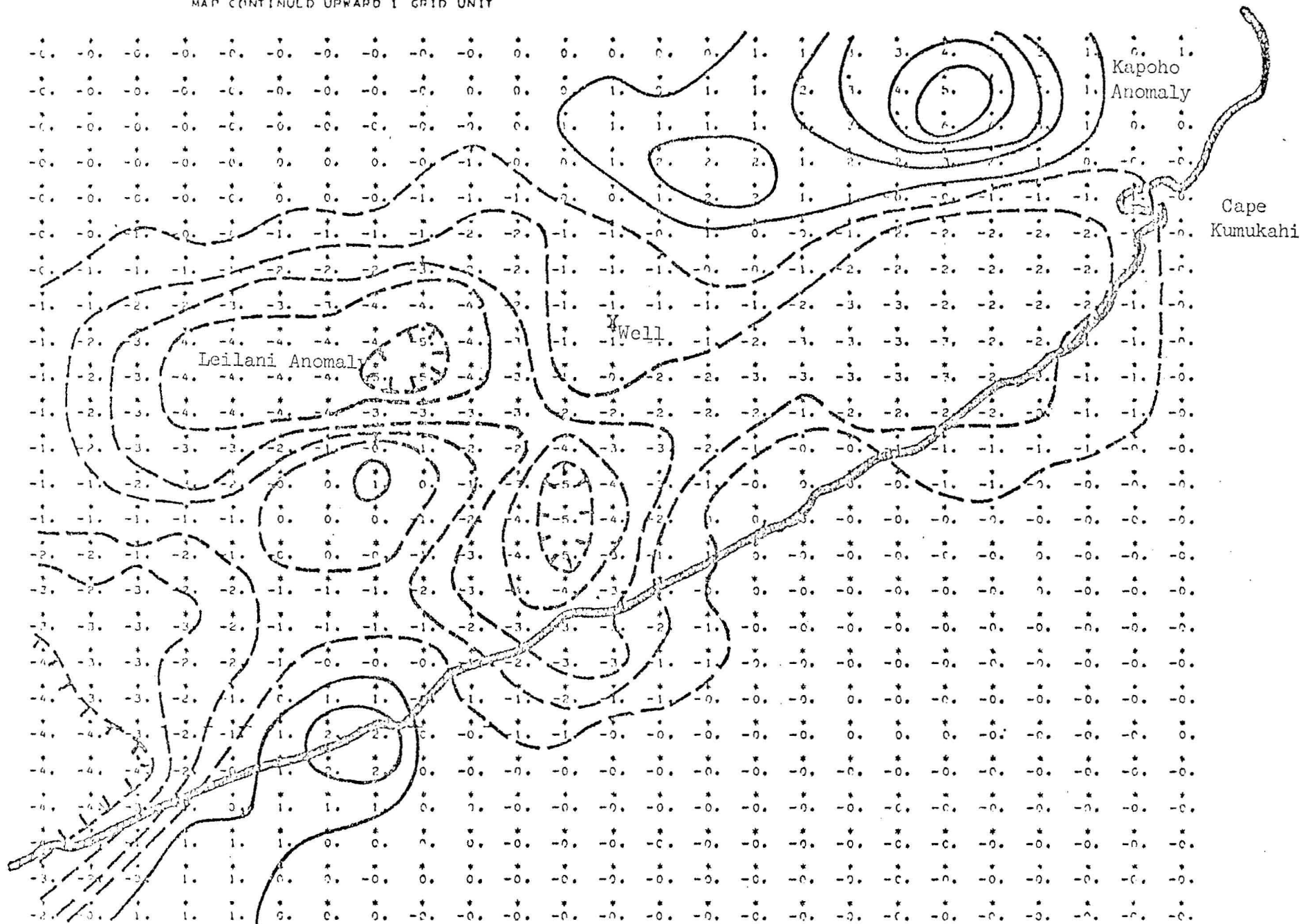Gay, S.P., 1963, Standard curves for interpretation of magnetic anomalies over long tabular bodies: Geophysics, v. 28, p. 161-200.

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Vacquier, V., Steenland, N.C., Henderson, R.G., and Zietz, I., 1951, Interpretation of aeromagnetic maps: Memoir 47, Geol. Soc. Am., 151 p.

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Task 2.4

Geoelectric Surveys for Geothermal Prospects: Hawaii
Hawaii Geothermal Project
Geophysics Program

Douglas P. Klein

Objectives, Financial Grants, Accomplishments

The two fundamental priorities in the geoelectric surveys were
to: (1) reconnoiter Hawaii Island to locate areas of anomalous
(low) resistivity which could possibly be generated by geothermal
processes, and (2) provide detailed maps and vertical profiles
of the resistivity structure in the most promising areas for
evaluation with regard to drilling decisions. Table 1 summarizes
the schedule of geoelectric field surveys under this project.

Priority (1) and part of (2), in terms of data acquisition
and preliminary interpretations were accomplished in the first
18 months of the project (July 1, 1973 to December 31, 1974) under
RANN funding (geoelectric surveys) of $63,500 (plus $30,000 for
subcontracting early reconnaissance surveys to G.V. Keller). These
results were summarized in 2 reports: Keller (1973) and Klein and
Kauahikaua (1975). Briefly, the results of these early surveys
indicated that the lower East Rift of Kilauea Volcano (the Puna
Area), showed the most promising resistivity anomaly. The areas
of reconnaissance surveys are shown in fig. 1 (from Klein et al.,
1976). The generalized resistivities of the areas are indicated
on this figure as mean values of all transient inductive soundings.
The types of surveys performed in each area are keyed to letters
on figure 1.

The second 18 months, January 1, 1975 to June 30, 1976,
funded under ERDA at $32,300 (geoelectric survey) was largely

Table 1

Schedule of Field Surveys Accomplished

DATE	DATA	GROUP
1973/June-July	bipole-dipole reconnaissance: Puna (9) Kilauea (3) Kohala, S.W. Flank (1) pole-dipole profiling: Puna (3)	G.V. Keller, contract with HGP
/ Aug - Sept	two-loop induction sounding Puna (23)	Hawaii Institute of Geophysics
/ December	Shallow Schlumberger and Wenner sounding Puna (2) Parker Ranch (2)	Hawaii Inst of Geophys (in cooperation w/ Sandia Corp.)
1974 January	Two-loop induction sounding Kilauea (2) Puna (8)	Hawaii Inst of Geophysics
/April	Deep Schlumberger Sounding Puna (5)	Hawaii Inst of Geophysics (in cooperation w/ USGS)
/June-July	Self-potential mapping in Puna	USGS (with the assistance of the Haw Inst of Geophys
/ July-Aug	Deep Transient induction sounding Puna (23) S.W. Rift, Kilauea (12) S.W. Rift, Maunaloa (10) Mauna Loa-Hualalai Saddle (4)	Haw Inst of Geophysics
1975/January	Two-loop profiling Puna (EMGUN)	Hawaii Inst of Geophysics
/April	Bipole-dipole mapping Puna (3) Bipole-dipole profiling Puna (1)	
1976/February	Deep transient induction sounding Puna (23)	

devoted to evaluating the data to choose a drilling site. Several follow-up data sets were acquired with the view to clear up ambiguities in the original Puna survey data. The field work during this time included a second major survey in Puna using the transient inductive method with improved equipment. The intent here was to study in detail the electromagnetic response of the east Rift in Puna in the zone that was considered most anomalous from a synthesis of previous data. This new data was acquired in digital form on magnetic tape. The analysis of the new data is not complete yet because we have been studying the various methods of handling a large volume of transient data (Kauahikaua, 1976) to choose a more efficient scheme before entering into what can be an expensive reduction/analysis.

Figure 2, modified from Klein 1975, shows the zones of lowest resistivity deduced from the Puna dc mapping surveys. The discussions regarding drilling largely centered around zones A and B which were the zones of least ambiguity in terms of data correlations. The transient sounding receiver sites of the first survey keyed to their half-space resistivities obtained by partial inversion of the data (Kauahikaua, 1976) are also shown. The source-receiver separations in this inductive survey were about 3 km. It can be seen that the zone of lowest deep resistivity is east-north-east of area A where drilling was performed.

The geoelectric data synthesis up to the time of drilling is reported in Klein, 1975; Furumoto, 1975; and Klein, et al., 1976. These reports do not include the self-potential data interpretations which were made and retained by the U.S.G.S. This data, however,

was presented at the meetings of the Drilling Site Selection Committee and was a significant factor in the overall geoelectric contribution.

The last part of the project, July 1, 1976 to September 30, 1976 ERDA funding at $23,200, has concentrated on a final interpretation and synthesis of all geoelectric survey data. One publication is in preparation (Kauahikaua, Klein and Zablocki, 1976) as well as a thesis (Kauahikaua, 1976) describing the final analysis of the 1st Puna inductive data set.

After our last survey, the equipment built for this project at HIG was loaned on request to the Fiji Geological Survey. They have been using it from Spring 1976 to the present to evaluate the Geothermal resources in their Islands under UN funding. J. Kauahikaua has been a field consultant to this work.

Future Work

Our primary priority for the last half of 1976 is to prepare a comprehensive report on all aspects of the geoelectric surveys on Hawaii Island. A fundamental part of this is to analyze the 2nd transient inductive data set obtained in Puna and to incorporate this with the previous data, and the latest drilling data, to form an evaluation of the transient method for geothermal exploration in basaltic regions like the East Rift. This type of report is essential to a correct wrap-up of the surveys and it will be of value to future considerations of geothermal exploration methods, not only in Hawaii, but in any igneous terrain where the advantages of inductive methods of electrical prospecting are most likely to be realized. To complete this wrap-up, we need $20,950.

The transient inductive method was our primary data aquisition method and it is a demonstrably viable method for fairly deep geothermal reconnaissance surveys as shown by our preliminary reduction of this data, which provided a useful general mapping of the anomalous zones in Hawaii.

We are, however, not satisfied with the standard final interpretational methods which are commonly applied to data of this type (Skokan, 1974). Although our preliminary analysis outlined anomalies of potential geothermal value, subsequently proven by drilling, we were not able to delineate the resistivity structure at depth to our satisfaction. Our analysis in fact shows very little structure, contrary to Skokan's (1974) analysis, i.e. we do not confidently delineate conductivity contrasts at depth in accord with Skokan's results.

Figure 3 shows the generalized results of our electric surveys in Puna in the form of a quasi vertical-profile. The transient inductive sounding points are plotted versus 1/3 source-receiver separation. For comparison the drill hole resistivity logs and temperatures are included. The inductive sounding values are the half-space resistivities obtained by partial inversion of the data (Kauahikaua, 1976). The residuals between the half-space response and the observed data were further tested to try to find the effects of resistivity layering. In all cases, there was no statistically significant indication of layering. It can be seen in fig. 3 that the inductive results are generally uniformly low for the whole Puna area and for all separations.

Neglecting the upper 100 m, the Puna area is one of very low resistivity overburden ($\sim$1 to 10 ohm-m) from sea level downward. This

is due in part to geothermal heating and in part to the ionic concentration of the fluids saturating the substrata. If it is largely due to the ionic solutions, then a geothermal anomaly would have a very low, resistivity contrast, perhaps indeterminable quantitatively with our present data. We think further analysis is in order, however, in view of the facts: (1) an additional inductive data set is available, (2) well data is available, and (3) a fairly comprehensive suite of laboratory data on the electrical properties of Hawaiian basalts is now available (Manghnani et al., 1976).

The budgeted time for the technician and part of the professional time is required for maintenance and repair of some of the survey instruments. Most of the professional time is to be spent on the above analysis and evaluation of data. Secondarily, we will take a more detailed look at the initial reconnaissance data in order to quantitatively compare the "normal" and "anomalous" areas on Hawaii. This is essential if maximum use is to be made of our experience in future surveys either here or elsewhere. Initial judgements were made on the basis of preliminary analysis and the subsequent effort was concentrated on the Puna data.

Finally, to be included in the evaluation is a report on our experience in obtaining ground contacts for the electric surveys. This is a serious problem in igneous terrain and where high currents are desired. In cooperation with Sandia Corporation, this project included a unique experiment in emplacing air-dropped electrodes in basalt. A write-up on the results of this experiment will be a valuable contribution to the general evaluation we propose.

Summary

   Geoelectric surveys have spent $149,000 of RANN and ERDA
money over a period of about 3.3 years. Practically all major
electric survey techniques (except magneto-telluric and induced
polarization) have been employed. Valuable experience has been
gained in geothermal-geoelectric prospecting on basaltic islands
in particular and igneous terrain in general.

   In view of the first objective of funding, locating a geother-
mal anomaly, the geoelectric task is complete. In a longer range
view, which includes a final report and evaluation of the surveys
for future reference, we request an additional $20,950.

   The scientific value of our experience could be maximized
we believe, by further field surveys to test improved transient
inductive techniques. It would also be of value we believe to try
magneto-tellurics in Puna concentrating on the 0.1 to 100 Hz range
in order to try to define the sources that give rise to this anomalous-
ly low resistivity area. Further surveys on some of the more westerly
islands might also be in order. These last suggestions, however,
are beyond our previous and immediate objectives. However, if future
consideration of any of these is to taken seriously, we do think
it essentialy to tie up our existing data sets into a final report
which points out their advantages, limitations and suggestion for
improvement as well as summarizing the basic facts of our results.
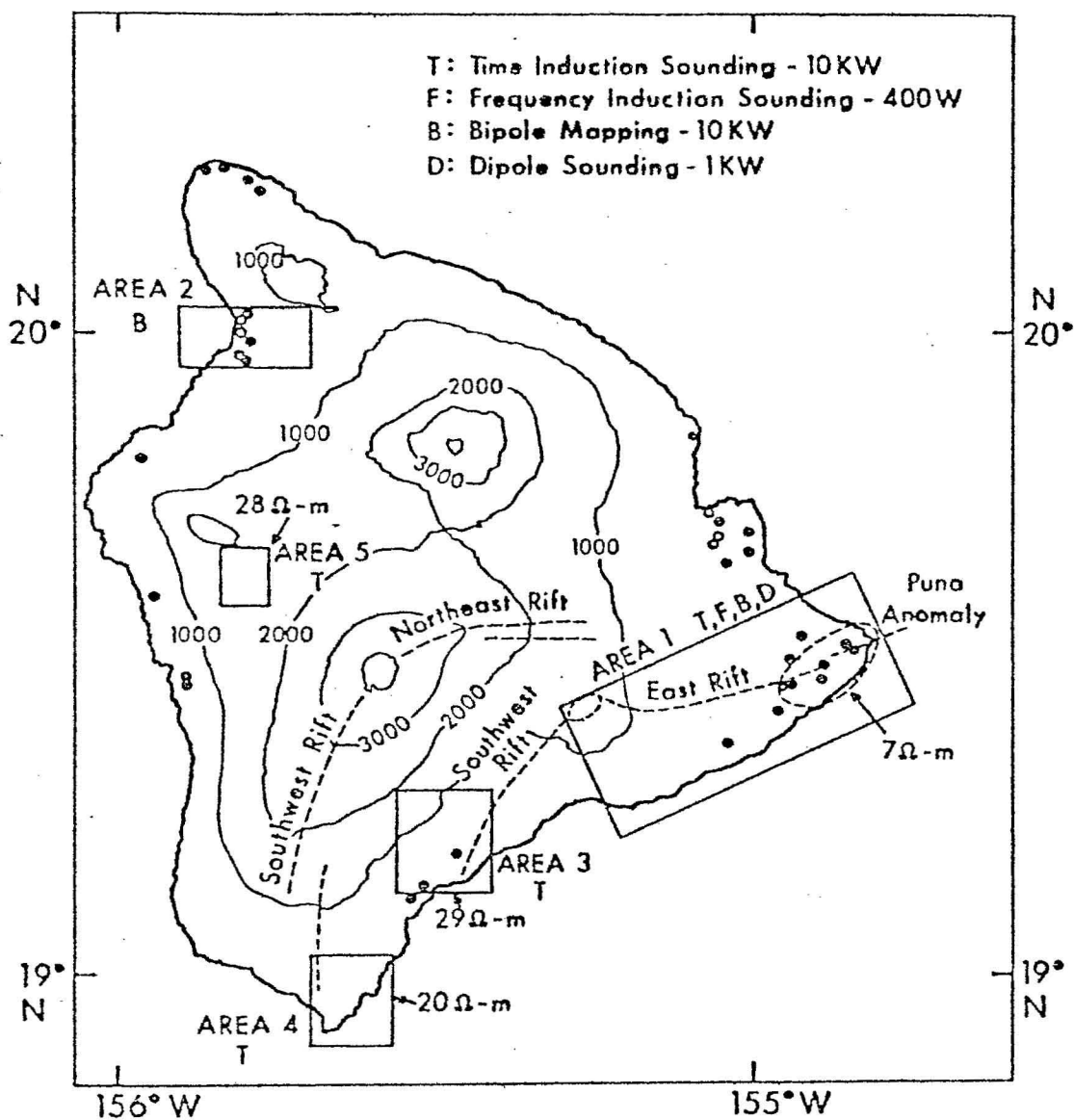
Figure 1. Regions of resistivity reconnaissance surveys.
Generalized resistivities are shown as mean
values of preliminary reductions for the tran-
sient soundings. Circles are locations of
shallow drill holes.

Figure 2. Resistivity lows located in Puna area. The Spatial distribution of transient inductive results is also shown.

PUNA RESISTIVITY DATA

ohm−m

Figure 3.

Generalized resistivity results for Puna plotted as quasi-vertical-profile. Drill hole temperatures and resistivity logs are shown.

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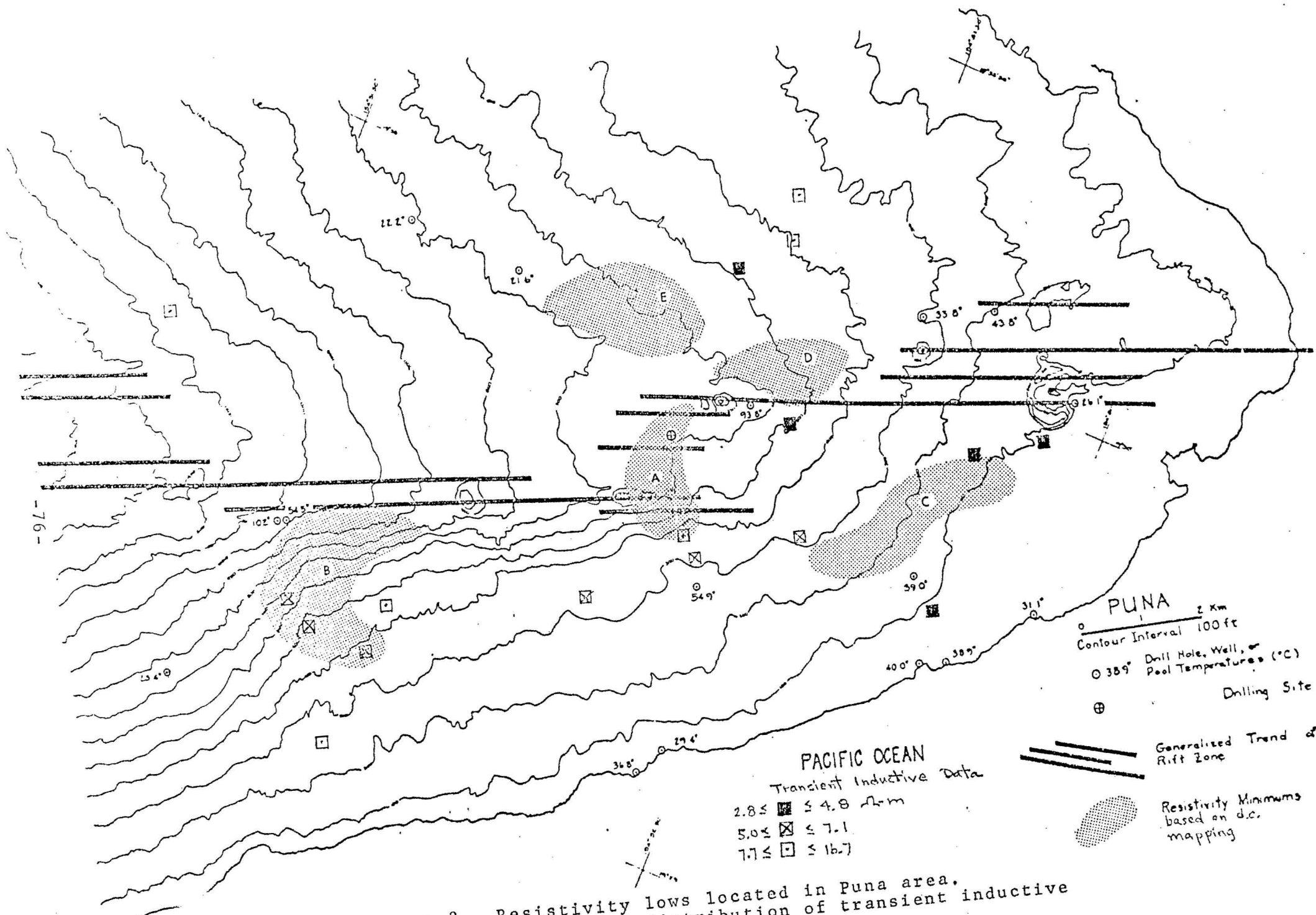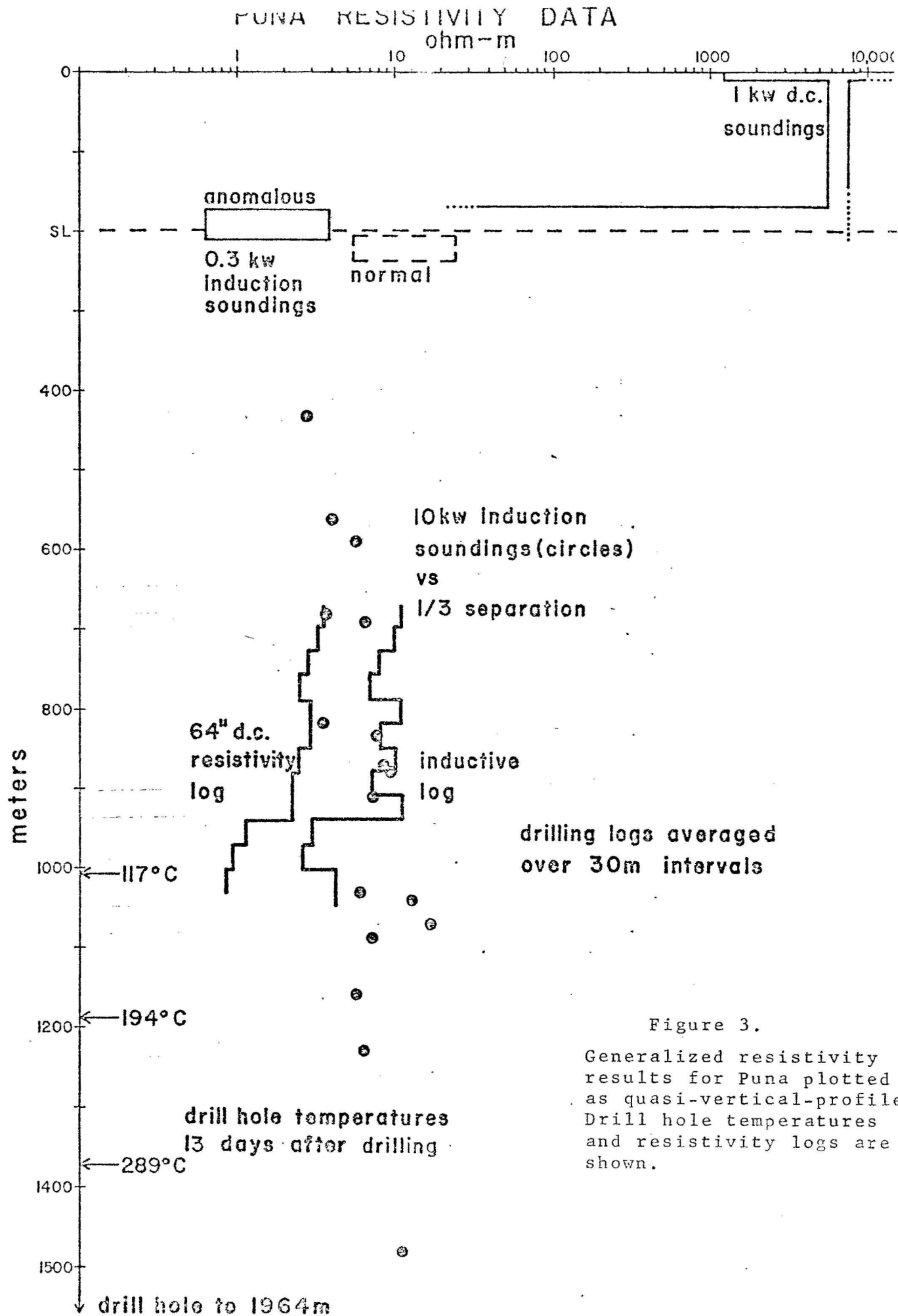
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BUDGET
Task 2.4 Geoelectric Surveys

A. Salaries and Wages

    1. Scientific Personnel

        a. Post-doctorate (D. Klein)
           4 mos. @ $1284/mo. $5136

        b. Professional (J. Kauahikaua)
           2 mos. @ $1104/mo   2208

        c. Professional (E. Sakoda)
           3 mos @ $880/mo   2640

    2. Technician Personnel

        a. Electronics techn. (C. Dodd)
           1 mo. @ $980/mo.   980

        TOTAL SALARIES AND WAGES $ 9,984

B. Fringe Benefits, 23% of total Salaries   2,296

      TOTAL SALARIES, WAGES, AND FRINGE BENEFITS   12,280

C. Equipment   -0-

D. Travel

    1. Domestic, roundtrip Denver, 1 person $339
               per diem (4 days @ $40/dy)   160
               transportation expenses   28
    2. Foreign   -0-

        TOTAL TRAVEL   527

E. Other Costs

    1. Publication
        a. Drafting, 40 hrs @ $4/hr $160

        b. Photography, 20 p @ $3.50/p   70

        c. Xerox repro., 500p @ 10¢/p   50

        d. Slides, $2.50/slide x 6   15

        e. HIG report, 60 p   783

        f. Page charges - Geophysics   -0-

      Total Publications   1078

    2. Computer (IBM 360/158)
        2.0 hrs at $234/hour   468

        TOTAL OTHER COSTS   1,546

F. Total Direct Costs   14,353

G. Indirect Cost (46% of Total Direct)   6,602

H. Total Project Costs $ 20,955

TASK 2.5

PETROGRAPHY, PETROLOGY AND GEOCHEMISTRY

P. Fan, C. Stone and D. Palmiter

Abstract

A successful 6440-foot exploratory geothermal well drilled
by the Hawaii Geothermal Project in the east rift zone of Kilauea
Volcano near Pahoa, Hawaii, penetrated a sequence of basaltic
pahoehoe, aa, and pillow lava. Ninety-two feet of core and 780
samples of cuttings were recovered. Intense alteration of the
rock below 4500 feet is suggested by a color change in the cuttings
from dark-gray to whitish or greenish-gray, and by an abundance
of secondary minerals, including quartz, pyrite and clays, partially
filling fractures. Temperature measurements taken in the completed
well also agree with the existence of an active hydrothermal system
below 4500 feet. Macroscopic examination of cores and cuttings
is complete, but microscopic, x-ray diffractive, and chemical
studies are only just beginning and require considerable work before
it will be possible to define precisely the characteristics of the
producing zone.

Introduction

The Hawaii Geothermal Project drilled a successful geothermal well to a depth of 6440 feet near Pahoa, Hawaii, between January and May, 1976. Geologic sampling involved the taking of 10 cores, totalling 92 feet of recovery, at roughly 600-foot intervals, and 780 cuttings samples. Cuttings were retrieved at 10-foot intervals, except between depths of 1420 to 3500 where the interval was decreased to every five feet for greater precision.

Initial geochemical investigations were directed toward studying the chemical and isotopic composition of Hawaiian ground-water to locate and evaluate potential geothermal areas. The most successful method of chemical geothermometry was the silica method. The data obtained by this method indicated that geothermal test hole No. 3 in the Puna District, east rift zone of Kilauea Volcano, had dissolved-silica calculated temperatures in the range of about 160°C to 275°C. Silica content in the hole is almost three times greater than the average for the island of Hawaii. (Fig. 1) These data were important considerations in selecting the present successful site for Hawaii Geothermal Well A. Two papers based on this research have been submitted for publication.

Work accomplished to date on the cores and cuttings consists mainly of macroscopic examination and description of the cores and cuttings, and x-ray diffraction studies at 200-foot intervals (see Fig. 2). Preliminary thin-section study is proceeding on the cores and will become a major effort as we continue our search of intrusive material within the section penetrated by the well.
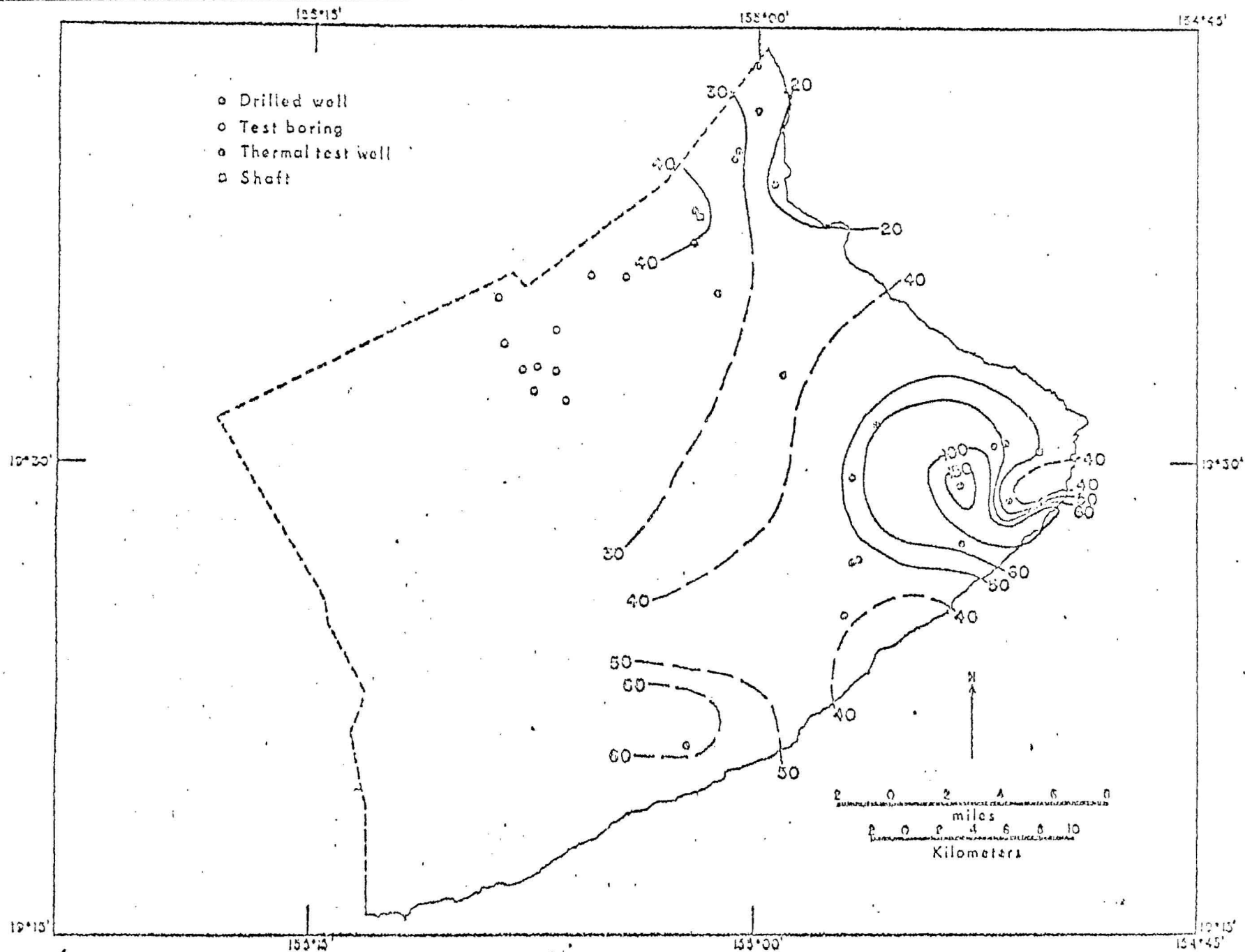
FIGURE 1.
Lines of equal silica concentration, in milligram per liter (me/1) of the Puna District, island of Hawaii.
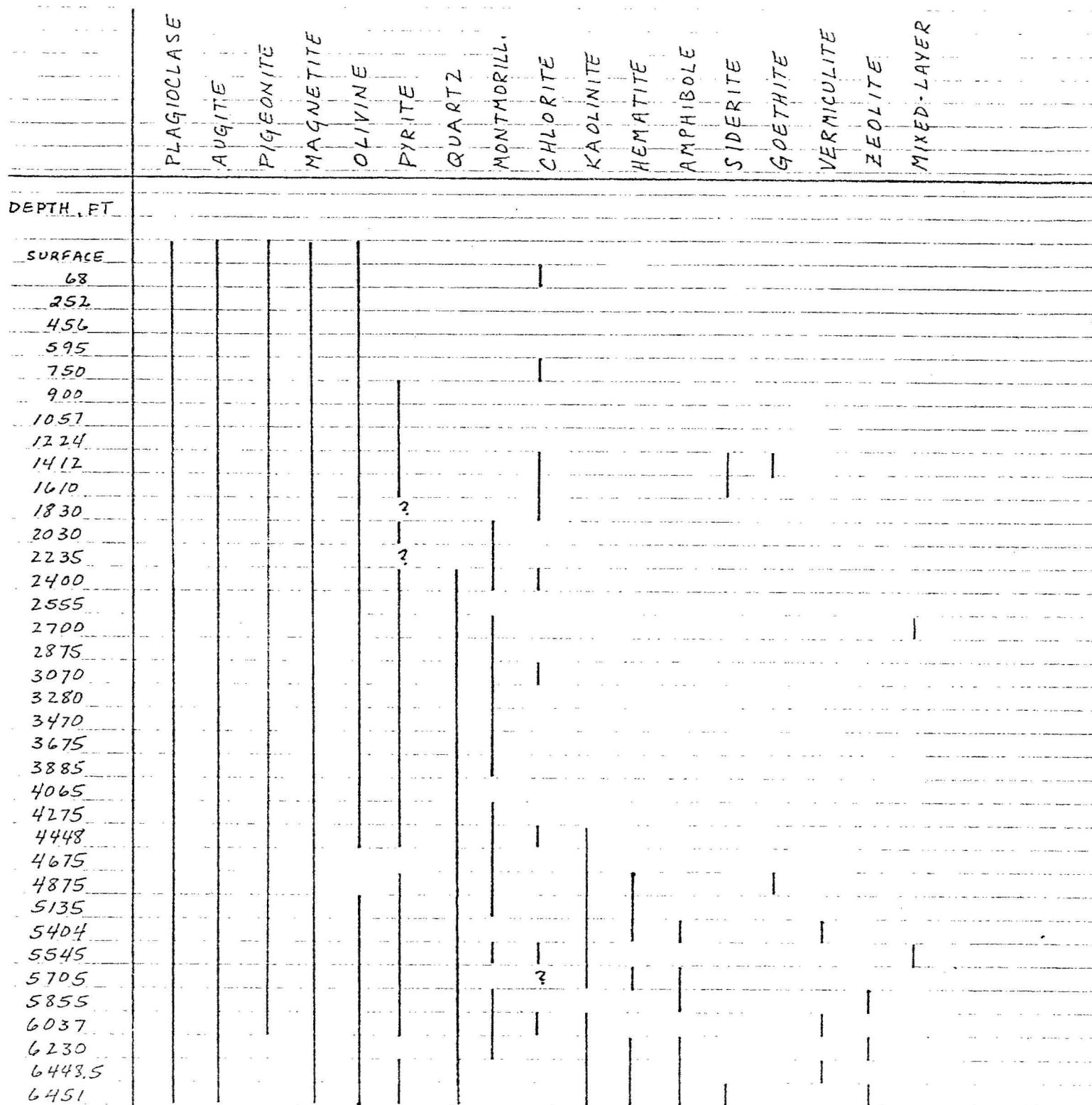
Macroscopic study reveals that the hole penetrates a sequence of subserial pahoehoe and as basalt flows to about 1700 feet below the surface, and submarine pillow lavas, also basaltic, from 1700 feet to the bottom (see Fig. 3). From the 4500-foot level to the bottom of the hole, intense whole-rock alteration occurs combined with secondary mineral deposition in fractures. Narrow zones within this bottom section, such as at 4890, 5080, 5430, and 5990-foot levels, show sealing of fractures, while other zones, such as at 5110, 5230, 5280, and 5960 feet, exhibit fractures containing euthedral crystals of secondary minerals, suggesting cavities. Sealed fractures seem to dominate the interval between 4500 and 5200 feet, whereas open fractures appear to be more common below this depth.

X-ray diffraction studies at 200-foot intervals indicate the presence of pigeonite, pyrite, quartz, montmorillonite, kaolinite, hematite, talc, vermiculites, gibbsite, and actinolite-tremolite within the 4500 to 6440-foot producing interval. Preliminary thin-section studies show alteration similar to that of greenstones in the lowermost cores.

FIGURE 2.

INITIAL X-RAY IDENTIFICATION *
HGP A

* WHOLE - ROCK ANALYSES

Fig. 3

this portion inferred

present sea level

thin pahoehoe flows alternating with aa flows, aa clinker, and cinder (flow unit probably less than 10 feet thick)

transition from submarine to subaerial mode of eruption (first appearance of pillow-like glass at 1740 feet)

most fractures filled by secondary minerals

pillow lavas, with individual flow units bounded by black, nonvesicular glass (flow units average 70 feet thick)

zone of open fractures

zone of intense whole-rock alteration with partial filling of fractures by secondary minerals

Statement of the Problem

The problems which we address principally are (1) to define the principle rock types, textures, and mode of emplacement of the samples recovered from HGP-A; (2) to examine the nature and extent of hydrothermal alteration of the basaltic cores and cuttings obtained during drilling of Hawaii Geothermal Well A, occurring as a result of circulating hot fluids; (3) to determine what effects these secondary mineral assemblages may have on the geothermal reservoir itself, and on engineering considerations; and (4) to ascertain how these data can best be used to successfully locate and evaluate future wells in Hawaii. Each of these principle problems is descussed more completely below.

In order to model the thermal budget of HGP-A, it is essential to know the (1) heat sources in the form of comparatively recent intrusives in the immediate vicinity of the well. If intrusives are present in the well, they should be recognized by their texture. This textural studies become an important part of determining the thermal history and current temperature conditions in the hole. Textures also have an important bearing on geophysical properties such as electrical, thermal, elastic, and density; and on the hydrologic properties of porosity, permeability, and resistivity.

(2) Hydrothermal alteration is a result of circulating hot fluids, and the nature of the secondary assemblage depends on the mineralogy of the country rock and its porosity and permeability; and on the chemistry and temperature of the circulating fluid. Since temperature is the most important of these parameters, indentifying the secondary minerals in Hawaii Geothermal Well A would

provide important data on the thermal history of the system and on present-day conditions. These data would also enable us to make reliable estimates of rock porosity and permeability. Susceptibility to alteration is known to depend on the degree of rock crystallization and on permeability so that determining the extent of alteration in the cores and cuttings would also aid in evaluating the permeability of the geothermal reservoir.

(3) Leaching, deposition, and ion exchange, and the secondary mineral assemblages which these produce, have a direct and important bearing on the physical properties of rocks and the fluids circulating through these rocks. They affect the electrical, thermal, and elastic properties along with density, porosity, permeability and resistivity. Therefore, in order to evaluate these data it is necessary to first identify the rock suite and secondly to determine the nature and extent of alteration which has occurred or still is occurring in the geothermal system. Significant deposition of secondary minerals in pore spaces and fractures could conceivably form an impervious caprock and a self-sealing goethermal field. Study of rock alteration would help to determine whether this has occurred. Additionally, engineers are concerned about the types of scale and corrosion to which their machinery may be subjected. A knowledge of the secondary minerals present in the geothermal system would enable them to take active precautions against the more corrosive elements.

Work to be Completed

It is proposed to complete the following research on the basalt cores and cuttings obtained during drilling of Hawaii

Geothermal Well A:

1. Major chemical analyses using an ARL X-Ray Fluorescence Quantometer. These analyses would be supplemented by Atomic Absorption determinations of Na and K, and wet chemical analyses to distinguish between Fe^{2+} and Fe^{3+}. Normative analyses would then be computed. Major chemical analyses are necessary because they provide a basis for evaluating alteration products and physical properties of the basalt cores and cuttings. Without these analyses, other data would have little, if any, significance.

2. Petrography and mineralogy by studying thin sections and computing modal analyses. These studies would provide data on (1) rock texture, which would distinguish lava flows from intrusives and aid in the evaluation of geophysical data; (2) degree of crystallization and porosity; and (3) the nature and extent of secondary alteration: whether it occurs by replacement, by filling pore spaces and fractures, or both, and the extent to which this has occurred. In addition, the data would aid in determining whether the alteration products are a result of former hydrothermal activity or present-day conditions, and in modeling the geothermal reservoir of Hawaii Geothermal Well A and of future wells in Hawaii.

(3) Trace element analyses for Ni, Co, Cr, Rb, Sr, Zr, and V using Atomic Absorption methods. It has been determined that each volcano in Hawaii has a unique trace element profile (Hubbard, 1969, unpub. Ph.D. dissertation). Trace element analyses would enable us to ascertain with greater certainty that the geothermal reservoir is contained solely in lavas of Kilauea Volcano and that

we have not reached Mauna Loa lavas, a change which might affect physical properties and which might not otherwise by obvious solely on the basis of major chemical analyses. Additionally, trace element data would be valuable in correlating data from this well with data obtained from future wells.

4. Study of hydrothermal alteration products using a Phillips Vertical X-Ray Diffractometer. Since the depth zones of alteration are a function of temperature, of pH change with steam separation, and of relative alkali ion concentrations, this data would enable us to establish a correlation between observed mineral zones and observed temperature conditions, pH changes, and alkali ion concentration. Such correlations would be extremely valuable in evaluating potential geothermal areas in the future.

BUDGET

Petrography, Petrology and Geochemistry - Task 2.5

A. Salaries and Wages

    1. 2 Grad. Assistant
        (12 mos., 50% @ $914/mo.) $10,968

    2. Student Help (Undergrad.)   1,000

                                  $11,968

B. Fringe Benefits   548

C. Equipment   -0-

D. Travel

    1. Domestic   750

E. Other Direct Costs

    1. Supplies and Materials   2,300

    2. Publications   400

                                2,700

F. Total Direct Costs $15,966

G. Indirect Costs: (46% of $11,968)   5,505

H. Total Costs $21,471

TASK 2.6--HYDROLOGY AND HYDROTHERMAL GEOCHEMISTRY

P. M. Kroopnick, R. W. Buddemeier, L. S. Lau, J. J. Naughton

The drilling phase of the Hawaii Geothermal Project (HGP-A) ended on July 22 after four hours of sonic flow. At this point the wellhead pressure was 68 PSIG, the temperature was 153°C and the enthalpy of the steam was calculated to be 600 BTU/lb. These results indicate that further detailed testing of the well is warranted. In fact, if the flow rates and temperatures observed to date persist after a more extensive flow test, this well could conceivably be exploited for commercial purposes. This proposal outlines the geochemical measurements to be performed during the expected comprehensive well testing program scheduled for 1976-1977.

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Results Completed to Date

The primary goal of the hydrology task of the H.G.P. during phases II and IIA was the characterization of the hydrology of the Puna District, Figure 1 (see Appendix I--Progress Report, January 1976, and report on baseline studies submitted along with the Statement of Environmental Impact--Negative Declaration). The monitoring of the surrounding wells will continue in order to assess the effects of discharging water from HGP-A on the surrounding low temperature wells (some of them supplying potable water).

The rate of ground water recharge in the Puna area remains one of the principle areas of concern. Preliminary results of radioisotope (tritium) and stable isotope (deuterium and oxygen-18) measurements suggest that the mean residence time of all the water in the district is less than a few years (Table 1). In addition, the stable isotope data indicate that on the average, the recharge area may be within a thousand feet in elevation of the well site. Table 2 contrasts some of the well-water $\delta^{18}O$ data with rainfall $\delta^{18}O$ at the same site. Note that the $\delta^{18}O$ of both the well-water and rain-water decreases with altitude. A well-water sample represents the rainfall integrated over a period of several months to a year; however, the rainfall data is an instantaneous measurement. Figure 2 shows the weekly rainfall from February to July 1976 at four of the sampling sites. Note the coherence to the high variability as each storm front blankets the Island. More important is the trend for $\delta^{18}O$ to decrease with altitude. Before the rainfall $\delta^{18}O$ data can be reliably compared

with the well-waters, rainfall measurement must be performed for at least one year and the integrated (mean) $\delta^{18}O$ value calculated. A thorough analysis of the recharge characteristics of the district is required if commercial steam utilization is planned.

Chemical studies of hot springs, shallow and deep wells are also used to assess the uniformity and extent of an aquifer, to estimate deep water temperatures and zones of highest rock permeability, and to determine the gas and mineral content of the waters to aid in environmental and economic planning. The application of chemistry to these studies is based on the chemical processes operating in the aquifer, the kinetics of rock/water interaction, the variability of different constituents, the solubility of the host rocks, and the type and temperature of the hydrothermal fluids. Chemical data from the Puna district wells is summarized in Appendix I. Table 3 lists the chemical and isotopic data for the deep well HGP-A. Systematics in these data are most easily discussed if one considers the well-water to be a mixture of seawater and rain-water. The chloride concentration is used to calculate the percentage of seawater contributing to the sample. The other ions are expressed as the percentage excess over that expected if they are derived from the simple mixture. Figure 3 shows the % excess for the 4 major cations. The wells are arranged in the order of increasing temperature. In general, we see that as temperature increases the Na and K also increases while Ca and Mg decrease. This effect is due to water/mineral chemical reactions occurring in the aquifer. The use of these relationships as a geothermometer is discussed later

in this proposal. Note that the chemistry of HGP-A is consistent with the trends shown by the shallow wells.

Preliminary isotope data for HGP-A (Table 3) indicates that the water is enriched in ^{18}O relative to local meteorite water implying partial equilibration with ^{18}O-enriched basaltic minerals at temperatures in excess of 200°C. The chloride and other ion concentrations suggest that the first water samples collected represent a 3% mixture of seawater and fresh water which has been subsequently subjected to high temperatures where chemical exchange with the host rock occurred. The low Cl, SO_4, and Na values measured after the production test are probably caused by steam water separation within the 6000' well casing. The Na/Cl ratio is the same for the 6/24 sample as for the 7/23 sample, indicating that no change in chemistry has occurred. The $\delta^{18}O$ measurement confirms this hypothesis indicating that the water sampled on 7/23 is residual condensed steam from 7/22. Of course, it is possible that both the isotopic and chemical variations could be due to an influx of shallow level ground water with a low Cl concentration and a more negative $\delta^{18}O$.

We have also performed preliminary analyses on a gas sample collected just before the production test by condensing steam in an evacuated bulb. The gases confirmed so far are CO_2, H_2S, and H_2. He, CH_4, and/or CO may also be present. No SO_2 steam condensate collected using the production test contained 110 ppm. sulfide. A 2" cycloidal separator designed to quantitatively eliminate both liquid water and air from a gas/steam sample will be used for future sampling.

In summary the results to date indicate that the shallow wells in the Puna district are recharged locally and that the residence time of the ground water is only a few years. The HGP-A water is chemically similar to the shallow water wells although it has a much smaller seawater component and has undergone more extensive high temperature chemical exchange with the surrounding country rock. The low major ion concentrations indicate little environmental degradation would occur during future production tests. Environmentally damaging concentrations of H_2S and Hg may be present and careful monitoring of these parameters is recommended.

Proposed Work

Continuing Work

In order to fulfill the original objectives of our hydrological, isotopic and geochemical surveys, the following subtasks need to be completed. These are:

1. Completion of analyses of samples taken during winter and summer 1976.

2. Down-hole sampling:

   a. One set of samples will be taken as soon as the well is cleared and logged, and appears to have stabilized. Exact samples will depend on logging results, but will include a vertical profile of at least 6 samples. (First set of down-hole samples collected on August 18 and 19, 1976.)

   b. At least one set of samples (vertical profile) will be taken 6-9 months after the first set. In addition to checking on the first set of results, this second set will permit sampling based on a more detailed assessment of the

logs, cores, and results of the first samples. Down-hole sampling will also be conducted before and after each steam-production test.

c. Other down-hole sampling may be indicated, depending on the nature and results of the production and development tests conducted.

3. The samples collected will be analyzed for at least major and minor elements, nutrients, heavy metals and isotopes (^{18}O, ^{2}H, T).

4. Collection and analysis under flow conditions: Once substantial volumes of water can be easily obtained, we will obtain samples from these fluids for all analyses specified above, plus a ^{14}C measurement (which requires a volume too large to be obtained by down-hole sampling).

5. Integration and analysis of data: Hydrologic, rain, surface water and test well analytical results will be correlated with each other and with the results of the petrologic, mineralogical and geochemical analyses of the drill cores and surface rocks in the area. At least one journal article will be prepared describing the results of the pre-production surveys.

Proposed Well Monitoring

During the coming year we expect several steam production tests of succeedingly longer duration. During each test we plan on collecting several samples of water, steam and entrained gases. A special sampling port will be installed at least 4 feet downstream from any orifice or elbow and at least 4 feet upstream of of an expansion orifice. Samples will be taken at the beginning

and end of the tests as well as throughout. Water and gas samples will also be collected just before and just after the production test.

Between steam production tests, steam and gas samples will be collected from the bleed line which should be left open continuously.

Justification of Analyses to be Performed

Chemical Measurement

The use of individual constituents or ratios of constituents for chemical investigations depends on their behavior on the rock/hot water environment. The geochemistry of many constituents present in thermal waters has been studied in laboratory experiments in New Zealand, Larderello, Iceland and elsewhere, and certain deductions can be made concerning their behavior in a hydrothermal system (Ellis and Mahon, 1964, 1967; Mahon, 1967; Ellis, 1969). For example, chloride, boron and caesium behave as soluble elements, concentrating in aqueous phase. Once liberated from a rock they remain in solution and do not readily enter into secondary mineral structures. Sodium, potassium, lithium, and rubidium are controlled in natural hot waters by temperature-dependent mineral equilibria, while the concentrations of silica, calcium, magnesium, fluoride, and sulphate in high temperature solutions are determined by the solubility of minerals such as quartz, calcite, chlorite, anhydrite, and fluorite.

Mahon (1966a) and Fournier and Rowe (1966) observed independently that the silica content of high temperature waters within hydrothermal areas is determined by the quartz-water

equilibrium solubility. This has made possible a simple chemical

method for determining the temperatures of the waters supplying

either drillholes or hot springs of high discharge. By assuming

that waters reach the surface by an adiabatic isoenthalpic expan-

sion of the original high temperature water to a steam-water

mixture, the silica concentrations on boiling surface waters which

correspond to particular underground water temperatures can be

calculated. Use of this method has enabled measurement of temper-

atures in New Zealand geothermal areas to within about $\pm 2°C$ (Mahon,

1966). Moreover, the measurement is made while drillholes dis-

charge, and the estimate is for waters which supply the discharge.

Physical measurements made downhole during static conditions are

often affected by convection within the hole. Using the Fournier

and Rowe data for quartz, $t = [1311/(5.196-\log SiO_2)] - 273$, we

calculate that the host rock surrounding HGP-A has a temperature

of 186°C (SiO_2 = 220 ppm). The only sample (Table 3) for which

analyses are complete at this time is for a water sample collected

about 2 hrs. after the well first began to flow due to prolonged

"air-lifting". This result is obviously too low since we measure

temperatures of 330°C. The silica temperature is also lower than

other geothermometric results to be discussed later. The reasons

for this discrepancy are not known at this time and will be inves-

tigated during future studies.

The Na/K ratio in natural hot waters is controlled by a re-

versible temperature-dependent rock mineral/water equilibrium

involving potash mica, potash feldspar and albite (Ellis, 1970).

Experimental high temperature rock/water interactions (Ellis and

Mahon, 1964, 1967), field results and the results of Hemley and Jones (1964) have enabled an approximate relationship to be established between the Na/K ratio in natural hot waters and temperatures. The sodium/potassium equilibrium adjusts after a temperature change relatively slowly, which enables useful information on conditions in the deep aquifer to be obtained.

Applying the Na/K thermometer of White and Ellis, $t = [855.6/(0.6269+\log (Na/K))] - 273$, to the first HGP-A sample collected gives a temperature of 213°C. Fournier and Truesdale (1973) also derived a Na/K geothermometer from which we calculate a temperature of 212°C. $t = [777/(0.4693+\log (Na/K))] - 273$. Fournier and Truesdale then extended their model to include the calcium ion concentration: $t = \dfrac{1647}{\log\dfrac{Na}{K} + \dfrac{1}{3}\log\dfrac{Ca}{Na} + 2.24} - 273$. The temperature calculated for HGP-A is 225°C.

The temperatures calculated from the silica concentrations and from the Na/K ratios often differ, the silica values invariably being the lowest. When a difference exists the silica temperature always corresponds very closely with that of the inflow water, whereas the Na/K ratio temperature relates to the maximum temperature. With cooling of water, e.g., through boiling on rising towards the surface, the Na/K exchange reaction is slower to readjust than the silica equilibrium (Ellis, 1970).

The reader should recall that the Na, K, Ca, and Si values used represent only the first water to be obtained from the well and may not be indicative of the true composition of the source water. With further analyses, the low temperatures calculated from the Na/K and Ca thermometers may still prove anomalous.

The equations used to calculate the temperatures were derived for areas where the host rocks are of ryolitic, ignimbritic, and/or sedimentary composition. Application of the geothermometers discussed above implicitly assumes the presence of minerals such as albite, K-feldspar, and plagioclase. The Island of Hawaii is made up of layers of olivine basaltic flows and cinders. Preliminary mineralogic analyses of HGP-A cutting indicates the presence of plagioclase, augite, pigeonite, magnitite and olivine in the upper section. At ~2500 feet pyrite and quartz along with vesicle fillings of quartz, calcite, and zeolite have been found. Below 4500 feet the rocks have been hydrothermally altered and are composed of the above minerals plus chlorite, kaolinite, montmorillonite, hematite, and amphibole. In view of this wide variety of minerals present at depth in the well, I feel that it is worthwhile to attempt to apply the standard geothermometers to the Hawaii basaltic system. On the other hand, I am not surprised at the lack of agreement with the measured temperatures. Clearly more work is needed on this aspect of geochemistry.

Isotopic Measurements

As discussed in the first section, the stable isotope composition of water can be used to assess the area of ground water recharge to the well. The classic deuterium vs. ^{18}O plot can be used to assess the relative effects of seawater dilution vs. high temperature exchange as well as the relative ratios of water to rock. The radioactive isotopes tritium and carbon-14 can be used to calculate the age of the water and hence indicate how long the well might be expected to produce steam.

Several isotope exchange reactions offer the possibility of deep temperature estimation from surface measurements in water or steam flows. Equilibrium constants for many isotope exchange equilibria are now available. In all isotopic equilibria models it is assumed that the equilibrium is achieved at deep levels and it "frozen in" until the analysis of material at the surface. Many isotopic equilibria have a slower rate of adjustment with changing temperature than chemical equilibria (e.g., Na/K or silica).

The relative ratios of $^{13}C/^{12}C$ in co-existing carbon dioxide and methane varies with temperature, and ratios determined for the two gases in geothermal discharges have been interpreted to give underground temperatures. As reviewed by Ellis et al. (1970), temperatures of 215-315°C were obtained for Larderello steam, and 245-250°C for deep Wairakei water.

The isotopic distribution $^{34}S/^{32}S$ between hydrogen sulfide and metal sulfides in altered rock, and between co-existing metal sulfides shows promise of being useful in estimating the temperature of rock alteration underground (Ellis, 1970). The oxygen isotopic fractionation between sulfate and water may also be useful as a thermometer (Cortecci, 1970; Mizutani and Rafter, 1969).

$$H_2^{16}O + S^{18}O_4^{2-} = H_2^{18}O + S^{16}O_4^{2-}$$

$$H_2^{32}S + {}^{34}SO_4^{2-} = {}^{34}S + {}^{32}SO_4^{2-}$$
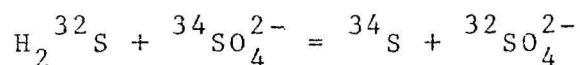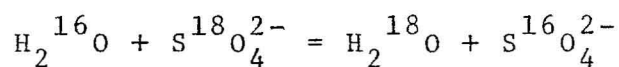
$$1000 \ln \alpha \, (HSO_4^- - H_2O) = 2.88 \, (10^6 \cdot T^{-2}) - 4.1$$

These sulfur thermometers will be tested if time and samples are

available.

Isotopic equilibria between species in solution and a mineral enable estimates to be made of temperatures which existed in the field before drilling, through analysis of drillcores and drillhole discharges. Equilibrium constants for the isotopic distribution of oxygen between water and the minerals calcite, quartz, alkali feldspars, and muscovite, were reported by Taylor (1967). A good example of the use of this isotope technique was given by Clayton et al. (1968) who showed that calcite in rocks intersected by a Salton Sea area drillhole was in isotopic equilibrium with the co-existing water, from temperatures of over 300°C down to at least 150°C. Blattner (1975) has shown that two mineral oxygen isotope geothermometry cannot be used indiscriminately, but that useful results can be obtained if samples are carefully collected.

The basic geochemical understanding of the distribution of carbon and oxygen isotopes can be enhanced by the study of these isotopes in hydrothermal and volcanic exhalations. Table 4 summarizes the excepted values for juvenile (magmatic) material and the results of analyses in Hawaii. At the bottom are listed samples from HGP-A and other Puna wells.

Note that the $\delta^{13}C$ value for CO_2 gas collected at sulfur banks is -3.3‰ and has not changed since 1954. On the other hand, a sample from the Puna rift has a $\delta^{13}C$ of -15‰ in agreement with a calcite crystal recovered from HGP-A at 950 feet. Recent analyses of deep sea basalt suggest that mantle carbon has a $\delta^{13}C$ of about -15‰ (Peneau et al., 1976). Further carbon isotope

studies in the HGP-A cutting and gases should prove very interesting. Radon and helium-3 have been reported as good indicators of mantle-derived material. H. Craig has consented to analyze several samples from HGP-A for these gases. Naughton has found that in general the helium concentration in the Puna area is exceptionally high.

Heavy Metals

Appreciable concentrations of arsenic and antimony are commonly found in natural thermal waters, but it is only the more saline, high temperature waters that contain noteworthy concentrations of iron, manganese, copper, zinc, lead and silver. Although concentrations of heavy metals such as copper, zinc, silver and lead are only at the parts per billion level in dilute waters of the Broadlands New Zealand field, drillholes at depths from 2500 to 6000 feet have intersected extensive mineralized bands containing sphalerite, gelena and chalcopyrite (Browne, 1969). Although the more saline thermal waters are capable of carrying higher concentrations of heavy metals in solution it is apparent that even dilute waters such as are found in the New Zealand areas are capable of producing extensive mineralization within present-day hydrothermal fields because of the large throughput of water which occurs.

From an environmental standpoint the metals must be monitored on a routine basis. The HGP-A well produces large quantities of FeS when left standing. This is probably due to reaction within the casing, but heavy metal analysis will be performed on the discharged water.

Gases

The usefulness of monitoring gas concentrations in drillholes was recently reviewed by Glover (1970) with special reference to the Wairakei system. He found that during the early years of production, few changes occurred in gas concentrations, but when hot water levels and down-hole pressures started to fall, changes became apparent. The changes were initiated by a change in the flow pattern in the aquifer from a single phase (water) to a two-phase (steam and water) system. Wells in which gas concentrations decreased were supplied by hot water which had lost steam and gas through boiling, while holes in which the gas concentrations increased gained a proportion of the free steam and gas. From the gas concentrations and CO_2/H_2S ratios in the discharges the type of steam separation processes occurring can be assessed. It is possible for example to determine whether the water loses steam in a single stage process, equilibrium between liquid and vapor being maintained at all times, or in a multi-stage process. During the first five years of production at Wairakei, steam separation from the migrating hot waters took place in a single stage process but in the last four years this changed to a multi-stage process. Preliminary analyses of the first HGP-A condensate gas collected gas has a CO_2/H_2S of about 2.6. This is significantly lower than any results reported from New Zealand where typical ratios are between 10 and 25. The HGP-A sample was collected just prior to the 7/22/76 production test. The well had been bled for over a week to keep it just below the flash point. It is thus expected that extensive reflaxing had occurred

within the well increasing the gas phase in H_2S. If this extremely
low value of 2.6 is substantiated by further sampling it would
indicate that extensive separation of steam and water is occurring
within the aquifer.

Engineering Applications of Geochemical Techniques

Mass Output and Enthalpy Measurements of Drillhole Discharges

A chemical method has been used in New Zealand (Mahon, 1966b)
for determining the enthalpy of steam/water mixtures discharged
from geothermal drill-holes. The method involves the measurement
of the gas content of steam in the discharge at two different
pressures and is based on the fact that the deep waters at Wairakei
contain carbon dioxide. This is also the case here in Hawaii. The
enthalpy of a steam/water mixture can be expressed in the form
$E = \dfrac{RH_1 - rH_2}{R-r}$ where E is the enthalpy, R the ratio of concentra-
tions of gas in the steam phase at pressures p_1 and p_2; r the ratio
of latent heats at pressures p_1 and p_2, and H_1 and H_2 the heat
contents of liquid (in equilibrium with vapor) at pressures p_1 and
p_2.

The method assumes (1) that there is no loss of heat along the
bypass pipe from which the gas samples are collected, either due
to conduction through the pipe wall or from change of heat into
kinetic energy and (2) that the gas is relatively insoluble in the
liquid phase under the conditions of temperature and pressure. The
first assumption is valid if the pressure difference between p_2 and
p_2 is not large. Ellis (1962) in a study of the distribution of
CO_2 and other gases between the high temperature water and steam
phases in the Wairakei discharges showed that at the pressure

present in the surface piping (<220 psig) practically all the CO_2 is concentrated in the steam phase.

Testing for Steam Dryness and Efficiency of Wellhead Separators

Before a drill-hole is used for production a wellhead separator is fitted and tests carried out to ensure that the separated steam is greater than 99.9% dry. A chemical method is used to determine steam dryness. Sodium or chloride ion concentrations are determined in the separated steam and water phases discharged from the separator. The proportion gives the percentage wetness of the steam.

$$\frac{\text{concentration of constituent (Cl or Na) in steam}}{\text{concentration in water}} \times 100$$

To prevent steam escaping down the water outlet of a wellhead separator a water levelling drum is fitted just downstream of the outlet. It is difficult from visual observation and physical tests to ensure that the drum is working efficiently and that steam loss is not occurring. The distribution of carbon dioxide between water and steam at the separating pressure is known from equipment, and comparing the actual carbon dioxide concentration present in the water with the experimental value enables free steam to be deleted. Valve settings are adjusted until the carbon dioxide concentration is equal to that expected from the distribution coefficient.
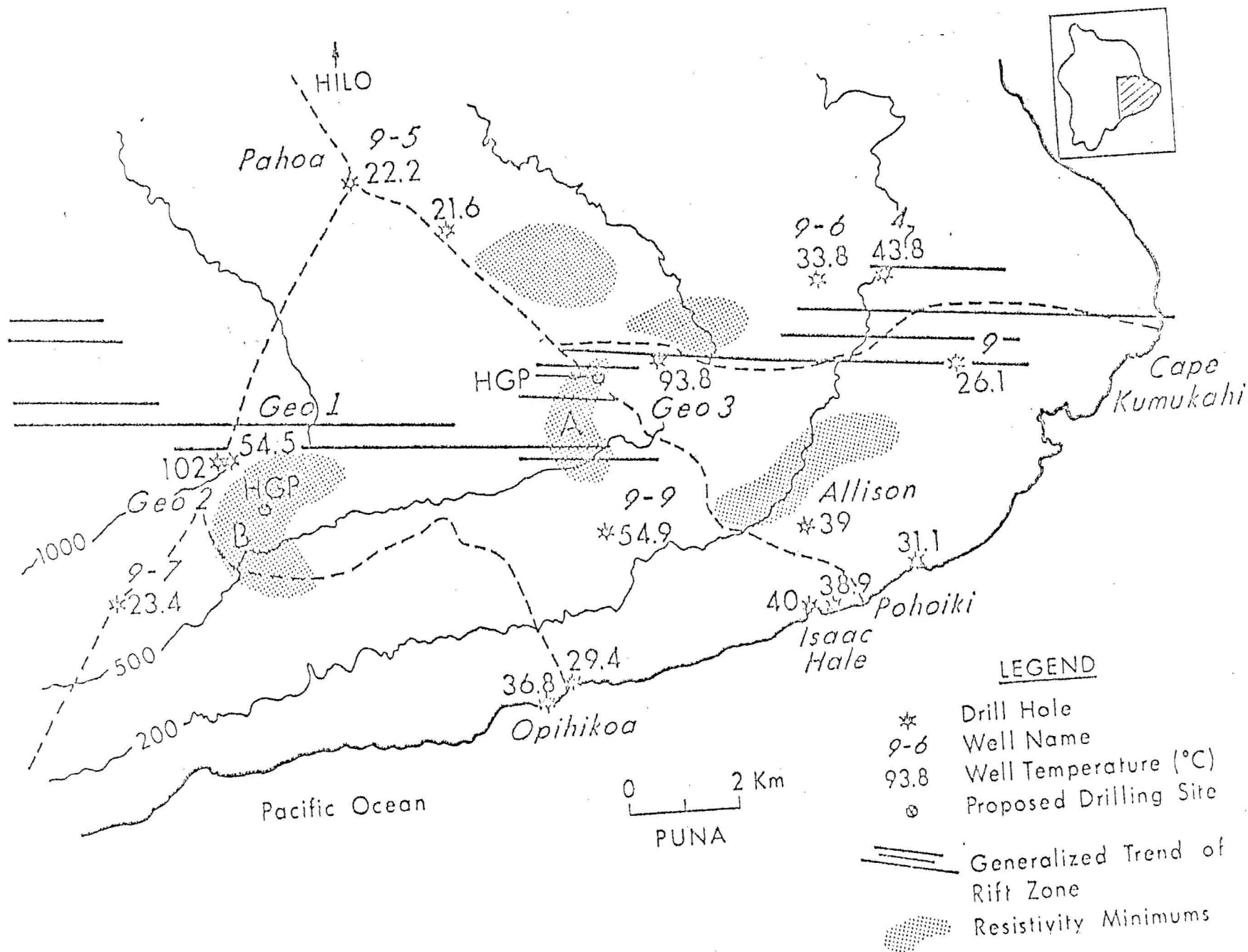
Figure 1. Map of the Puna area of the Island of Hawaii.

Figure 1. The $\delta^{18}O$ of weekly rainfall collected from February to July, 1976 at four sampling sites along the main road between Hilo and the Hawaii Volcanoes National Park.
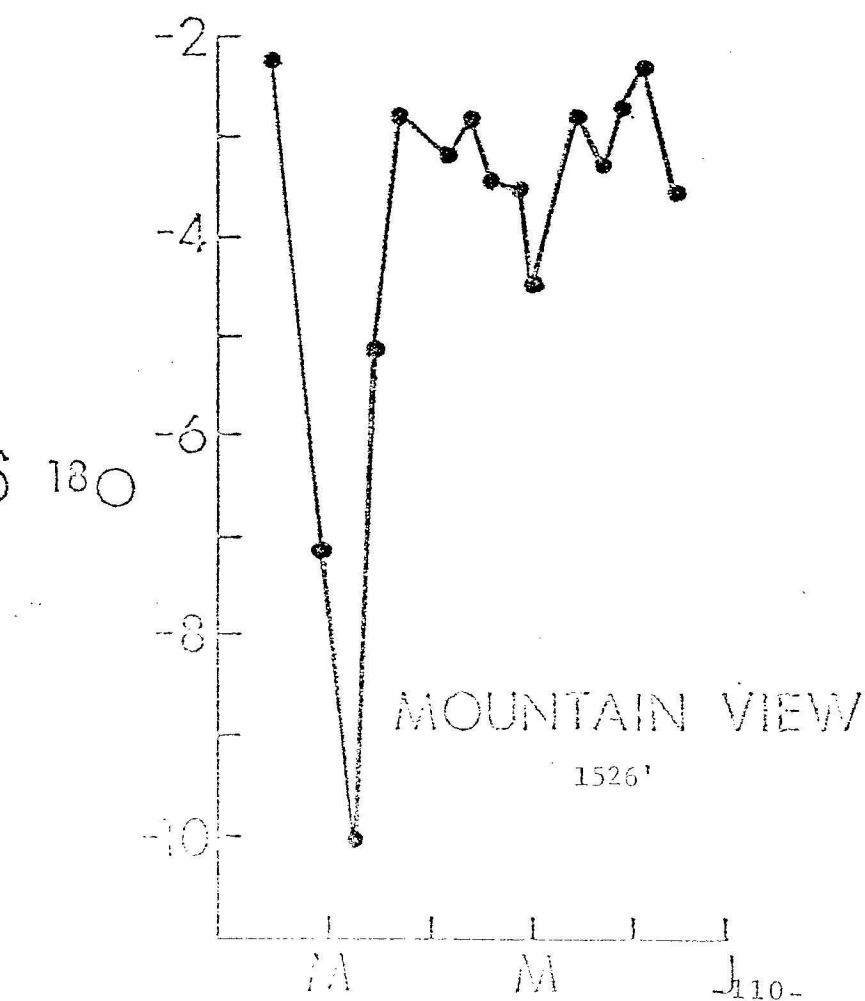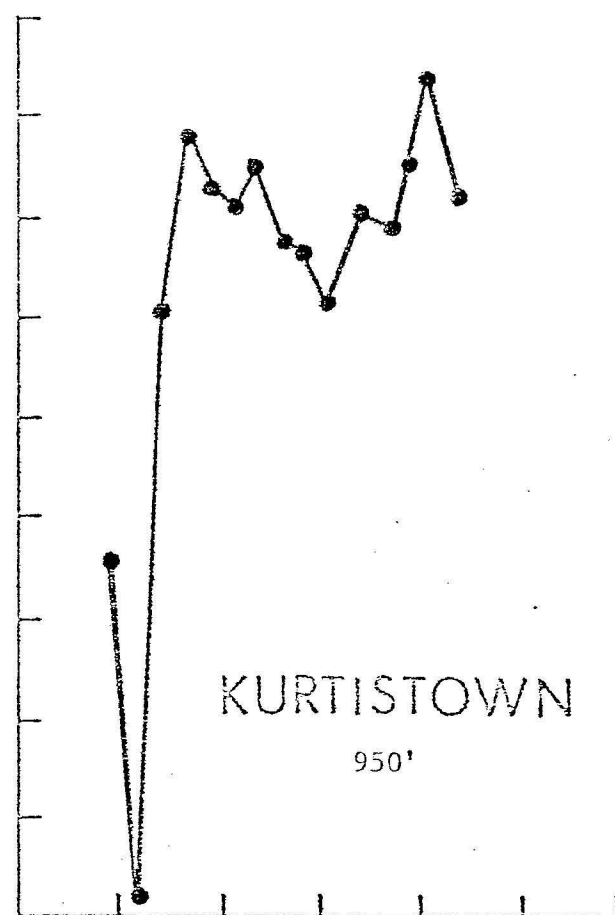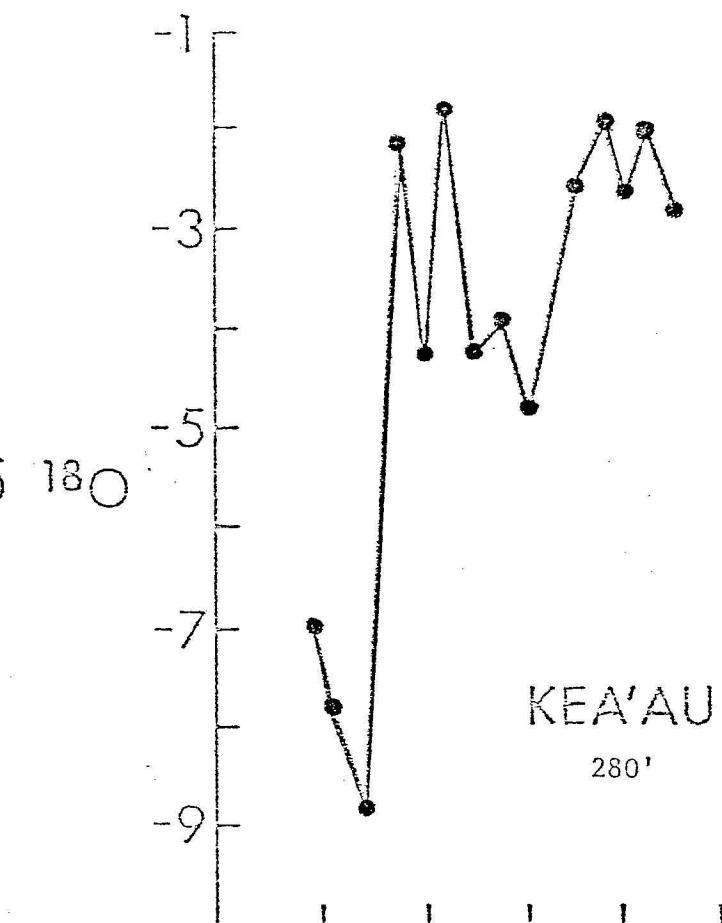
Figure 3. Major ion concentrations of Puna area wells expressed at the % excess (or depletion) over that expected if they were formed by mixing fresh water with sea water. The wells (numbered 1-10) are arranged in approximate order of increasing temperature.

TABLE 1

Puna District, Hawaii

Tritium Activities of Well Water Samples[**]

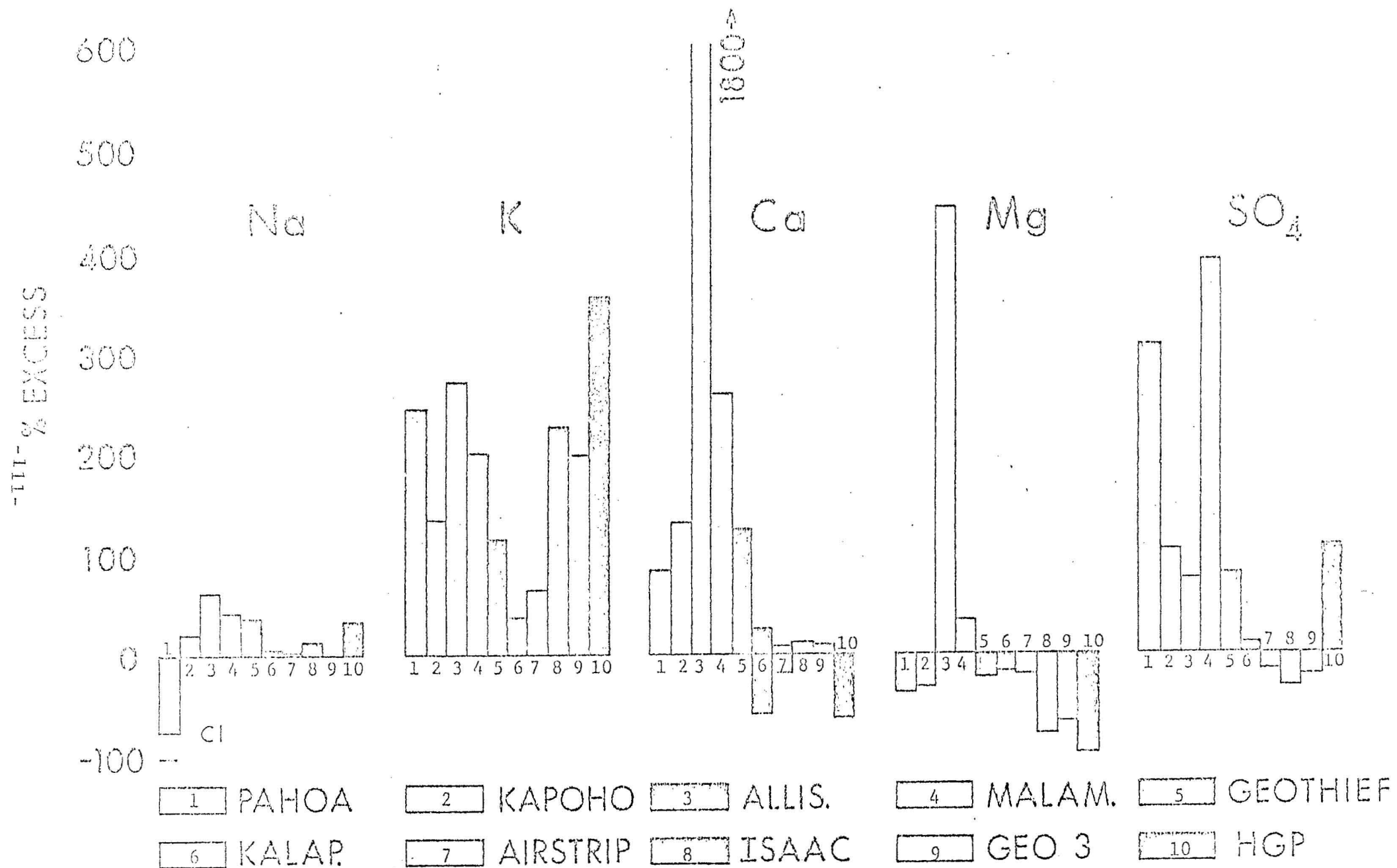| Old No.	Name	Date Sampled	TU	Activity of Fresh Water Fraction	
9-5	Pahoa Station	1-6-75	9.9 ± 1.1	9.84[†]	9.86[††]
		7-21-75	10.64 ± 1.17	10.58	10.60
9-7	Kalapana Station[*]	1-6-75	16.7 ± 1.8	16.17	16.7
		7-21-75	17.99 ± 2.00	17.99	17.99
9	Kapoho Shaft	1-6-75	14.1 ± 1.5	14.01	14.04
		7-21-75	10.45 ± 1.18	10.49	10.44
9-6	Airstrip Well		Lost		
		7-22-75	11.08 ± 1.20	11.2	11.15
	Allison Well	1-7-75	12.9 ± 1.7	13.02	12.98
	Isaac Hale Spring	1-7-75	8.5 ± 1.0	10.35	9.48
9-9	Malama Ki Well	1-7-75	15.6 ± 1.6	19.35	18.39
		7-22-75	8.57 ± 1.03	11.63	10.20
	Geothermal #3	1-7-75	10.3 ± 0.8	12.34	11.55
		7-21-75	7.29 ± 0.90	8.82	7.98
	Rainwater (Kalapana Station)	1-6-75	9.1 ± 1.2		

[*] A water sample collected at this station on 4-3-72 had a tritium activity of 17.3±2.8 TU.
[**] Current Oahu rainwaters have a tritium activity of 8-20 TU depending on the season.
[†] Assuming sea water has zero activity.
[††] Assuming sea water has an activity of 4 TU.

TABLE 2

δO^{18} Data for Well and Rain Waters

Location	Elevation (ft.)	Date Sampled	δO^{18} well	δO^{18} rain	Date Sampled (if different)
Isaac Hale Park Spring	5	01/07/75 10/28/75	-5.5 -5.9	-5.4	01/21/75
Kapoho Shaft	38	01/06/75 10/28/75	-6.6 -6.6	-2.3	02/12/76
Allison Well	140	01/07/75	-5.8	-4.8	07/21/75
Airstrip	287	01/06/75 07/21/75	-5.3, -5.3 -6.1	-4.0 -6.2 -5.7	01/13/76
Malami Ki	274	01/06/75 07/21/75	-4.6 -5.1	-3	
Geothermal #3	600	01/07/75 07/21/75	-4.7, -4.6 -5.3		
Pahoa	705	01/06/75 07/21/75	-6.7 -6.7	-3	
Kalapana	752	01/06/75 07/21/75	-5.4, -5.5 -6.3	-4.6 -4.6 -3.4, -3.4	01/03/75-01/06/75 06/04/76-06/06/76
Mt. View Station	1526	01/13/76		-7.0	
Keller Well	4000	07/21/75	-7.6		
Uwekahuna Rain Gauge	4000	01/13/76		-8.4	
Uwekahuna Nat'l Park Obs.	4000	01/13/76		-7.3	
MLO rd.	8000			-7.6	02/26/76

TABLE 3

GEOTHERMAL WELL

Major ion concentrations (mg/1)

	Cl	SO_4	CO_3	Na	Mg	Ca	K	SiO_2	Hg	$\delta^{18}O$ (‰) SMOW
water used in drilling	6.3	16.1	.6	15.8	1.8	2.1	2.1	-	-	-
first H_2O flow 6/24	552.0	76.0	1.0	407.0	1.2	5.0	52.0	-	6 µg	-
after steam 7/3	610.0	160.0	0.45	-	-	-	-	151	-	- T = 7±2 T.U.
before production test 7/22 0847	757.0	-	-	-	-	-	-	-	-	-2.0 water -3.7 steam
after production test 7/23 0920	190.0	72.0	-	133.0	-	-	-	220	-	-3.9 water
seawater 1‰	553.0	77.5	4.1	307.0	37.0	11.8	11.1	3	0.06 µg	

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TABLE 4

Summary of Stable Isotope Values Measured
for Primary (Mantle) Materials in Hawaii

		$\delta^{13}C$ (PDB)	$\delta^{18}O$ (SNOW)
SULFUR BANKS	9/15/54	−3.37	
	10/15/54	−3.23	
	3/1/55	−3.14	
B	DEC 74	−3.6	(38.06 ?)
E	DEC 74	−3.14	31.87
PUNA RIFT	1954	−15	
BASAL (PERCHED,DIKE) WATERS ON OAHU		~ −18	
BASALT/CHONDRITES		−15 to −25	
DIAMONDS/CARBONATITES		−3	
JUVENILE CARBON IN STEADY STATE CRUSTAL MODEL		−12	
ATMOSPHERIC CO_2			~ 41
MODERN CARBONATE			~ 30.5
JUVENILE WATER			7
ATMOSPHERIC O_2			23.5

HGP A

		$\delta^{13}C$ (PDB)	$\delta^{18}O$ (SNOW)
calcite vug 950'		−18	26.8
water before flash			−2
after flash			−3.9
steam before flash			−6.5
after flash			−3.7
local wells geo3 malam.			~ −5
local rain pahoa malam.			~ −3

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Appendix I

PROGRESS REPORT - HYDROLOGY

R. Buddemeier, P. Kroopnick and L. S. Lau

January 1976

The hydrology task officially was initiated only with the beginning of Phase II of the Hawaii Geothermal project. However, the cooperation and assistance of Hawaii County, U.S.G.S., and researchers from ongoing H.G.P. tasks permitted us to begin sampling prior to the formal contract period.

The primary goals of the task are characterization of the hydrology of the Puna District and analysis and interpretation of chemical and isotopic characteristics of geothermal fluids, either naturally occurring at the earth's surface or encountered as a result of drilling.

This progress report presents only data newly obtained by task personnel. A substantial body of data on the chemical and isotopic composition of non-geothermal Hawaiian groundwaters, previous analyses of Puna District waters, and hydrologic data on the area has been assembled and will be used in comparison and interpretation, but for the sake of brevity is not included in this report.

A total of eight major sources of groundwater (wells, shafts and springs) form the nucleus of the water sources studied (see Figure 11). Of these, five show temperatures consistently above ambient. All have been sampled (surface samples) in January and also in July or October. Geothermal No. 3, which is the hottest well and which is the only well showing a distinct thermocline,

has also been sampled below the surface layer. Rainwater samples were also collected and analyzed.

Chemical data are presented in Table 2, and isotope analysis resulted (^{3}H and ^{18}O) are reported in Table 3. In addition to some analyses still in progress, the ^{2}H analyses remain to be performed in order to use ^{2}H/^{18}O ratios to ascertain the elevation of the source rainfall and/or evidence of geothermal alteration.

Although only preliminary interpretations have been made, several observations are of interest. First, the surface layer in Geothermal No. 3 is not only hotter but also more saline than the underlying waters. This implies that the well lies down-gradient from a thermal source which is advecting hot saline water up from depth.

Second, all of the tritium values are within or only very slightly below the range of values for contemporary rainwater (a long and continuing series of rainwater ^{3}H measurements on Oahu provide conparison data). Even without allowance for the (unknown) tritium activity of the saline water component in the saltier water sources, this indicates that the mean residence time of all of these waters does not exceed a few years.

Third, the similarities in the seasonal variations in δ^{18}O between rain and groundwater suggest that recharge to the surface waters may have a time constant of less than a few months. This is true for the hot as well as the normal water sources.

Finally, some logical patterns of water chemistry as a function of temperature may be seen. With the exception of Allison well, SiO_2 content increases as water temperature increases; with the

exception of Kalapana well, the Mg/Cl ratio of the water decreases as temperature increases. Both observations are consistent with an increased rate of reaction of the hot rock with geothermal fluids at elevated temperatures.

In addition, one water sample was retrieved from the Keller test well on Kilauea. Although small and contaminated with drilling mud, we were able to analyze for Cl (62.9 mg/l) and $\delta^{18}O$ ($-71646°/_{oo}$). Both values are consistent with the expected characteristics of higher elevation perched groundwater.

Major future activities will consist of analyses of fluids obtained by down-hole sampling in the test well, and sampling of all the water sources near the test well. After the end of the drilling operation additional samples will be collected to test for the existence of any extended effects of the drilling. All the data will be analyzed and integrated with geophysical data into a general hydrology-oriented model of the geothermal area.

Table 2. Chemical Data (a)

USGS No.	Name	Date	T, °C	pH	Na	K	Ca	Mg	Cl	HCO₃	SO₄	SiO₂	N (b)	P	Sr
2986-01	Pahoa Station (Well 9-5)	1-6-75		7.30	36.0	2.72	1.58	2.7	13.5	48	21.1	50.0	0.252	0.078	
		7-21-75	23.3	6.65	19.3	2.7	1.6	1.9	9.8	44	27.3		0.57	0.129	und
2487-01	Kalapana Station (Well 9-7)	1-6-75	28.5	7.68	89.6	5.20	5.30	6.6	132.2	38	37.2	44.5	0.070	0.056	
		7-21-75	20.8	7.05	78.8	5.0	5.9	5.6	120	36.8	28.6		0.16	0.194	0.1
3080-02	Kapoho Shaft (Well 9)	1-6-75	25.5	7.80	85.8	6.60	42.4	37	16.9 (c)	372	20	53.6	0.378	0.233	
		7-21-75	22.1	7.10	86.5	6.2	23.2	25.7	95.7	328	22.7		4.47	0.268	0.2
		10-27-75			92.0	5.8	32.0	27.8	105	330	23.0		2.51		0.25
3081-01	Airstrip Well (Well 9-6)	1-6-75	36.8	7.42	238	13.6	23.0	28	303.5	48	204	71.3	0.014	0.040	0.2
		7-22-75	33.5	7.75	223	16.8	12.5	27.2	316	44	211		0.39	0.076	
2881	Allison Well	1-7-75	37.8	7.35	216	10.8	13.4	15	281	132	69.2	24.1	>14	<0.002	
	Isaac Hale Park Spring	1-7-75	36.0	7.75	2020	86.0	32.4	200	3534	56	507	81.5	1.218	0.016	
		10-27-75			2140	87.5	98.0 (c)	239	3660	61.0	552		<0.01		1.3
2783-01	Malama Ki Well (Well 9-9)	1-7-75	52.2	7.02	2105	109	66.8	210	3811	144	471	100.7	0.280	0.006	
		7-22-75		7.45	2890	149	117	293	5120	128	598		0.41	0.013	2.2
	Geothermal #3	1-7-75	93.0	6.85	2050	190	76.8	52	3274	30	314	96.6	0.003	0.006	
		7-21-75			2000	195	81	59	3410		335		0.32	0.076	1.4
	Geothermal #3 (d) (Thief)	7-21-75	74	1.4	1740	158	71	62.5	2980	20	317			0.053	1.2
	Rain at Kalapana Station	1-6-75			4.5	0.25	0.25	0.75	7.2		~2.5	0	0.024	<0.002	

(a) All concentrations are in mg/l
(b) January N values are $NO_2 + NO_3$; others are $NO_2 + NO_3 + NH_4$
(c) Suspect datum
(d) This sample taken 50-60' below water surface

Table 3. Isotopic Data   32

Groundwater Samples	Date	^{3}H (T.U.)[a]	δ^{18}O (‰)[b]
Pahoa Station (Well 9-5)	1-6-75	9.9 ± 1.1	
	7-21-75	10.6 ± 1.2	-6.70
Kalapana Station (Well 9-7)	1-6-75	16.7 ± 1.8[c]	-5.42[d]
	7-22-75	18.0 ± 2.0	-6.33
Kapoho Shaft (Well 9)	1-6-75	14.1 ± 1.5	
	7-21-75	10.5 ± 1.2	-6.33
Airstrip Well (Well 9-6)	1-6-75		-5.29[d]
	7-22-75	11.1 ± 1.2	-6.13
Allison Well	1-7-75	12.9 ± 1.7	
Isaac Hale Spring	1-7-75	8.5 ± 1.0	
Malama Ki Well (Well 9-9)	1-7-75	15.6 ± 1.6	-4.57
	7-21-75	8.6 ± 1.0	-5.08
Geothermal #3	1-7-75	10.3 ± 0.8	-4.66[d]
	7-21-75	7.3 ± 0.9	-5.33
Rainwater Samples			
Kalapana	1-6-75	9.1 ± 1.2	-5.01
	7-22-75		-5.80
Airstrip	1-6-75		-4.04
	7-22-75		-6.21
Isaac Hale	7-22-75		-4.78

[a] T.U. = Tritium Unit = 0.0072 d.p.m./ml of water

[b] Per mille relative to Standard Mean Ocean Water (SMOW)

[c] Activity was 17.3 ± 2.8 T.U. on 4-3-72

[d] Average of two determinations

BUDGET

Hydrology and Hydrothermal Geochemistry - Task 2.6

A. Salaries and Wages

    1. 1 Grad. Assistant
        (9 acad. mos., 50% @ $914/mo.
        and 3 sum. mos., 100%) $6,855

    2. Student Help (Undergrad.)   2,240

                                        $ 9,095

B. Fringe Benefits   343

C. Equipment   -0-

D. Travel

    1. Domestic   1,100

E. Other Direct Costs

    1. Supplies and Materials   1,000

    2. Publications   400

                                        1,400

F. Total Direct Costs $11,938

G. Indirect Costs: (46% of $9,095)   4,184

H. Total Costs $16,122

Task 2.7

PHYSICAL PROPERTIES OF ROCKS

M.H. Manghnani, C.S. Rai, T. Hanada

Abstract

We propose here a twofold program, the first part of which
will be to investigate the physical, elastic, electrical and
thermal properties of the core drill samples that have been
obtained from the recently drilled hole to $\sim$ 6,455 ft as well
as from the Keller [1974] hole to $\sim$ 4,137 ft. The physical
properties to be investigated include density (ρ), porosity (ϕ),
and permeability. The elastic properties of interest are:
compressional (V_p) and shear wave (V_s) velocities and Q^{-1} as function
of porosity, fluid saturation, pressure (to 200 bars) and tem-
perature (to 300°C). The electrical properties of these rocks
will be investigated as a function of porosity, fluid content,
pressure and temperature. The thermal properties include ther-
mal conductivity (and diffusivity) as a function of porosity,
fluid saturation and temperature.

These studies will be followed by a completion of the
ongoing laboratory measurements of various physical, elastic,
electrical and thermal properties of the Hawaiian basalts;
analysis of the relationships among various parameters, and
interpretation of the data in terms of the overall field pro-
gram in geophysical exploration. It is anticipated that the
laboratory data will provide useful parameters for the explora-
tion and modeling studies.

Mr. Rai, a graduate student who is working on this project, will complete his PH.D. thesis in about a year's time.

I. INTRODUCTION

Geophysical techniques used in the exploration for geothermal
energy sources include, among others, electric and electromagnetic
soundings, heat flow measurements, seismic (reflection, refraction,
and micro-seismicity), magnetic and gravimetric surveying. The
goals of all the geophysical exploration measurements are to
detect and interpret the anomalies defined in the physical quan-
tities measured in terms of possible exploitable geothermal
energy. To do the last requires knowledge of the effect of
temperature and pressure, rock structure (porosity, permeability),
and fluid content on the parameters being measured. From the
standpoint of economic feasibility and the successful exploita-
tion of geothermal energy source areas, factors such as depth,
temperature, porosity (and permeability), and fluid content of
the reservoir have to be evaluated and considered in designing
an energy recovery system and determining cost factors. A know-
ledge of the physical properties of _in situ_ rocks, therefore,
has values from viewpoints of successful exploration and model-
ing of potential geothermal systems.

The purposes of this task are oriented toward (1) understand-
ing how the physical properties of the Hawaiian basaltic rocks
(including the drill hole samples) relevant to electrical, ther-
mal, and seismic exploration for geothermal energy in volcanic
areas are affected by as a total system reflecting the composition
and structure of the rock, its fluid content, changes in fluid
and fluid content and the effect of pressure and temperature

with increasing depth; (2) establishing interrelationships among the various measured physical properties; and (3) correlating the laboratory data with the available logging data in an effort to gain better evaluation of the in situ properties for the purposes of modeling geothermal resources. It is specifically proposed to carry out laboratory investigations of physical parameters (density, porosity and permeability), and elasticity (V_p, V_s, and attenuation Q^{-1}) of selected typical basalts on the island of Hawaii, including the basalt samples from the two drill holes (HGP-A and Keller holes), as a function of porosity (and permeability), fluid content, temperature (in a few cases to basalt melting temperatures) and pressure corresponding to the economic exploitable depth of the resource ($\sim$2 km). The program of the study proposed would contribute to our basic understanding of the physical properties of basaltic rocks, in general, and in particular would aid in the exploration and possible development of geothermal energy in volcanic (basaltic) areas, such as Hawaii.

These data will also be needed later in interpreting the drill hole logs and interrelating them to surface results so that the knowledge can be applied in different areas with a minimum amount of auxiliary drilling. Since the prospective geothermal regime is bounded by ocean water not only laterally but also by the underlying Ghyben-Herzberg lens, the porosity and salinity of the fluid content are the two most important factors governing the electrical resistivity.

II. STATEMENT OF THE PROBLEM

The problems covered here lie in three areas of laboratory research on the Hawaiian basaltic rocks: (A) electrical properties, (B) thermal properties, and (C) elastic properties:

(A)   Electrical Properties

A typical geothermal reservoir would be characterized by relatively low electrical resistivity. Since electrical resistivity of a rock is a function of mineral composition, porosity (and permeability), amount and type of fluid content, temperature, and pressure it is important to know the effect of these parameters for interpreting the field data.

Although a number of investigations have been conducted to study the electrical properties of various rocks and minerals under various conditions [Wyllie and Gregory, 1953; Keller, 1960; Brace et al., 1965; Brace and Orange, 1968; Parkhomenko, 1967; Duba, 1972; Dovorak, 1973] very few data are available on basalts [Bondarenko, 1972; Hermance et al., 1972; Presnall et al., 1972] and, especially, the porous basalts commonly found in volcanic areas such as Hawaii. Furthermore, in the previous studies on basalts, the interrelated and combined effects of porosity (and permeability), fluid content (amount and type), temperature and pressure on electrical resistivity were not fully investigated. Since the start of this research, the major thrust has been to fill in this gap.

We have so far studies the effect of porosity, fluid content, and pressure on the electrical resistivity; however, in addition to the effects, the effect of temperature should also be investigated.

Based on the laboratory data, a low resistivity anomaly ($\sim$5 ohm-meter) observed in the Puna district at a depth of $\sim$1 km [Klein and Kauahikaua, 1975] could be due to the presence of porous ($\phi \sim$15%) basalts saturated with saline waters at 300°C, or due to partially molten basalt. Although the drilling results in the present case, supported the first possibility, seismic field-work and high-temperature laboratory velocity data on basalts (saturated and unsaturated) would greatly aid in distinguishing one out of two or more such possibilities in future exploration and interpretation.

B. Thermal Properties

   In thermal modeling of any geothermal reservoir one
needs to know, among other parameters, the thermal diffu-
sivity (and conductivity) of subsurface rocks under in situ
conditions. The thermal conductivity of Hawaiian basalts
has been investigated as a function of porosity and olivine
content by Robertson and Peck [1974] but its dependence on
temperature and saturation has not been investigated. In
order to evaluate the in situ thermal properties of Hawaiian
basalts, we propose to determine the effect of temperature on
thermal diffusivity properties of dry and saturated basalts.

C. Elastic Properties

   In seismic techniques for geothermal exploration in
volcanic areas, one looks for anomalously low-velocity and/
or high-attenuation zones associated with "hot spots"
[Hayakawa, 1970]. In spite of difficulties in interpreting
seismic results (because of complex structure of volcanoes
and high vesicularity of basaltic rocks), the measured
velocities gradients can provide useful information about
the temperature distribution beneath the area of interest.
The seismic velocities and attenuation, theoretically at
least, can be used to locate a magma chamber. The seismic
method when used together with the electrical resistivity
data should be useful in estimating the depth to a possible
magma chamber. Thus, it is of real need to understand (a)
the effects of porosity, fluid content, and temperature (at

modest pressure $\sim$ 2 kbar) on the V_p and V_s velocities in basalts, and (b) the effects of pressure and temperature on V_p and V_s, and Q^{-1}.

III. STATUS OF THE WORK COMPLETED

During the first fifteen months of this project (June 1975-August 1976),   fair progress has been made in the laboratory measurements of the physical properties of the Hawaiian basalts which have been previously well characterized in terms of chemistry and mineralogy [Macdonald and Katsura, 1964; Macdonald, 1968]. Mr. Rai, graduate student, is studying the electrical and elastic properties of the Hawaiian basalts, in partial fulfillment of his Ph.D. thesis requirements. Dr. T. Hanada has conducted the thermal diffusivity measurements. The following is the summary of the work completed and in progress.

A. Electrical Properties

Choice of samples: When we started the work, very meager resistivity data existed on basalts. With this in mind we chose about one hundred samples from Prof. Macdonald's collection of chemically analyzed basalts to study whether resistivity was dependent on chemical composition. The results showed no dependence, except for alteration effects which generally lowered resistivity. Porosity was found to be the most important factor. To study this effect, the A.C. (500 Hz) resistivity of various types of basalts, ranging in porosity from <5 to 40%, has been investigated as a function

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of pore fluid saturation (tap water, mixtures of distilled
water and sea water, and sea water) at ambient pressure as
well as to pressures of up to 4 kbar.

For the various fluid saturations, the Archie's law is
found to hold well.

$$f = \frac{\rho_{sat.}}{\rho_{fluid}} = A \phi^{-n}$$

where, f is the formation factor, $\rho_{sat.}$ and ρ_{fluid} are the
resistivities of saturated rock and fluid, respectively;
ϕ is the fractional porosity; and A and n are constants
for given saturation. For 1:1:: sea water : distilled
water saturation, the equation is $f = 10.1 \phi^{-1.36}$ (see
Figure 1). The Archie's law is also found to hold well at
various pressures (see Figure 2); the correction for porosity
change under pressure (estimated to be 1-2% at 2 kbar) has
not been applied.

Pressure dependence of resistivity of saturated basalts
of variable porosity (Figures 3 and 4) shows rapid changes
in resistivity up to 1 kbar (cracks closing in) after which
the increase is gradual. Low-porosity basalts ($\phi < 2\%$)
show higher $d\rho/dP$ values. Figures 3 and 4 also show that
ϕ plays a major role in the electrical properties of basalts.

Figure 5 shows a correlation between resistivity and
V_p, which could be used to predict one property if the other
is known.

Initial work on the resistivity of basalts to melting
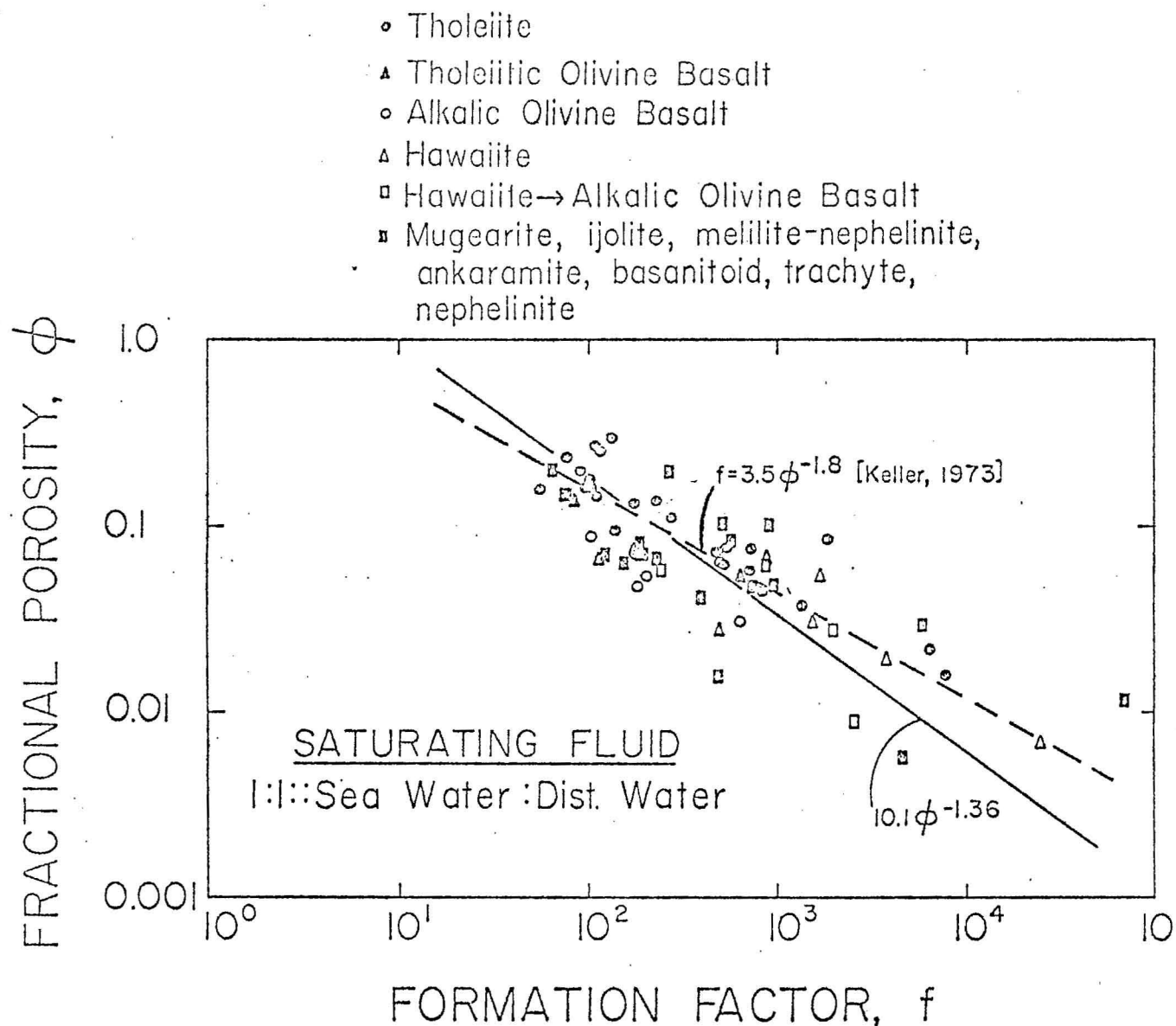temperature and above (Figure 6) has been encouraging. The

Figure 1. The relationship between "effective" (connected) fractional porosity φ and formation factor f for various types of Hawaiian basalts saturated with fluid 1:1:: sea water:distilled water. The best-fit line f = 10.1 $\phi^{-1.36}$ represents the Archie's law.
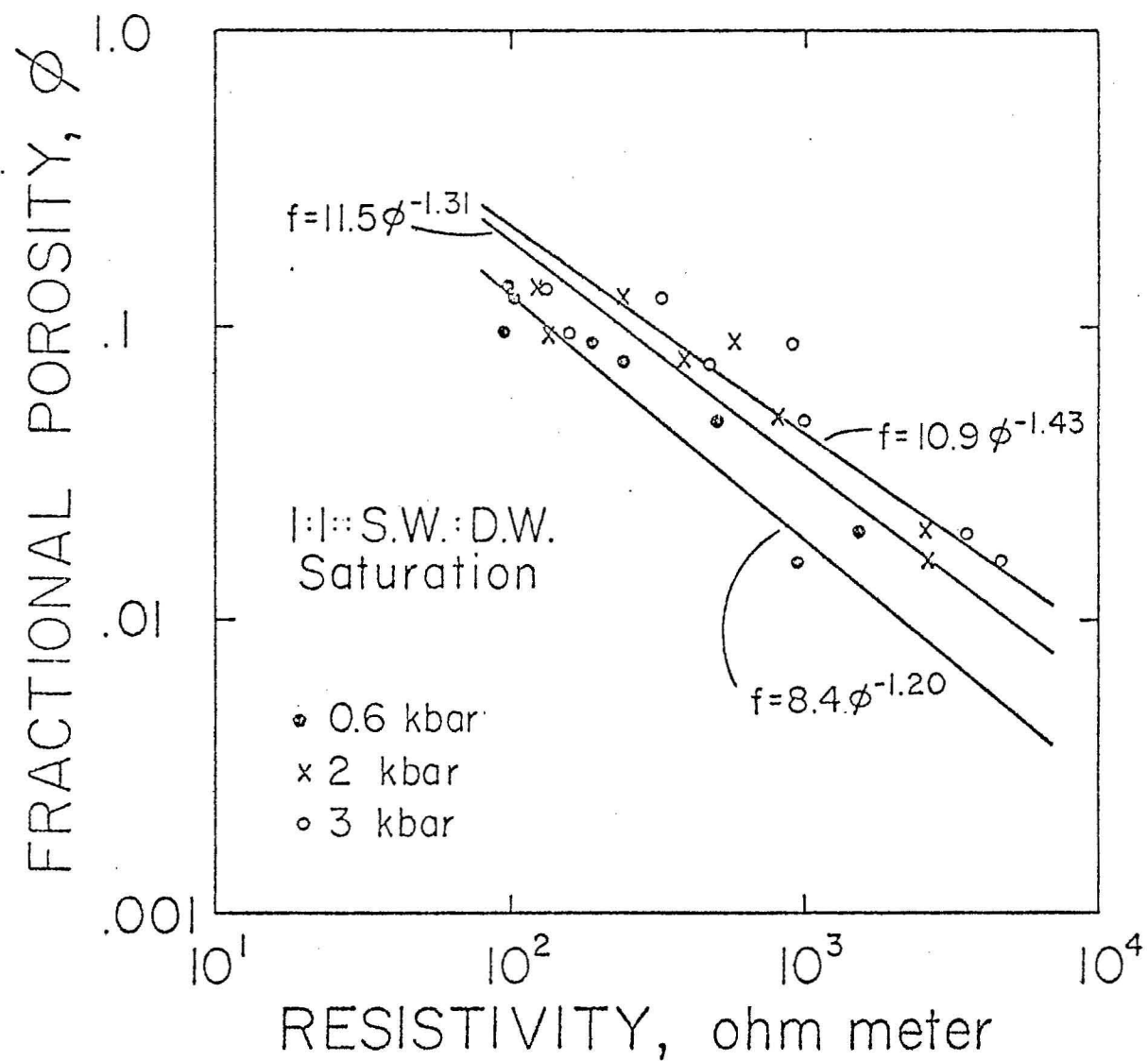
Figure 2. The relationship between "effective" porosity vs. resistivity for Hawaiian basalts saturated with fluid 1:1::seawater: distilled water at different pressures. The "effective" porosity is that at 1 bar and has not been corrected for pressure here.
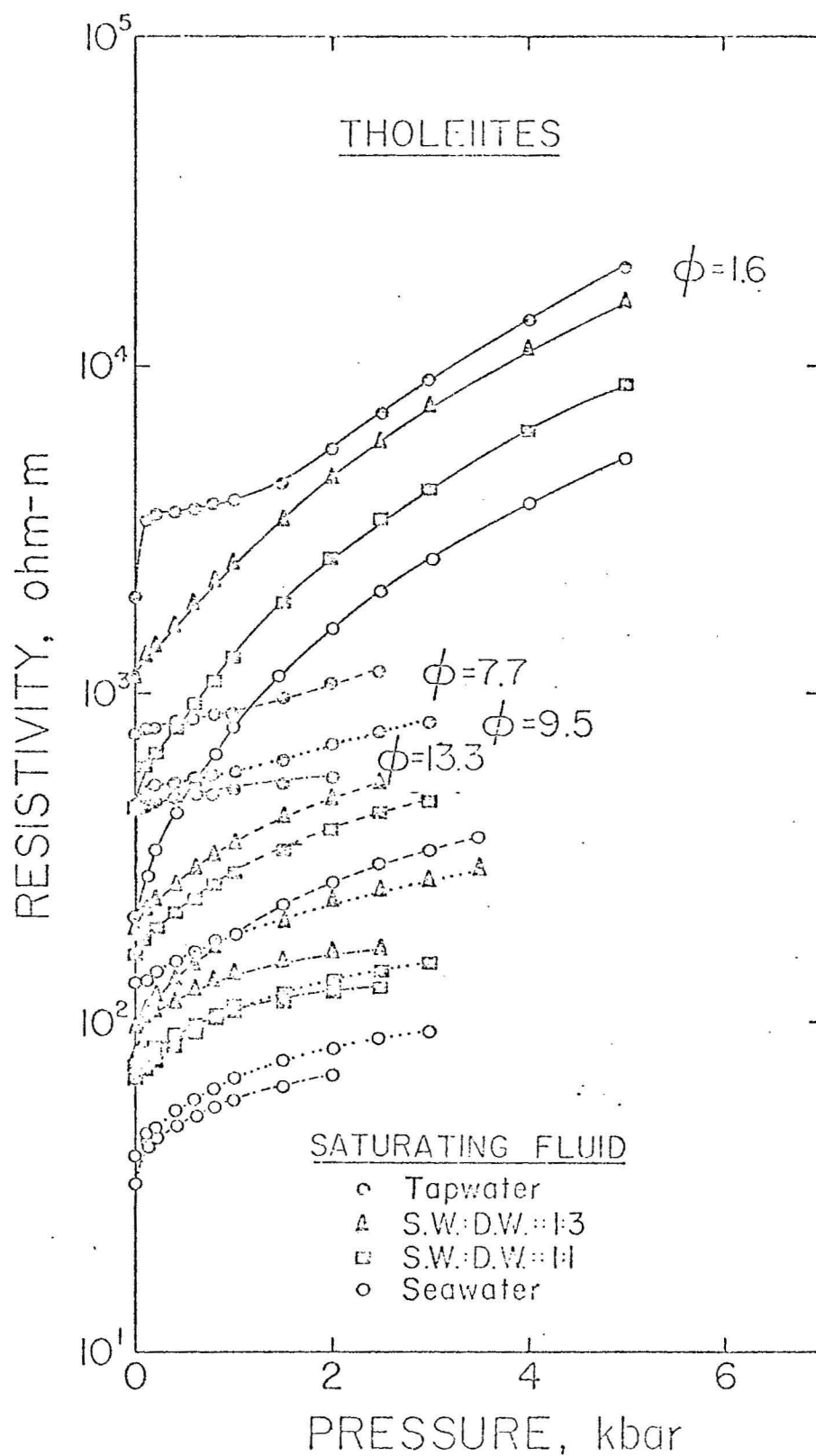
Figure 3. Pressure dependence of resistivity of four tholeiites of varying porosity and saturated with different fluids.
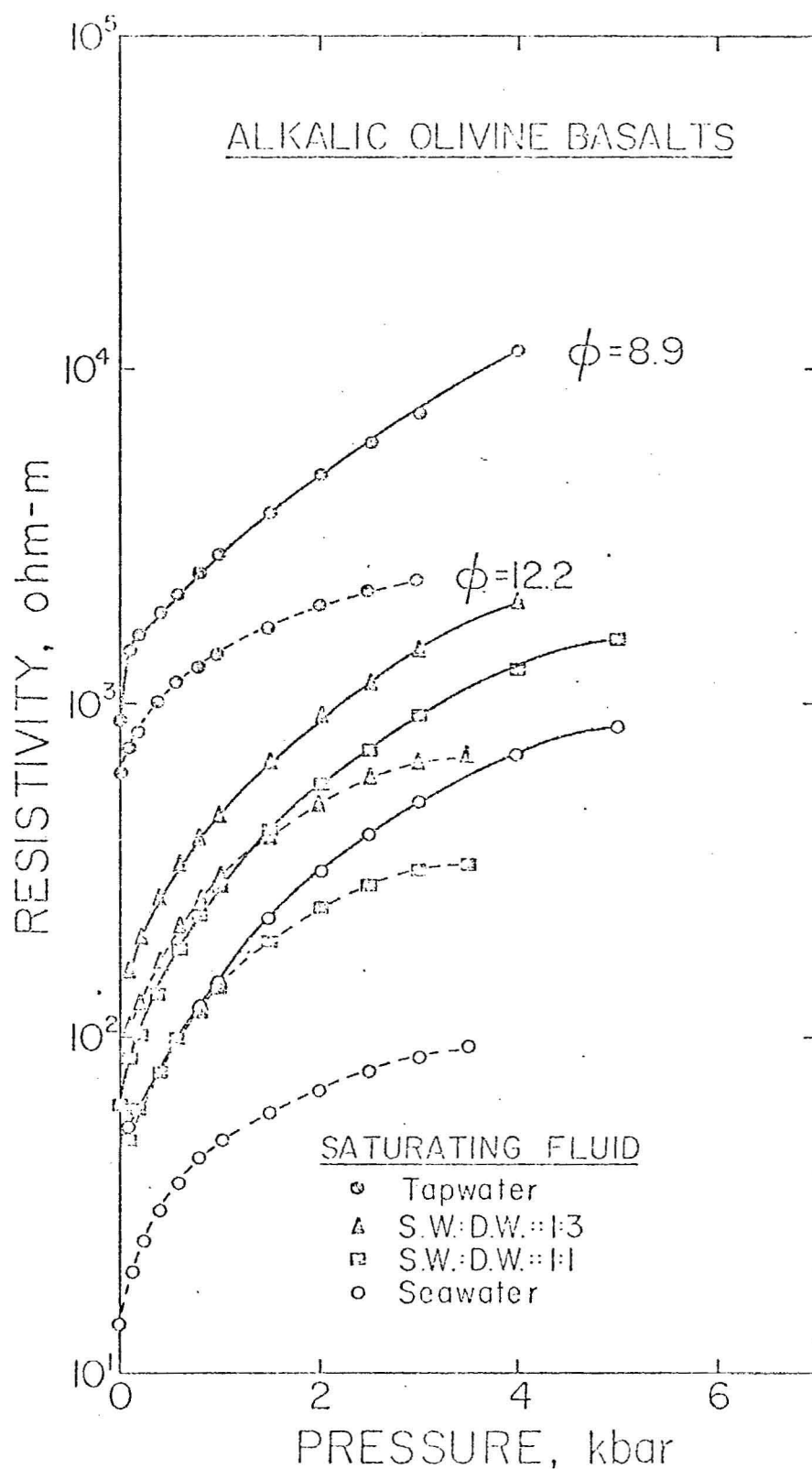
Figure 4. Pressure dependence of resistivity of two alkalic olivine basalts of varying porosity and saturated with different fluids.
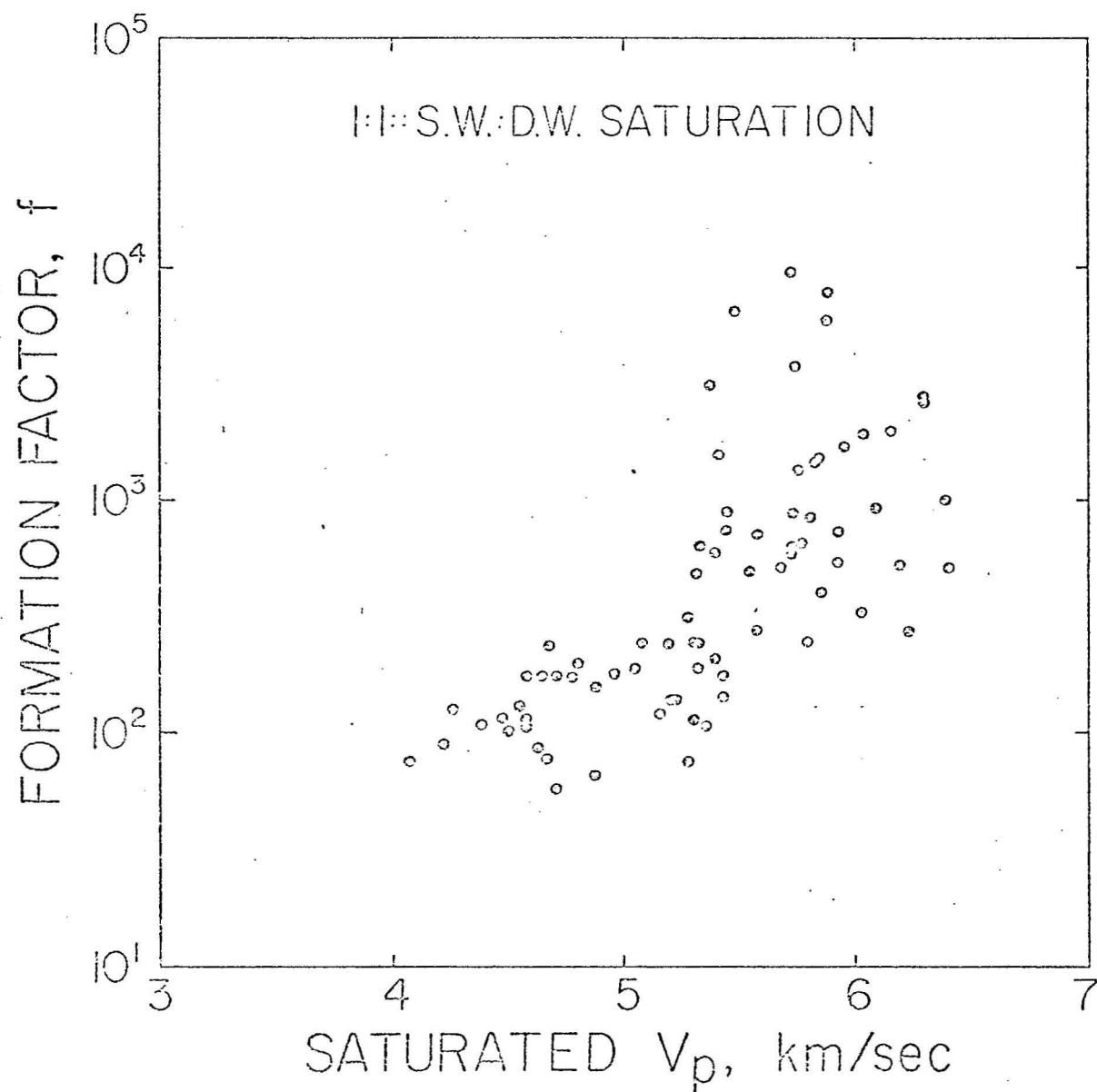
Figure 5. Formation factor vs. V_p in various types of basalts
having variable "effective" porosity and saturated
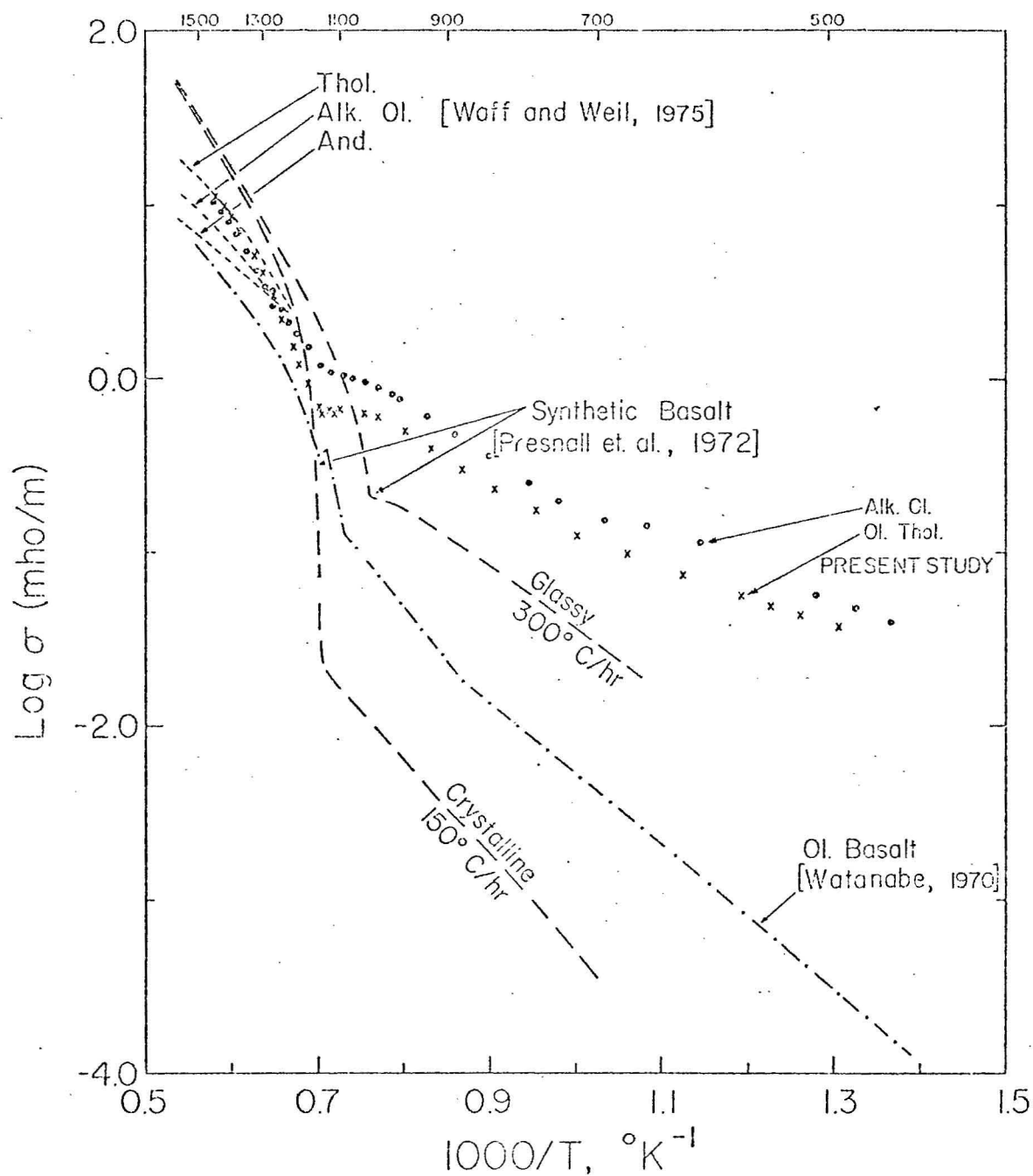with fluid 1:1:: sea water: distilled water.

Figure 6. Preliminary electrical conductivity measurements on two Hawaiian basalts (alkalic olivine and olivine tholeiite) to melting temperatures under controlled fo_2. Note the abrupt change in conductivity at the onset of melting. The results are compared with conductivity data on the other types of basalts.

results indicate that the low resistivities in the range 0.1-2 ohm meter are indicative of molten basalt. More experiments under controlled atmosphere and heating/cooling rates need to be undertaken in order to determine the effects of partial melting on the resistivity of basalts.

B. Thermal Properties

Measurements of the thermal diffusivity, k, of twenty-nine Hawaiian basaltic rocks of varying porosity were made in the temperature range of 300°K to 650°K, using the Ångström method [Kanamori et al., 1969]. The basalts included all the major rock types--tholeiitic, alkalic and nephelinitic--such as tholeiites, tholeiitic olivine and alkalic olivine basalts, trachyte, basanite, basanitoid, mugearite, hawaiite, nephelinite and ankaramite.

Porosity and temperature dependences of thermal diffusivity. The thermal diffusivity k decreases with increase in porosity (Figure 7). For the tholeiitic olivine basalts with porosity of 10.7, 12.7, 14.5, 16.8 and 18.9% the measured thermal diffusivity at 330°K are 7.42, 6.79, 6.13, 5.86 and 5.76 x 10^{-3} cm^2/sec respectively. Temperature dependence of k can be expressed as $k = A + B/T + CT^3$, where A, B and C are material constants. Figure 8 shows the reciprocal of the thermal diffusivity plotted vs. the absolute temperature. This temperature dependence of thermal diffusivity suggests that heat energy, in this temperature range, is transferred in the rock mainly by phonons. An analysis
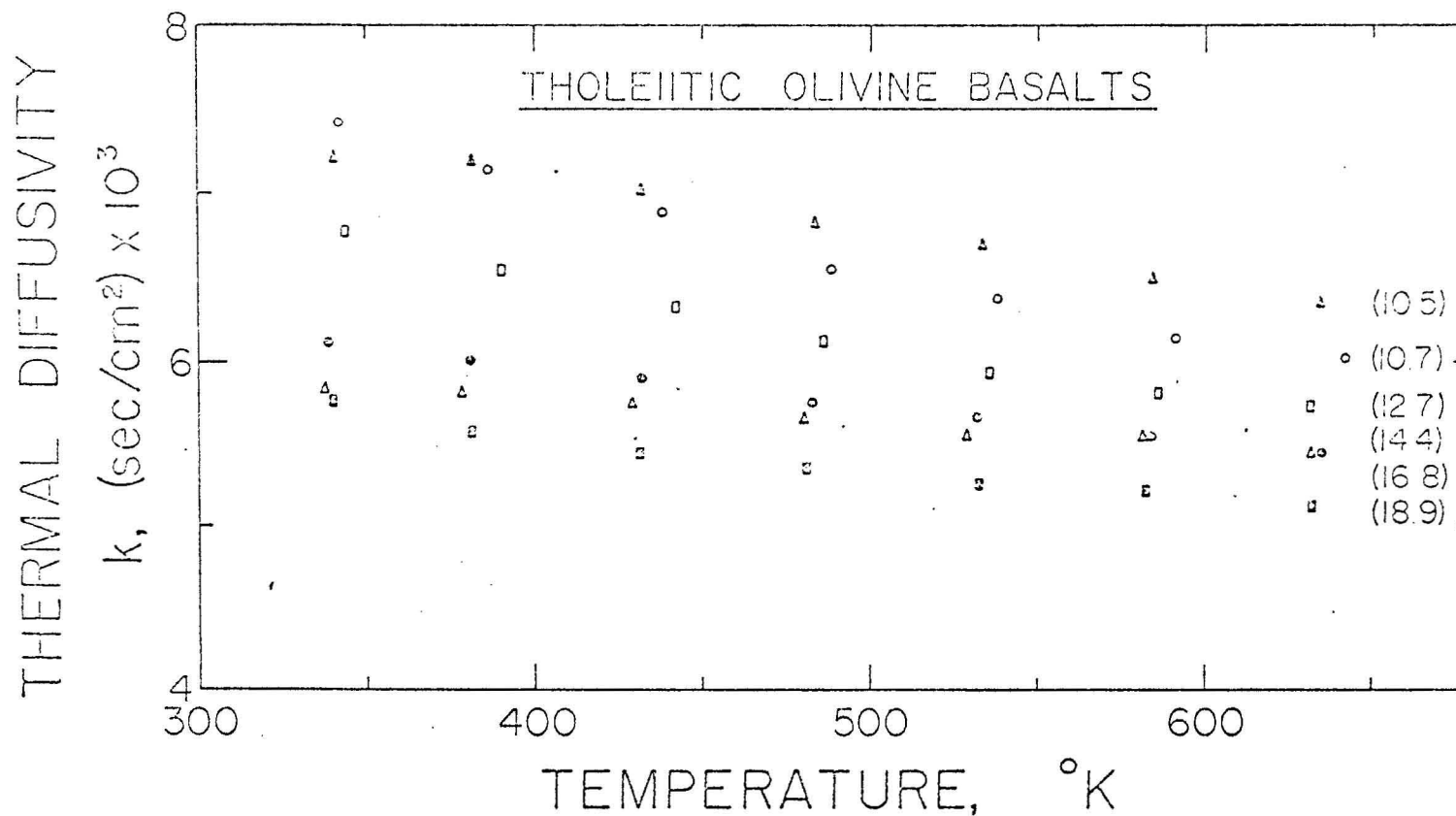
-140-

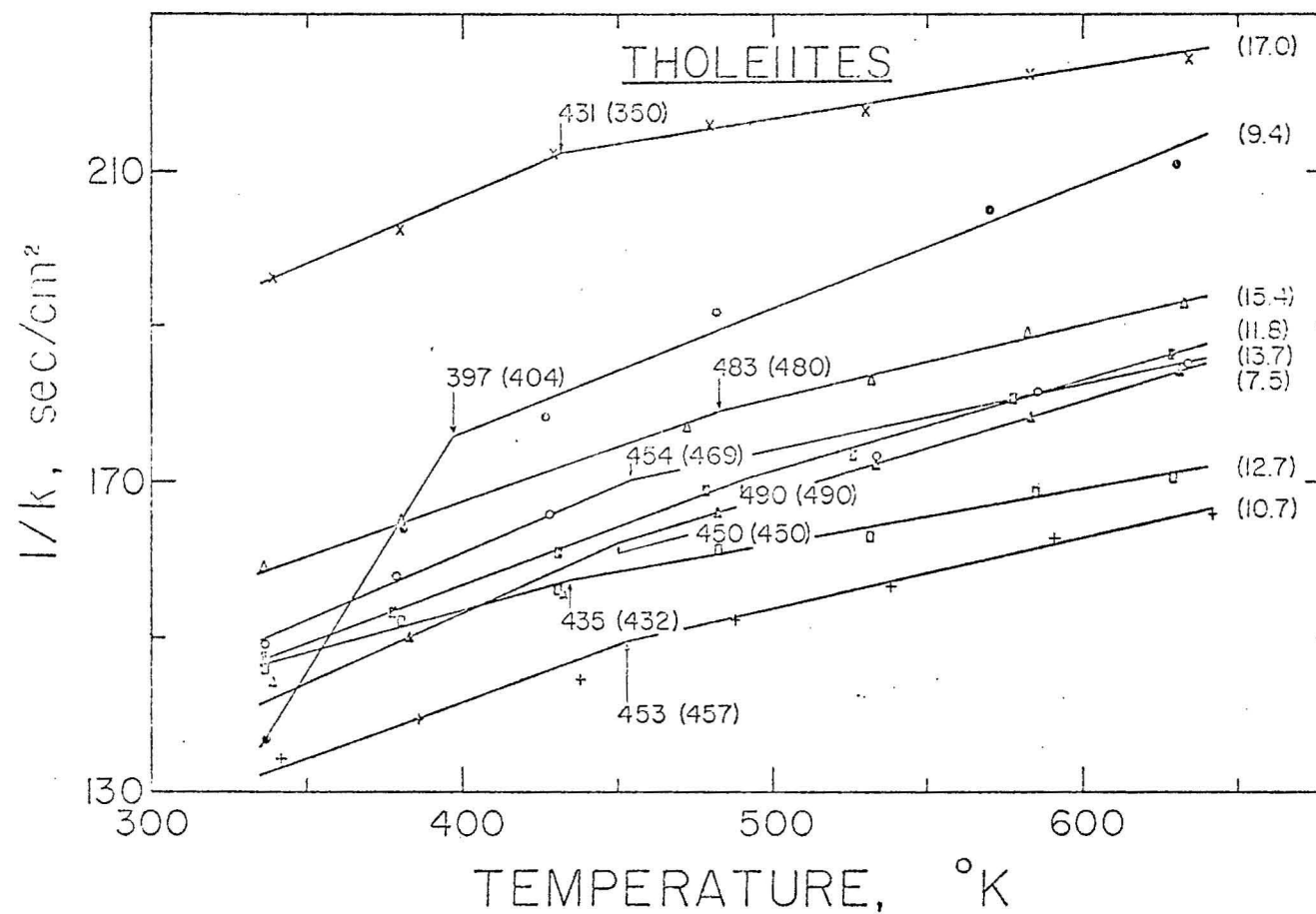Figure 7. Temperature dependence of thermal diffusivity k of 6 tholeiitic olivine basalts of varying porosity (10.5-18.9%).

Figure 8. 1/k vs. T for tholeiites. The values of θ_D, estimated from the change in slope, are indicated by arrow (designated as $\theta_{thermal}$) and those calculated from the elastic data are shown in parentheses (designated as $\theta_{acoustic}$).

Figure 9. Comparison of the Debye temperature values estimated from thermal and elastic measurements, respectively.

of the temperature dependence of the thermal diffusivity shows that each 1/k vs. T curve consists of two straight lines having different slopes; theoretically, it can be shown that the temperature at which a change in the slope occurs is coicident with the Debye temperature (θ_D) calculated from the P- and S-wave velocity measurements. Figure 9 shows the comparison between the θ_D values calculated from the thermal diffusivity and elastic measurements. The Debye temperature is a useful thermal parameter from which specific heat C_p can be estimated when no such measured values are available.

Although the temperature and porosity dependence of k and its interrrelation with the elastic properties are well understood, there is now a practical need to investigate the effect of temperature on the thermal diffusivity of saturated porous basalts. Virtually no such data exist.

C. Elastic Properties

The measured elastic properties (V_p, V_s) of the saturated and dry Hawaiian basalts at ambient pressure and temperature were correlated with the electrical and thermal properties (sections III.A and B). Next, the V_p and V_s, and Q^{-1} measurements in saturated basalts under in situ pressure (to 2 kbar) are planned; the results will be correlated with the electrical and any seismic field data.

IV. PROPOSED WORK FOR THE PERIOD OCT. 1976- SEPT. 1977

In light of the knowledge gained, it is proposed to carry out the following in order to accomplish the goals of the proposed research:

A. Laboratory Studies of Samples from the Geothermal Holes

   (i)   To investigate the physical and electrical prop-
erties of the core samples from the two geothermal
holes (HGP-A and Keller (1974)). Investigations
will include:

     (a)   electrical resistivity of saturated core samples
as a function of temperature (to 400°C) <u>at</u>
<u>1 kbar</u>.

     (b) V_p and V_s and Q^{-1} measurement in <u>dry</u> and <u>satura-</u>
<u>ted</u> samples as a function of pressure (to 2 kbar).

     (c)   thermal diffusivity of saturated and dry sam-
ples as a function of temperature to 400°C.

     (d)   correlation among the above physical properties.

  (ii)   To correlate the laboratory and logging data avail-
able for both geothermal holes.

B. Laboratory Studies of the Hawaiian Basalts

It is planned to complete the ongoing laboratory inves-
tigation of electrical, thermal and elastic properties of
the Hawaiian basalts mentioned in section III.A through C.
Emphasis will be put on evaluating the effects of pressure
on the elastic and electrical properties of saturated basalts,
and of thermal properties under temperature.

C. Correlation and Modeling Studies

   (i)   Laboratory data for the drill core samples will
be correlated with the available logging data.

(ii)   Evaluation of the laboratory data will be made

         in terms of the field geophysical data.

(II)   A model describing the subsurface thermal,

         elastic and electrical properties will be prepared

         based on the laboratory, logging, and field data.

AVAILABLE FACILITIES

All the apparati for carrying out the electrical, thermal, and elastic wave velocity measurements are available in the High Pressure Laboratory of the Hawaii Institute of Geophysics, except for an X-Y recorder to be used for the thermal diffusivity and Q^{-1} measurements. The recorder, presently being used, is on loan from another project.

PUBLICATIONS

1. Manghnani, M.H. and C.S. Rai, Electrical and elastic
    properties of Hawaiian basalts as function of pressure
    and temperature, to be submitted for publication in the
    proceedings of the ONR-CSOM Conference, "Physical
    Properties and Nature of Earth's Crust," Vail, Colorado,
    6-9 July 1976.

2. Manghnani, M.H., T. Hanada, and H. Mizutani, Thermal diffu-
    sivity and elasticity of Hawaiian basalts, in preparation.

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Hawaii Geothermal Project,

Geosciences – Task 2.7

Budget

October 1, 1976 - September 30, 1977

		Estimated Requitements
1.	Salaries and Wages	$18,672
	Scientific Discipline Personnel	
	M.H. Manghnani, Task Leader, 100% time for summer month @ 2,450/mo.	2,450
	Post-doctorate Assistant, 75% of time for 12 months @ 9,607/yr.	9,607
	1 Graduate Assistant @ 441 per month (50%) for 9 academic months and 100% time for 3 summer months	6,615
2.	Fringe Benefits	2,463
3.	Equipment	
	Recorder (Hewlett Packard) (for thermal diffusivity and Q^{-1} measurements)	3,750
4.	Travel	900
	Domestic	900
5.	Other Direct Costs	4,000
	Supplies and materials	2,700
	Publications	500
	Machine shop services	400
	Computer services	200
	Other: communications	200
6.	Indirect Charges	
	46.00% of salaries and wages	8,589
	TOTAL PROJECT COST	$38,374

TASK 3.1

NUMERICAL MODELLING

P. Cheng, K. H. Lau and D. Epp

Progress to Date

The primary objectives of this task have been (1) to assist the assessment of geothermal resources on the Island of Hawaii; (2) to estimate the capacity of the Puna geothermal field; (3) to predict the lifespan and performance of a geothermal well under different operating and resource conditions; and (4) to study the environmental impacts on the Ghyben Herzberg lens resulting from withdrawal and reinjection of geothermal fluids.

During the past three years, our major effort has been devoted to the development of transient two-dimensional computer codes to study (1) the formation of an island geothermal reservoir, and (2) the effects of withdrawal and reinjection of fluids on such a reservoir, with the ultimate goal of the simulation of the Puna geothermal field. Some effort has also been spent on obtaining analytical solutions for the prediction of heat transfer rate from hot dikes or sills, as well as the size of the associated hot water zones. The results of the investigation by the task have been reported in 15 publications (See Refs. 1-15). The following are the highlights of results obtained.

Numerical Studies

Prior to the drilling of the HGP-A well, it has been generally assumed that the geothermal reservoir on the Island of Hawaii is constantly recharged from the ocean, owing to the high porosity and permeability of the basaltic formation. It has been speculated that while aquifers at shallow depth on the island may be unconfined from the top, confined aquifers may exist at depth due to self-sealing effects. The heating of the groundwater in the

aquifers is provided by a magma chamber at shallow depth, the rift zone, as well as numerous hot intrusives. An overly simplified view of the Hawaii geothermal reservoir is shown in Fig. 1.

As the detailed geological and hydrological conditions at the Puna area were unknown prior to the drilling, the strategy adopted by the numerical simulation group has been to study simplified situations during the initial phase of the work. These simplified models, which consider different effects one at a time, will aid in a qualitative understanding of the physical processes involved. After maturity and expertise have been developed and geophysical exploration data on the Puna area has been analyzed, more realistic models will be considered. The research work will then culminate in the development of a general computer code, capable of predicting the characteristics of the Puna geothermal field. For the initial model, the Hawaii geothermal reservoir (Fig. 1) is idealized as a two-dimensional porous medium bounded by caprock from the top, heated by impermeable bedrock from below, and recharged from the ocean through vertical boundaries (Fig. 2). To simplify the mathematical formulation of the problem, the following additional assumptions have been made:

A. The temperature of the fluid is everywhere below boiling for the pressure at that depth.

b. Properties of the groundwater and the rock formation such as the thermal conductivities, specific heats, kinematic viscosity, and permeability are assumed to be homogeneous and isotropic.

C. The Boussinesq approximation, used in classical free convection problems, is employed.

The mathematical model is based on the conservation laws of heat and mass, as well as the Darcy law for flow through a porous medium. With the above
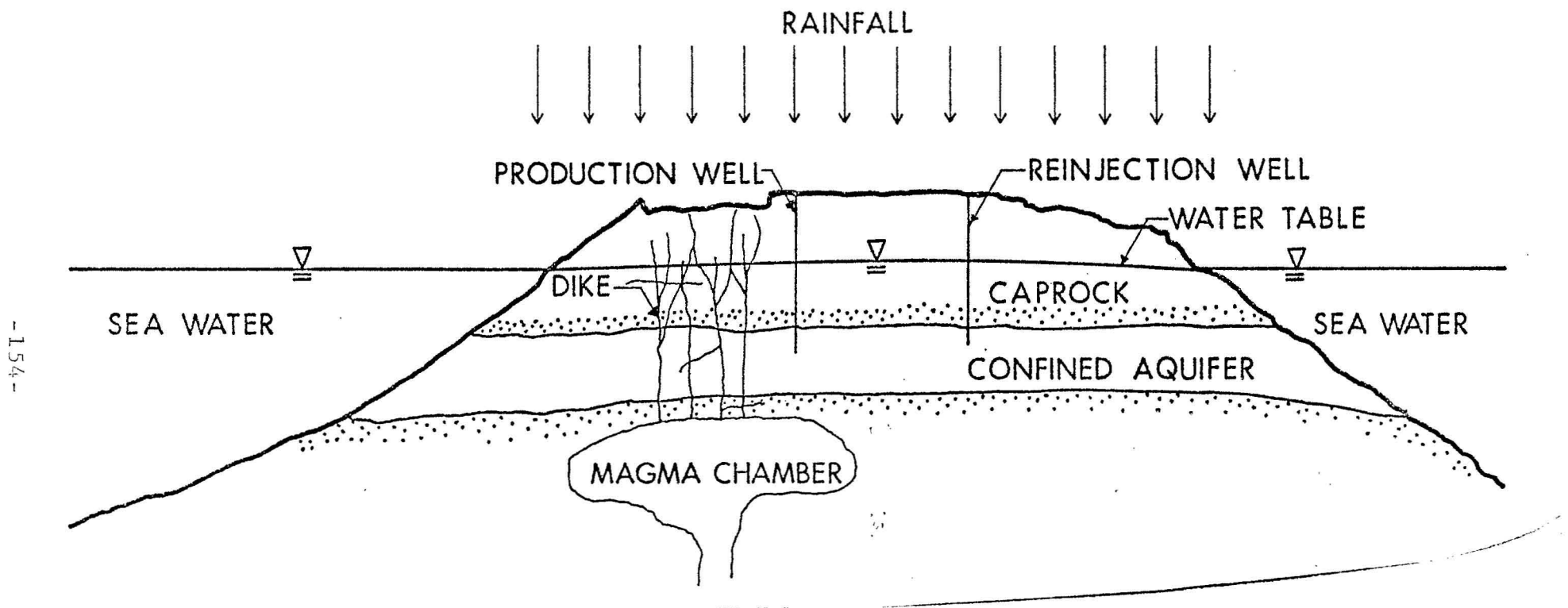
FIG. 1 ISLAND AQUIFER WITH GEOTHERMAL HEAT SOURCE

Z

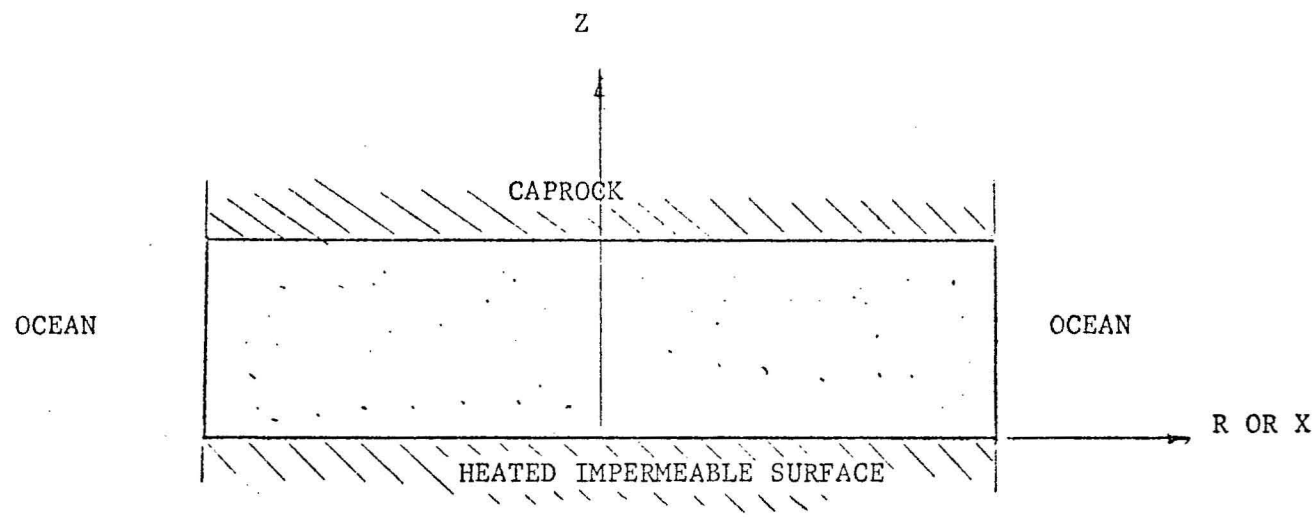CAPROCK

OCEAN

OCEAN

R OR X

HEATED IMPERMEABLE SURFACE

Fig. 2 Island Aquifer Heated from Below

approximations, the governing equations in rectangular coordinates can be combined and reduced to the following two coupled non-linear partial differential equations:

$$\frac{\partial^2 P}{\partial X^2} + \frac{\partial^2 P}{\partial Z^2} = \varepsilon \frac{\partial \theta}{\partial Z} \quad , \tag{1}$$

$$D\left[-\frac{\partial P}{\partial X}\frac{\partial \theta}{\partial X} - \left(\frac{\partial P}{\partial X} + 1 - \varepsilon\theta\right)\frac{\partial \theta}{\partial Z}\right] + \frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Z^2} \quad , \tag{2}$$

where

$$P \equiv \frac{p - p_a}{\rho_a g h} \quad , \qquad \theta \equiv \frac{T - T_s}{T_m - T_s} \quad , \qquad \tau \equiv \alpha t / \sigma h^2 \quad , \qquad X \equiv x/h \quad , \qquad Z \equiv z/h \quad ,$$

$$L \equiv \ell/h \quad , \qquad \varepsilon \equiv \beta(T_m - T_s) \quad , \qquad \text{and} \qquad D \equiv \rho_a K g h / \alpha \mu = \frac{Ra}{\varepsilon} \quad ,$$

with p, T, ρ, and μ denoting the pressure, temperature, density, viscosity; α and K denoting the thermal diffusivity and permeability of the medium; g the gravitational acceleration; T_m denoting the maximum temperature of the impermeable surface, and the subscript "s" denoting the condition in the ocean; ε and D are dimensionless parameters. With appropriate boundary and initial conditions, Eqs. (1) and (2) have been solved numerically for the investigation of the following problems.

(1) Free Convection in Geothermal Reservoirs

Formation of an island geothermal reservoir [15] Consider the idealized aquifer as shown in Fig. 2 having an aspect ratio of 4, initially isothermal and motionless, is suddenly heated by an intruded magma chamber at a shallow depth. The subsequent developments of isotherms in the reservoir having

D = 4,000 (Ra = 200) is shown in Fig. 3 where τ = 0.001 corresponding to 200 years on the real time scale. It is shown in the figure that the isotherms move gradually upward and reach a steady state condition approximately at τ = 0.035 corresponding to approximately 7000 years. It is found that the time required to reach steady state increases as the value of D decreases.

Effects of Rayleigh number [3] Figs. 4-6 show the steady state convection pattern and isotherms in a reservoir at different values of Ra. As shown in Figs. 4a and 4b, cold water from the ocean moves inland along the lower portion of the aquifer and is gradually being heated by the hot bedrock. Near the point of maximum heating, the fluid rises as a thermal plume. As the hot water reaches to the top, it spreads around the caprock and is finally discharged to the ocean in the upper portion of the aquifer. A comparison of Figs. 4a and 4b shows the closed convective cells disappear as the value of Ra is increased. The effect of Ra on the isotherms is shown in Fig. 5. It shows that for small values of Ra (Ra = 50 for example), the shapes of the isotherms are similar to those by heat conduction. As the values of Ra increase, the isotherms develop into mushroom shapes. The results have important implications on the selection of a drilling site. It indicates that for a reservoir with large value of Ra and having a hot heat source, a large amount of hot water is indeed available at shallow depths. Fig. 6 shows the vertical temperature profiles at different locations in an island aquifer. The dimensionless temperatures at the center line of the thermal plume increases rapidly from nearly zero at the caprock to almost unity somewhat below the caprock. The vertical temperature profiles along the thermal plume is shown to be different from the rest of the profiles which have a temperature reversal at a lower elevation. It is worth mentioning that the temperature reversal occurs because of the lateral movement of groundwater. It is interesting to note that temperature vs. depth measurements obtained by
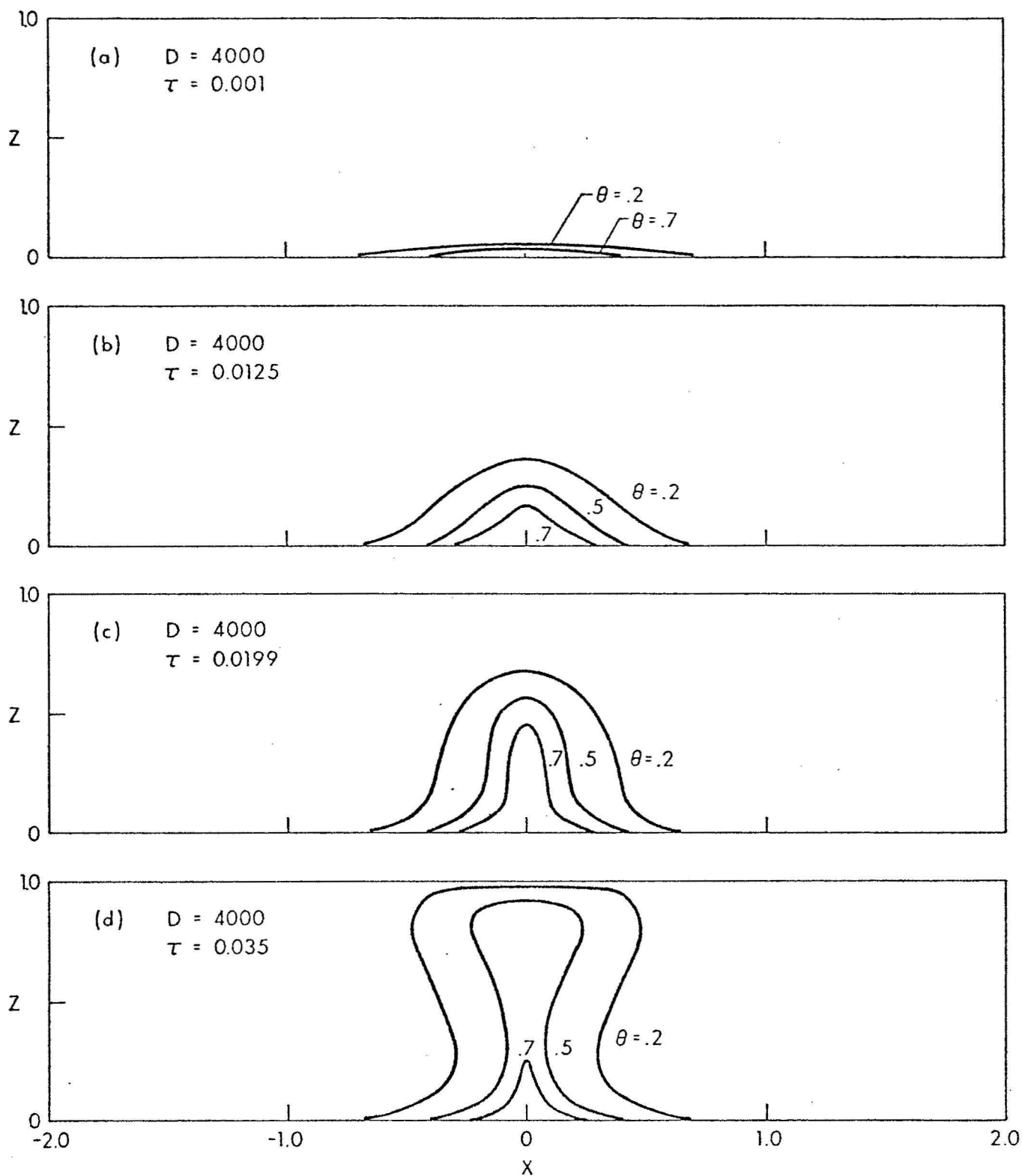
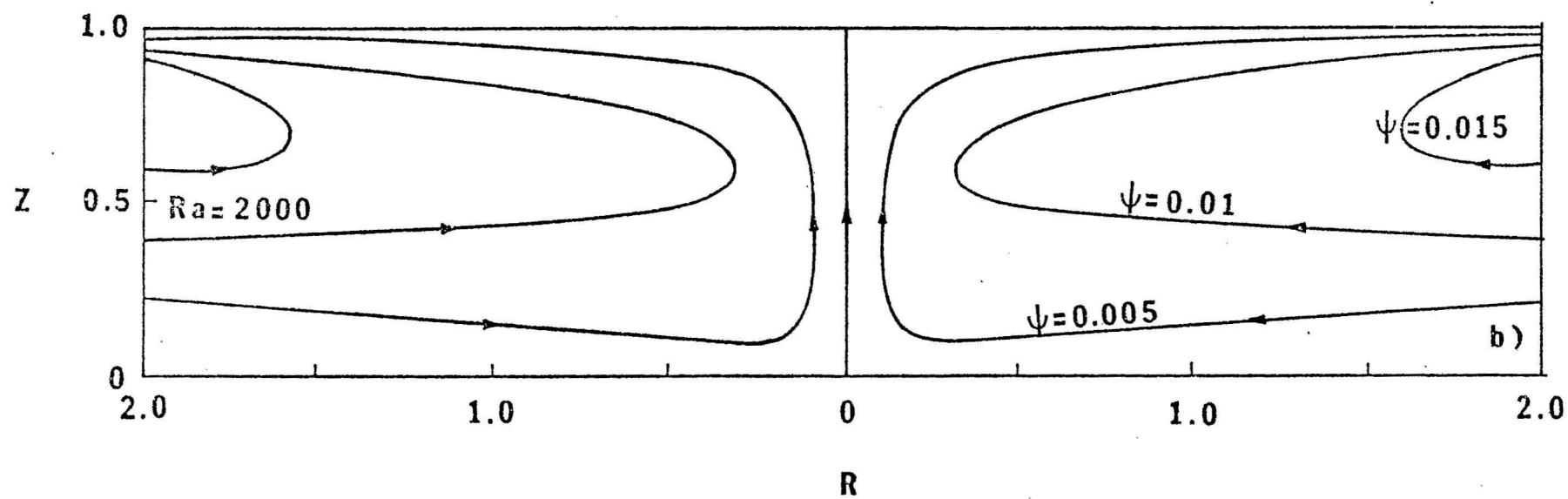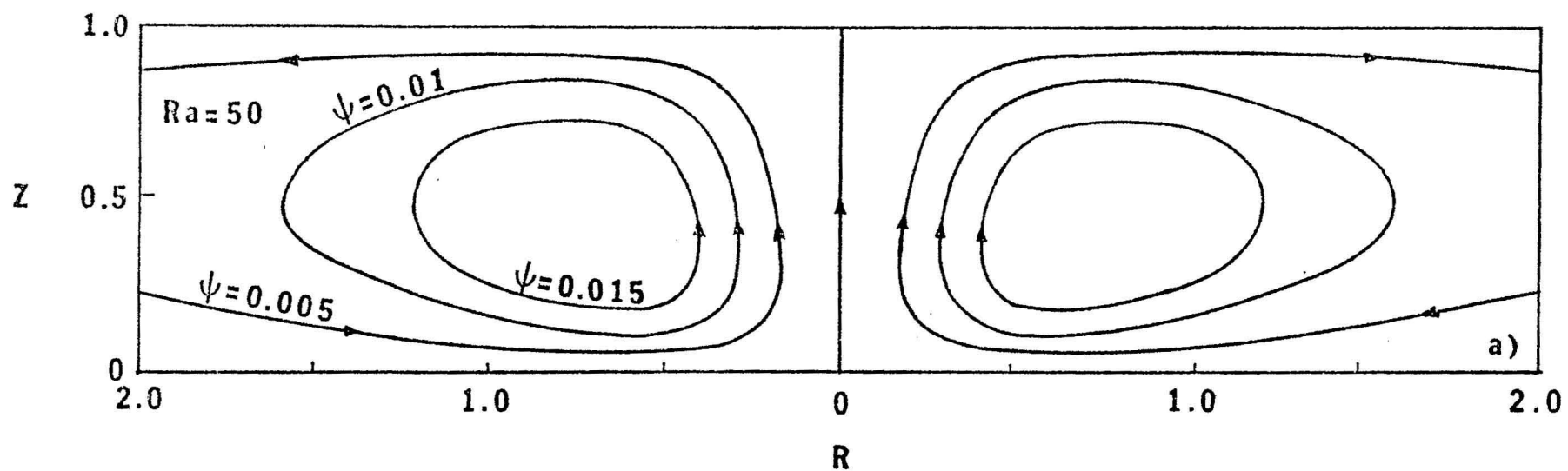FIG. 3 DEVELOPMENT OF ISOTHERMS IN A GEOTHERMAL RESERVOIR AT D = 4000

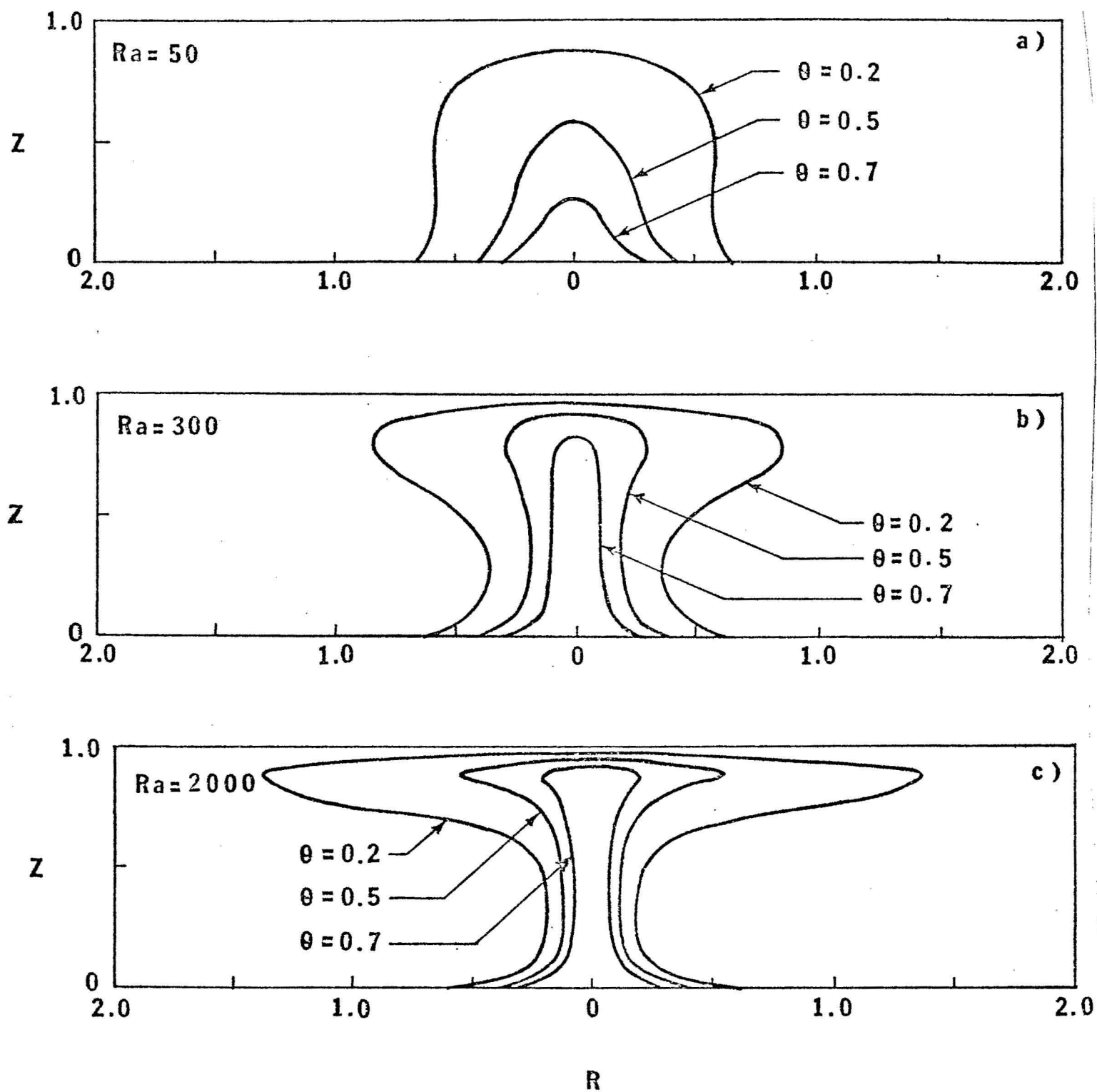FIG. 4 STREAMLINES FOR A CYLINDRICAL ISLAND AQUIFER

FIG. 5 TEMPERATURE CONTOURS IN A CYLINDRICAL ISLAND AQUIFER
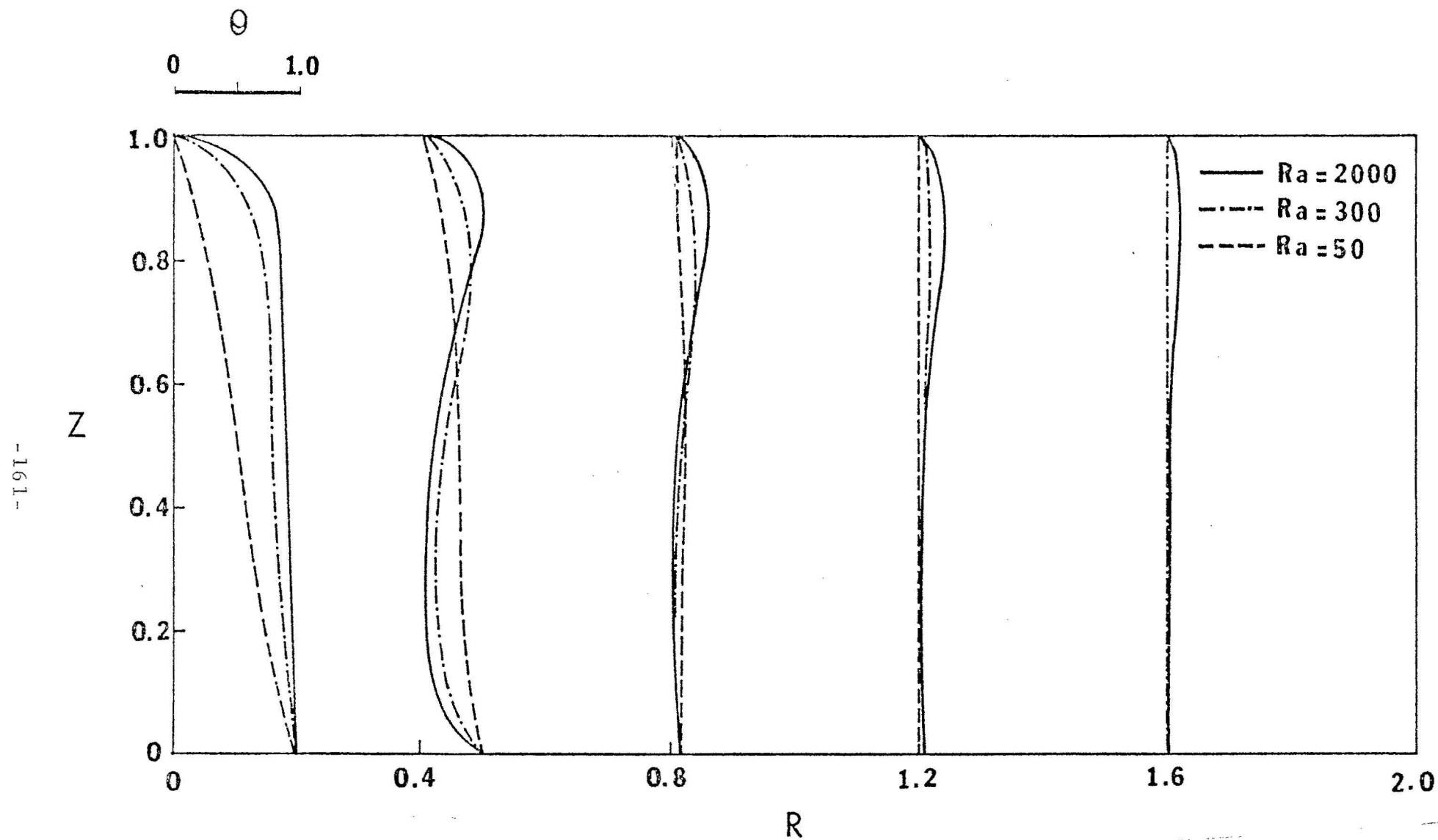WITH CAPROCK TEMPERATURE SPECIFIED

-160-

FIG. 6 VERTICAL TEMPERATURE PROFILES IN A CYLINDRICAL ISLAND AQUIFER
WITH CAPROCK TEMPERATURE SPECIFIED

Keller [16] show also a temperature reversal behavior (Fig. 7). A comparison between theory and measurements shows a striking similarity (Fig. 8).

Effects of Thermal Boundary Condition at the Caprock [3] Fig. 9 shows the steady temperature distribution in a geothermal reservoir with an adiabatic caprock. The effects of thermal boundary condition on the caprock can be shown by comparing the isotherms in Fig. 9 to those of Fig. 5 which is for a reservoir with a heating-conducting caprock. As is expected, temperature distribution everywhere in the reservoir having a non-heat conducting caprock is higher than that with a heat conducting caprock. However, the increase in temperature is most significant in the region adjacent to the caprock. The larger the value of Ra, the smaller the region in which temperature is affected. In other words, for large value of Ra, the effect of thermal boundary condition on the caprock is confined to a small region adjacent to the caprock, with the temperature distribution in the rest of the reservoir remained unaffected. The effect of thermal boundary condition at the caprock on the total heat transfer rate of the bedrock is presented in Fig. 10, where it is shown that the heat transfer is relatively independent of the thermal boundary condition at the caprock.

Effects of Heating Length and Dike Intrusion [3] The effects of heating length of the bedrock on steady state convection pattern and its associated isotherms are shown in Figs. 12 and 13. The number of convective cells and the associated thermal plumes is dependent upon the value of f, that is, the ratio of the heating length to the height of the reservoir. It is shown that two convective cells are generated for f = 2, and four convective cells are generated for f = 3. The effects of dike intrusion on convection pattern and temperature distribution are shown in Figs. 11c and 12c. Comparison of figures in Fig. 11 and 12 respectively shows that the convective pattern and
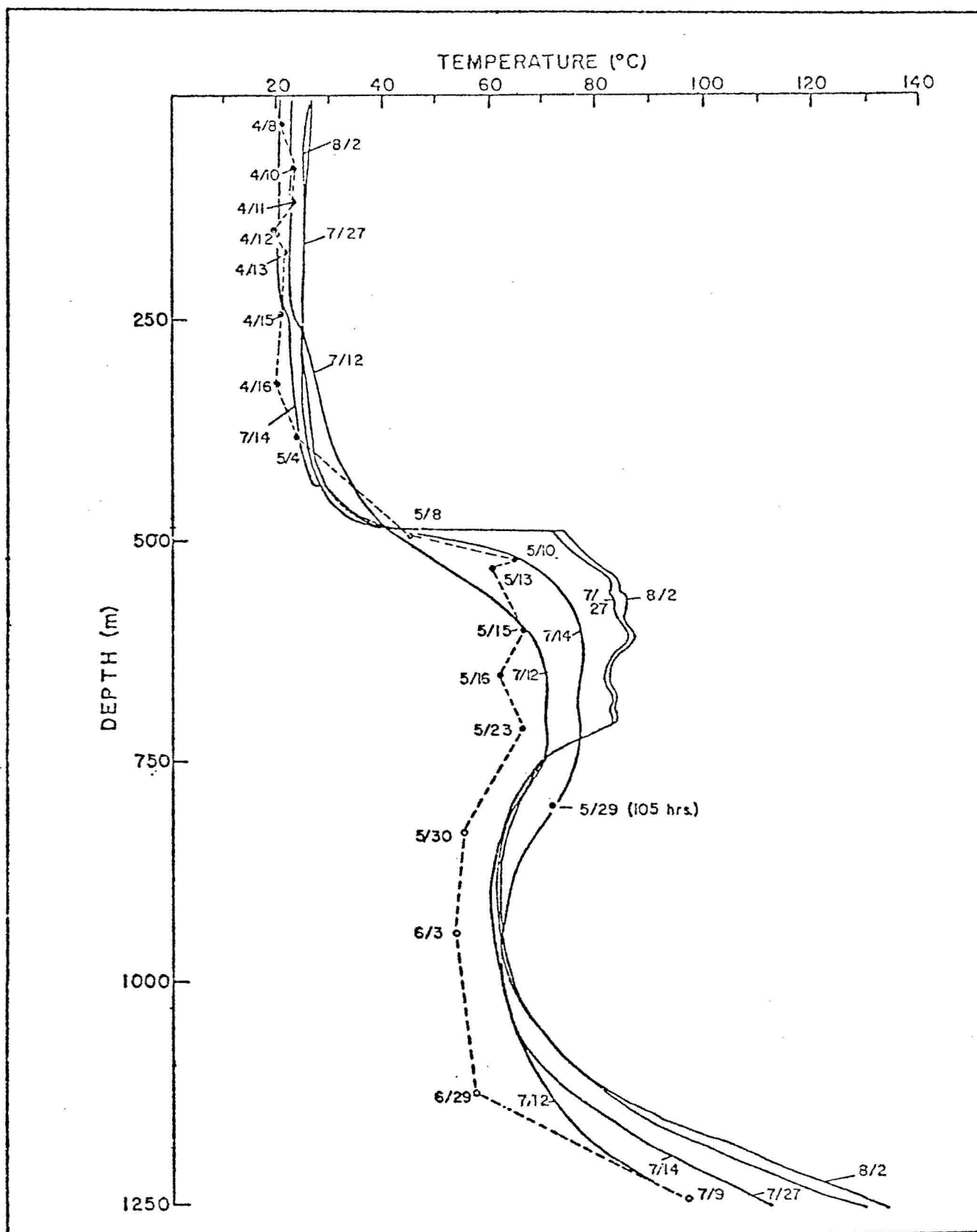
FIG. 7 TEMPERATURE PROFILES IN THE KILAUEA DRILL HOLE
MEASURED BY KELLER

-163-
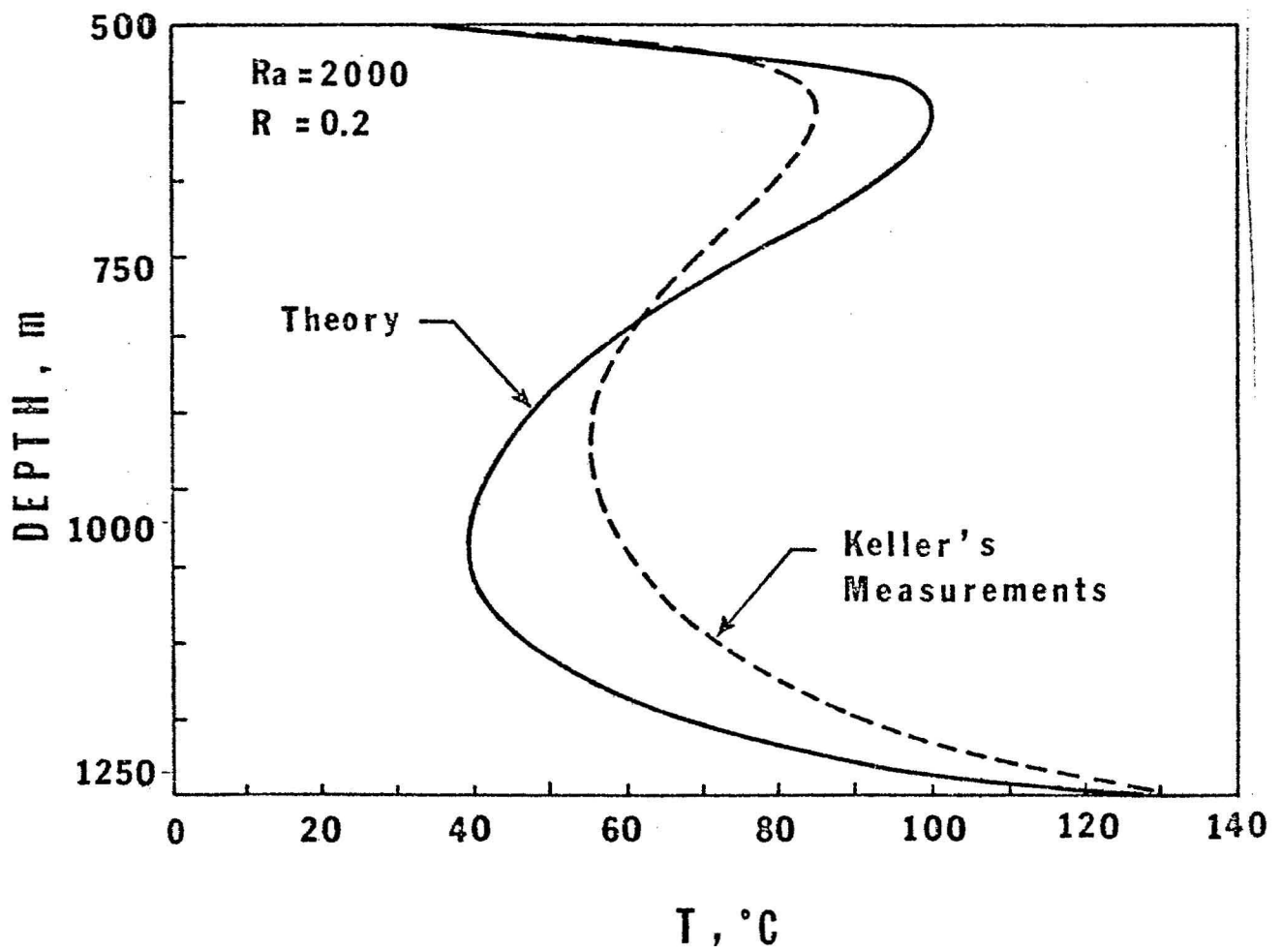
FIG. 8 COMPARISON OF THEORY AND MEASUREMENTS
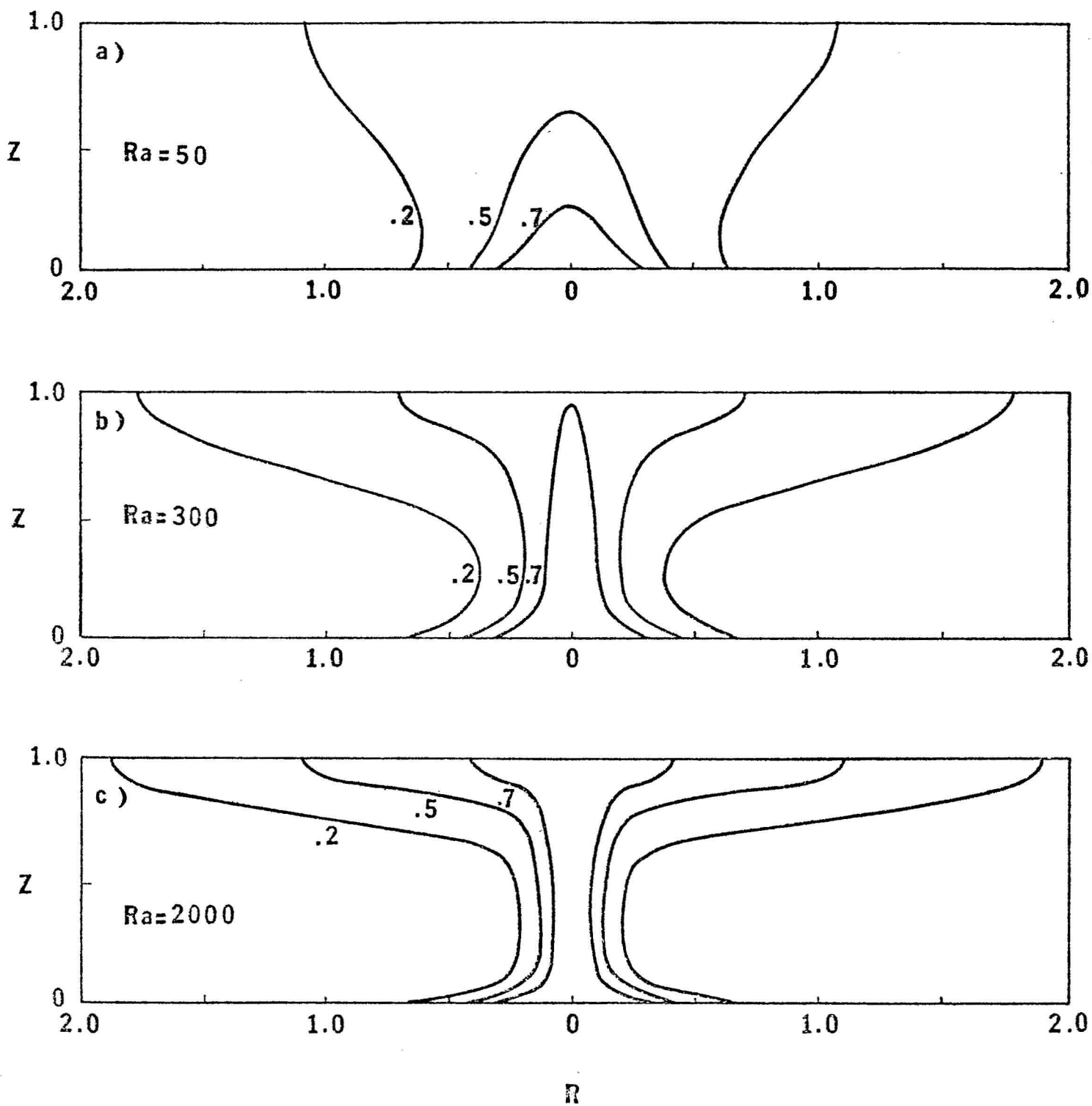
FIG. 9 TEMPERATURE CONTOURS IN A CYLINDRICAL ISLAND AQUIFER
WITH ADIABATIC CAPROCK
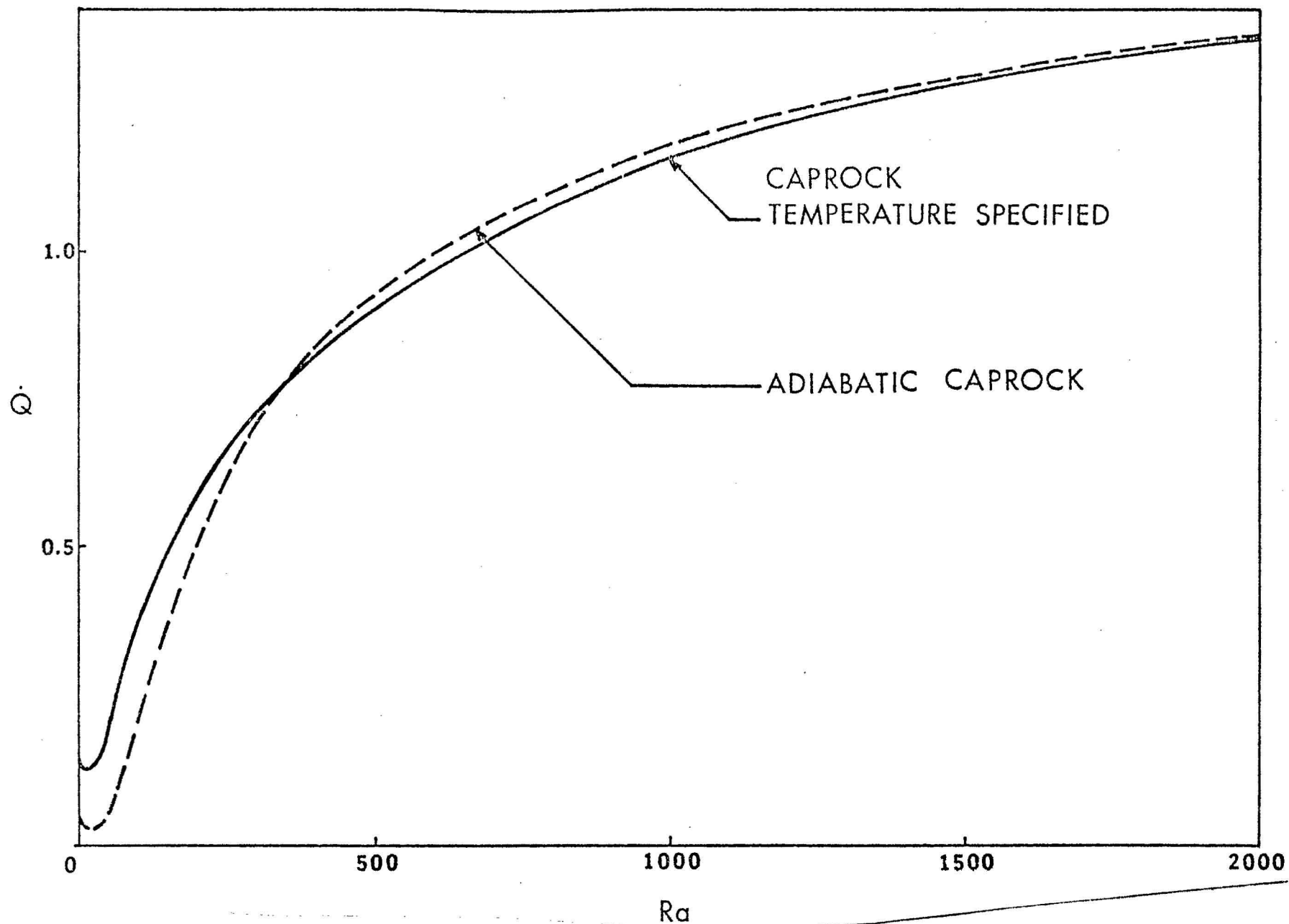
FIG. 10 EFFECT OF THERMAL BOUNDARY CONDITION OF CAPROCK ON SURFACE
HEAT TRANSFER RATE OF THE BEDROCK
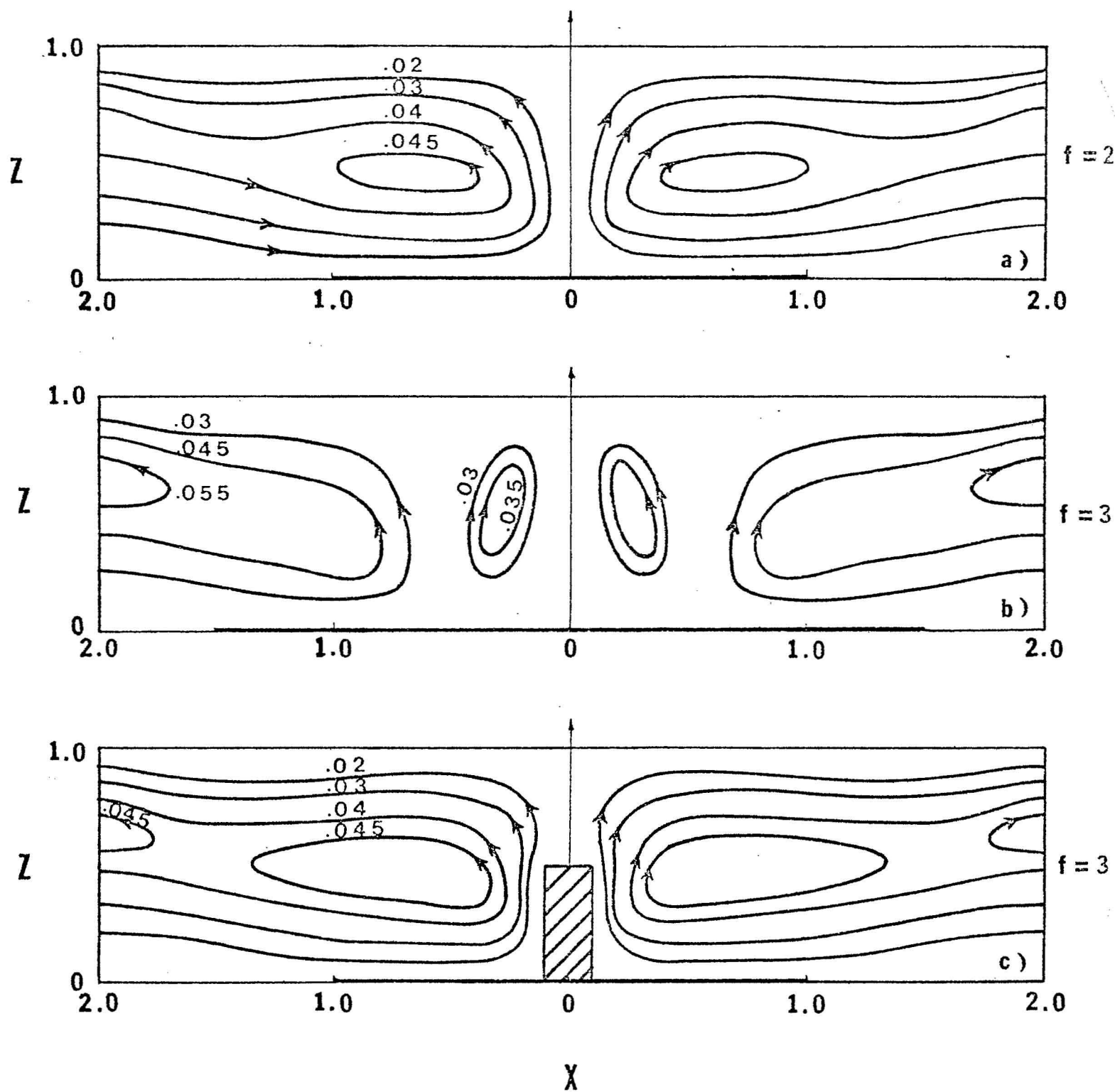
FIG. 11 THE EFFECTS OF HEATING LENGTH AND MAGMATIC INTRUSION ON STREAMLINES IN A RECTANGULAR RESERVOIR WITH HEAT-CONDUCTING CAPROCKS
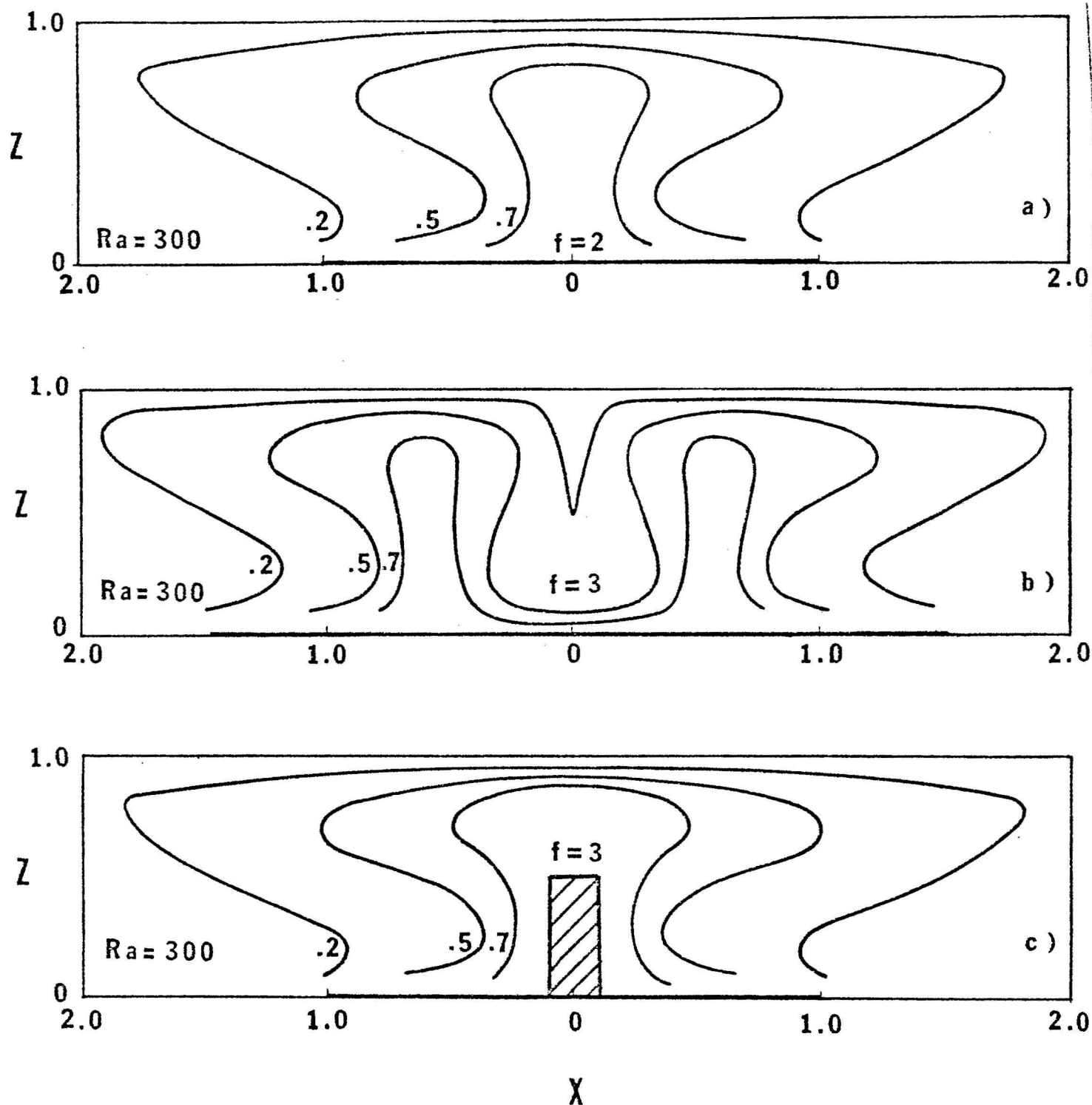
FIG. 12 THE EFFECTS OF HEATING LENGTH AND MAGMATIC INTRUSION
ON THE ISOTHERMS IN A RECTANGULAR RESERVOIR WITH
HEAT-CONDUCTING CAPROCKS

the shape of isotherms depend not only on the size of the heating length but also on the manner it is heated, i.e., whether it is heated vertically or horizontally. For example, although Figs. 11b and 11c have the same heating length, the convective patterns and their associated temperature contours (as shown in Figs. 12b and 12c) are completely different.

(2) Combined Free and Forced Convection in Geothermal Reservoirs [4,15]

During the production stage of a geothermal field, pressure gradients can be generated by man-made withdrawal or reinjection of fluids. As a result, the convective movement of groundwater in the geothermal reservoir depends not only on the bouyancy force but also on the induced pressure gradients. The contraction of isotherms have important implications to the lifespan of a geothermal well.

Fig. 13 shows the contraction of isotherms of a rectangular geothermal reservoir with an aspect ratio of 4 and with D = 7000 (or Ra = 350). The dash lines indicate the isotherms before the withdrawal of fluid, while the solid lines indicate the isotherms after 30 years (Fig. 13a) and 100 (Fig. 13b) years of continuous withdrawal of fluids at a rate of $7 \times 10^{6} lb_{m}$/hr-ft from a point sink located at X = 0 and Z = 0.5, i.e., directly above the point of maximum heating. While it is shown in the figure that isotherms hardly change after 30 years of operation, the temperature of the groundwater above the sink decreases noticeably after 100 years of operation.

Fig. 14 shows the contraction of isotherms resulting from the withdrawal of fluid along a line sink located vertically upward from the point (0, 0.5) to the top of the aquifer having D = 7000. The isotherms before the withdrawal of fluid are the same as those in Fig. 13 and are shown by dash lines. The solid lines are the isotherms after 30 years of continuous withdrawal of fluids at the rate of $1.7 \times 10^{7} lb_{m}$/hr-ft. At this rate of withdrawal, it is
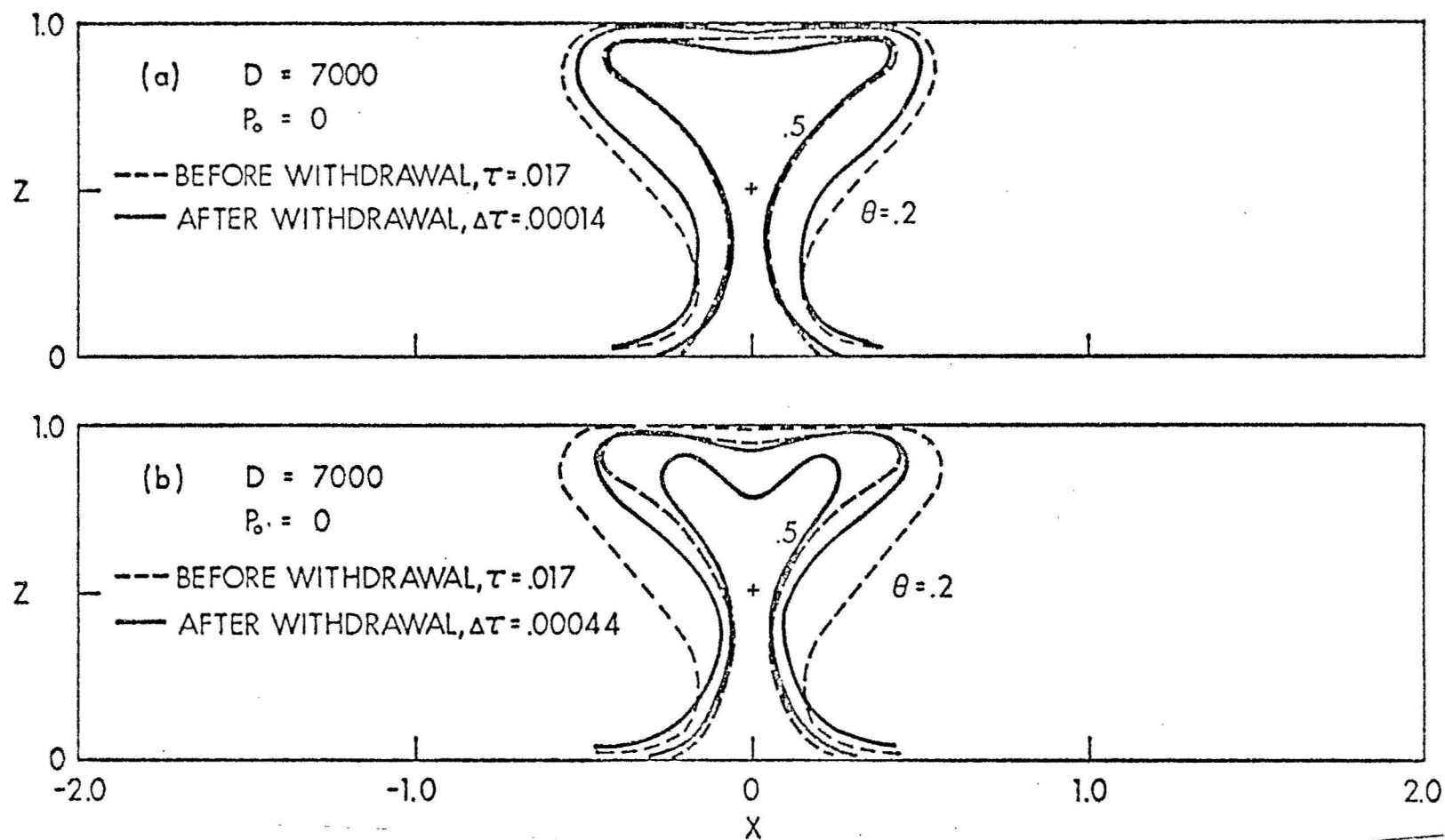
FIG. 13 CONTRACTION OF ISOTHERMS IN A GEOTHERMAL RESERVOIR RESULTING FROM WITHDRAWAL OF FLUIDS FROM A POINT SINK
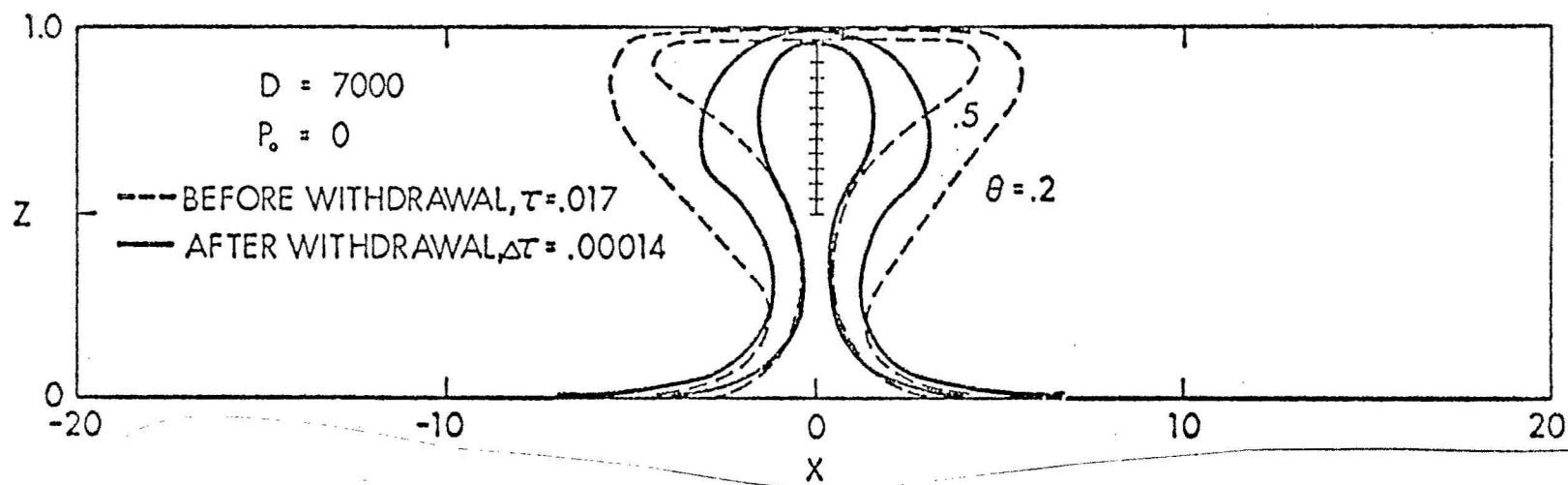
FIG. 14 CONTRACTION OF ISOTHERMS IN A GEOTHERMAL RESERVOIR RESULTING
FROM WITHDRAWAL OF FLUIDS FROM A LINE SINK

shown that the temperature of groundwater in the upper portion of the reservoir decreases noticeably after 30 years of operation. It should be noted that the rate of contraction of isotherms not only depends on the withdrawal rate but also on the size of the heating length, i.e., the temperature distribution of the bedrock.

Analytical Studies

It will be of great interest if some simple algebraic equations can be obtained for the calculation of heat transfer rate and size of the hot water zone adjacent to intruded bodies. With this in mind, some effort has been devoted to obtain analytical solutions for convective heat transfer from vertical or horizontal heating surfaces embedded in a porous medium. The methodology used to solve Eqs. (1) and (2) approximately is akin to the boundary layer theory in classical viscous flow. The following analytical solutions have been obtained.

Convective Heat Transfer from Vertical Plane Surfaces. Closed-form solutions have been obtained for steady free convection from a vertical plane surface at a temperature T_w, embedded in a porous medium at T_∞. The expressions for the size of the hot-water zone (i.e., the so-called thermal boundary layer thickness) and the total surface heat transfer rate are given by [8]

$$\delta_1(x) = 6.3 \left[\frac{\mu \alpha x}{\rho_\infty g \beta K (T_w - T_\infty)} \right]^{1/2} , \qquad (3)$$

and

$$q_1 = 0.88 S k (T_w - T_\infty)^{3/2} \left[\frac{\rho_\infty g \beta K L}{\mu \alpha} \right]^{1/2} , \qquad (4)$$

where L and S are the length and width of the surface. The corresponding

expressions for combined free and forced convection about vertical plane surfaces are given in Ref. 13. The analysis for withdrawal and reinjection of fluids along vertical plane is given in Ref. 11. The analysis for free convection about vertical intrusives with cylindrical shapes is given in Ref. 7.

Convective Heat Transfer from Horizontal Plane Surfaces. The thermal boundary layer thickness and the total surface heat transfer rate for a horizontal heating surface with a length L and a width S are given by [10]

$$\delta_2(x) \simeq 4.2 \left[\frac{\mu\alpha x}{\rho_\infty g\beta K(T_w - T_\infty)} \right]^{2/3} , \tag{5}$$

and

$$q_2 \simeq 1.4 Sk(T_w - T_\infty)^{4/3} \left[\frac{\rho_\infty g\beta KL}{\mu\alpha} \right]^{1/3} . \tag{6}$$

The corresponding expressions for combined free and forced convection about horizontal plane surfaces are given in Ref. 14. The analysis for free convection about horizontal plane surface with axisymmetric temperature distribution is given in Ref. 12.

To gain some feeling of the order of magnitude of various physical quantities given by Eqs. (3) – (6), computations were carried out for a heating surface of 1 km by 1 km at a temperature of 300°C embedded in an aquifer at 15°C. The physical properties used for the computations are $\beta = 3.2 \times 10^{-4}/C$, $\rho_\infty = 0.92 \times 10^6$ g/m^3, C = 1 cal/g-°C, $\mu = 0.18$ g/sec-m, k = 0.58 cal/sec-°C-m, and K = 10^{-12} m^2. With these values, the boundary layer thickness along a dike increases from zero at the origin to 70 m at 1 km with the total heat transfer rate equal to 75 MW. For a horizontal heating surface of the same size, the boundary layer thickness increases from zero at the origin to 200 m at 1 km with a total heat transfer rate equal to 20 MW.

Future Work

Our major effort during the next year will be directed to the modifi-
cations of the existing computer codes for the simulation of the Puna
geothermal area. Recent data from geophysical exploration and well testing
suggest that some of the assumptions made in the computing codes do not
correspond to the conditions that exist at the Puna area. For example, from
the examination of mud loss during drilling and from core samples taken from
the well, it appears that layered structure exists in the rock formation, and
that there is no evidence of a caprock being formed. Analysis of the water
samples taken from the well shows that the groundwater has an extremely low
salinity, indicating that the groundwater is most likely to be of meteoric
origin with little recharge from the ocean. Furthermore, as a result of
geophysical exploration, the geology of the Puna area is now better known.
There is evidence that a magma chamber, about 3 km in diameter exists at a
depth of 5 km under Halemaumau. It is believed that the movement of magma
into and out of the reservoir is accompanied by inflation and deflation of
Kilauea. Intrusive activity, inferred from earthquake activity and extrusive
activity along the Puna rift, are commonly associated with deflation of
Kilauea. Apparently, magma is forced into the reservoir under Halemaumau and
from there moves eastward along the rift. The HGP-A well is located on a
dislocation in the rift zone. The hypothesized magma and groundwater movements
produce a very complex thermal regime. It would be difficult, if not impossible,
to incorporate all of these hypotheses into a single thermal model. Therefore,
it is proposed to modify the existing computer codes by taking into account
the layered structure of the formation, the recharge from the top in the form
of rainfall, and temperature distribution of the bedrock with due consideration
of the rift zone and other hot intrusives. The effect of withdrawal of fluids

in the Puna area will also be studied numerically. Results will be compared with data obtained from drawn-down and build-up tests to predict the characteristics of the reservoir.

For the sake of comparison, a conductive model will also be carried out to show the effect of groundwater movement on the temperature distribution in the reservoir.

Work started early this year on the numerical studies of environmental impact associated with reinjection and withdrawal of geothermal fluids on the Ghyben-Herzberg Lens and coastal waters will be carried to its completion during next year. The results of these studies will have applications to geothermal areas in some other localities in the Island of Hawaii or along the West Coast.

Results of the investigation will be presented in a series of papers which will be submitted for publication to leading scientific and professional journals.

References

1. Cheng, P., and Lau, K.H., "Steady State Free Convection in an Unconfined Geothermal Reservoir," _J. of Geophysical Research_, Vol. 79, 4425-4431, 1974.

2. Cheng, P., and Lau, K.H., "Modelling of Hawaiian Geothermal Resources," _Geothermics_, Vol. 2, 90-93, 1973.

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4. Cheng, P., and Lau, K.H., "The Effect of Steady Withdrawal of Fluid in Confined Geothermal Reservoirs," presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 20-29, 1975, San Francisco, California. To appear in the book, _Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources_ (1976).

5. Cheng, P., "Heat and Mass Transfer in Liquid-Dominated Geothermal Reservoirs," _Letters in Heat and Mass Transfer_, v. 3, 81-88 (1976).

6. Cheng, P., "Numerical and Analytical Studies on Heat and Mass Transfer in Volcanic Island Geothermal Reservoirs." _Proceeding of NSF Workshop on Geothermal Reservoir Engineering and Wall Stimulation_, 219-224, 1975, Stanford University, Stanford, California.

7. Minkowycz, W.J., and Cheng, P., "Free Convection About a Vertical Cylinder Embedded in a Porous Medium." _Int. J. of Heat and Mass Transfer_, v. 19, 805-813 (1976).

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11. Cheng, P., "The Influence of Lateral Mass Efflux on Free Convection Boundary Layers in a Saturated Porous Medium," accepted for publication by _Int. J. of Heat and Mass Transfer_. Hawaii Geothermal Project, Tech. Report No. 13, April 1976.

12. Cheng, P., and Chau, W.C., "Similarity Solution for Convection of Groundwater Adjacent to Horizontal Impermeable Surface with Axisymmetric Temperature Distribution," submitted for publication to Water Resources Research. Hawaii Geothermal Project, Tech. Report No. 14, April 1976.

13. Cheng, P., "Combined Free and Forced Boundary Layer Flows About Inclined Surfaces in a Porous Medium," accepted for publication by Int. J. Heat and Mass Transfer. Hawaii Geothermal Project, Tech. Report No. 15, 1976.

14. Cheng, P., "Similarity Solutions for Mixed Convection From Horizontal Impermeable Surfaces in Saturated Porous Media," accepted for publication by Int. J. Heat and Mass Transfer. Hawaii Geothermal Project, Tech. Report No. 16, 1976.

15. Cheng, P., and Teckchandani, L., "Transient Heating and Withdrawal of Fluids in Geothermal Reservoirs," presented at the Symposium on the Nature and Physical Properties of the Earth's Crust, Vail, Colorado, August 2-5, 1976.

16. Keller, G.V., "Drilling at the Summit of Kilauea Volcano," prepared for NSF, Colorado School of Mines, March 1974.

Budget Worksheet
Numerical Modelling
Task 3.1

October 1, 1976 - September 30, 1977

1. Salaries and Wages $24,790

   Scientific Discipline Personnel

   Faculty Associate, P. Cheng, Professor-
   100% of time for 2 summer months @
   $2924 per month   5,848

   Faculty Associate, K.H. Lau, Associate
   Professor-100% of time for 1 summer
   month @ $2104 per month   2,104

   Administrative Assistant @ $890 per
   month-50% of time for 8 months   3,560

   1 Graduate Assistant, D. Epp @ $982 per
   month-100% of time for 4 months   3,928

   1 Graduate Assistant @ $850 per month-
   50% of time for 12 months   5,100

   1 Graduate Assistant @ $850 per month-
   50% of time for 10 months   4,250

2. Fringe Benefits . . . . $ 2,154

3. Equipment . . . .   -0-

4. Travel . . . . $ 2,000

   Domestic 2,000

   Foreign . . . .

5. Other Direct Costs . . . . $ 4,600

   Supplies and Materials   200

   Publications   900

   Machine Shop Services . . . .

   Computer Services   3,500

6. Indirect charges: 46.00% of Salaries & Wages . . $11,403

                    Total Project Costs $44,947

TASK 3.2

WELL TEST AND ANALYSIS

P. Takahashi, B. Chen, P. Yuen, D. Kihara

(Detailed proposal to be supplied on September 7.)

Budget Worksheet
Well Test & Analysis
Task 3.2

October 1, 1976 - September 30, 1976

1. Salaries and Wages $18,246

   Scientific Discipline Personnel

      Research Associate, A. Seki @ $1026
         per month-100% of time for
         8 months   8,208

      Administrative Assistant @ $890 per
         month-50% of time for 8 months 3,560

      1 Graduate Assistant @ $882 per month-
         50% of time for 8 months 3,528

      Support Personnel
         Pre-Baccalaureate Students 2,950

2. Fringe Benefits . . . . $ 2,595

3. Equipment . . . . $ 4,053

   Rentals   1,000

   Additional Kuster Equipment   2,053

   Spare Parts & Maintenance   1,000

4. Travel . . . . $ 5,780

5. Other Direct Costs . . . . $ 8,300

   Supplies and Materials   1,500

   Publications   800

   Machine Shop Services   500

   Computer Services   2,000

   Other: Contingency   3,500

6. Indirect charges: 46.00% of Salaries & Wages . . $ 8,393

                  Total Project Costs $47,367

TASK 3.3

PHYSICAL MODELLING

P. Takahashi and B. Chen

The physical model is a necessary balance to the ongoing software investigations. The physical model will not only serve as a convenient check on the mathematical model, but will simulate conditions not easily attempted by software. Most of the experimental work on heat transfer in a porous medium has been devoted to the study of the onset of free convection or convection of water at low temperature. None of the reported investigations approached the problem on a total systems basis while considering the high [2012°F (1100°C) for magma, 527°F (275°C) at wellhead] temperatures expected.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. From dimensional analysis, it can be shown that the controlling parameter for free convection in a geothermal reservoir is the so-called modified Rayleigh number which is defined as $\text{mod Ra} = \dfrac{\beta g \Delta T L K}{\alpha \nu}$

where β = coefficient of thermal expansion

α = thermal diffusivity

ν = kinematic viscosity

g = gravitational constant

ΔT = difference in temperature between the reservoir and ocean

L = height of aquifer

It is well known that to insure similarity between the physical and mathematical models and the actual reservoir, the value of the modified Rayleigh number must be the same. The critical Rayleigh number for the onset of free convection in a porous medium bounded by two isothermal plates has been found to be 40 in the literature. Rayleigh numbers a thousand times larger can be expected for some localities on the island of Hawaii.

The physical modelling program has been ongoing for two and a half years now. The program can be divided into three phases: preliminary unpressurized model, preliminary pressurized model, and final pressurized model. The status as of August 31, 1976, can be summarized as follows:

MODEL	SIZE	PRESSURE	TEMPERATURE MAX.	PROBES	STATUS
Preliminary #1	3 ft^3	Atmospheric	212°F	10	completing experimental runs
Preliminary #2	3-1/3 ft^3	200 psi	382°F	23	undergoing tests
Final	30$^+$ ft^3	300$^+$ psi	500$^+$°F	23	design contemplated

The unpressurized models can simulate a geothermal reservoir with Rayleigh number up to 1,000. To simulate a reservoir with a higher Rayleigh number, the pressurized model must be used. In all of these models, glass beads have been used as the porous medium. Temperature measurements are made by resistance temperature detector probes. Heat sources are provided by a Stan-trol heater and controller sensor system which is capable of varying heater surface temperature between ambient and 1800°F. A Sanborn dual channel recorder was used for continuous pressure and temperature measurements. As shown in the table, preliminary models are operational and some measurements have been made to compare the results with numerical modelling. Additional funding is requested to continue the program.

The results of the tests from the physical model should be useful in the following ways:

1) A check can be made of fundamental information. For example, does convection initiate at a Rayleigh number of 40?

2) Data can be obtained to aid the various computer models in refining predictive capability.

3) The concept of geothermal reservoir self-sealing can be investigated.

4) Reinjection can be tested.

5) One of the classical points of contention, "Is a geothermal reservoir an open or closed system?" can be studied.

Budget Worksheet
Physical Modelling
Task 3.3

October 1, 1976 - September 30, 1977

1. Salaries and Wages . . . . $ 9,227

    Scientific Discipline Personnel

        Faculty Associate, B. Chen, Associate
            Professor-100% of time for 1 summer
            month @ $2276 per month   2,276

        Faculty Associate, P. Takahashi,
            Associate Professor-100% of time for
            1 summer month @ $2276 per month   2,276

        1 Graduate Assistant @ $850 per month-
            50% of time for 11 months   4,675

2. Fringe Benefits . . . . $ 335

3. Equipment . . . . $ 4,000

4. Travel . . . . $ 1,000

    Domestic   1,000

    Foreign . . . .

5. Other Direct Costs . . . . $ 5,000

    Supplies and Materials   1,000

    Publications   500

    Machine Shop Services   500

    Computer Services   1,000

    Other: Contingency   2,000

6. Indirect charges: 46.00% of Salaries & Wages . . $ 4,244

                    Total Project Costs $23,806

TASK 4.1

GEOTOXICOLOGY

B. Siegel and S. Siegel

The following program is proposed as a continuation of our current
research and monitoring activities concerned with emission of mercury and
other toxic elements at natural and man-made geothermal vents. This proposal
is specifically based upon a follow-up to the projected well-flowing experiment
to begin in October 1976. It is also designed in recognition of the signif-
icantly higher instantaneous mercury levels noted during the well-flashing
experiment of 22 July 1976. We are less concerned with the specific values
for atmospheric mercury found at that time than we are with the upward trend
in these air values over previous measurements.

During October 1976, two field measurements will be obtained; the first
will be during the initial phase of well-flowing, and the second after
approximately 3-4 weeks. Our measurements to date indicate that mercury is
being injected into the atmosphere and, at least, in part being returned to
the land surface in the general drill site area. Gaseous forms of mercury
can be absorbed directly by vegetation via leaves and other surfaces; fall-
out mercury may re-enter the aquifer by percolation, but in view of the heavy
ground cover can also be absorbed by roots and soil microbiota. Therefore,
in addition to continuing surveillance with respect to air mercury, we believe
it is necessary to resume soil and plant analyses. It should be remembered
that we have already completed base-line measurements on soil and vegetation
samples in and around the drill site; it, therefore, should be possible to
determine over the year following the projected well-flowing whether or not
there are in fact environmental consequences of geothermal mercury. This will

be accomplished during four intensive field trips to the Hawaii Geothermal Site, distributed over the 10 to 12 months following the reopening of the test well.

During these field studies, samples of air, waters, soil, and indicator plants (particularly nut grass, staghorn fern and ohia) will be collected. Following previous practice, comparative samples will also be taken at the fumarole and caldera sites in Hawaii Volcanoes National Park. The Park sites have been the object of sampling in our research since 1971, hence we have excellent background concerning mercury emission there.

At the same time we will continue to carry out fixed-gas aerometry emphasizing SO_2, H_2S, and CO. Our base line data with respect to SO_3 emission taken during the experimental flashing on 22 July fell below the detection level, but its recognized potential as a toxicant warrants further determinations and will, therefore, be included in our field measurements. Finally we expect to have the capability for selium determinations within the next few months and this element which appears in nature in relatively volatile form will also be measured. Whether or not a comprehensive program of selenium analysis is needed will depend upon preliminary measurements seeking to relate its presence to sulfur compounds and mercury. We believe that mercury, because of its distinctive thermodynamic properties both in the free and combined forms, may prove to be the best index for the general assessment of emission of the heavier toxic elements.

It should be pointed out that although one of our principal objectives has been and continues to be the environmental impact of emissions both at natural and man-made vents, we are at the same time developing from these studies new and scientifically valuable data in the field of biogeochemistry and geobiology.

Hawaii Geothermal Project

Budget Worksheet

Geotoxicology - Task 4.1

1. Salaries and Wages . . . . $ 5,211

   Scientific Discipline Personnel

        Faculty Associate, B. Siegel, Associate Professor,
            100% of time for 1 summer month @ $2444 per
            month   2,444

        Faculty Associate, S. Siegel, Professor, 50%
            of time for 1 summer month @ $3333 per month . . .   1,667

        Support Personnel – Pre-Baccalaureate students   1,100

2. Fringe Benefits . . . . $ 52

3. Equipment . . . . $ 990

   Ion Electrodes and Accessories for arsenic studies   330

   Ion Electrodes and Accessories for selenium studies   330

   Ion Electrodes and Accessories for mercury studies   330

4. Travel (domestic only) . . . . $ 1,500

5. Other Direct Costs (supplies only) . . . . $ 900

6. Indirect Charges: 46% of Salaries and Wages . . . . $ 2,397

        Total Project Costs $11,050

PUBLICATIONS

The list below summarizes the publications produced during the course of the Hawaii Geothermal Project by the Geophysical Program.

Journal and Monograph Articles

A.T. Abbott. Imagery from infrared scanning of the east and southwest rift zones of Kilauea and the lower portions of the southwest rift zone of Mauna Loa, island of Hawaii. In Utilization of Volcano Energy, Proceedings of a Conference held at Hilo, pp. 10-12, 1974.

John L. Colp and Augustine S. Furumoto, editors, Utilization of Volcano Energy, Proceedings of a Conference held at Hilo, Hawaii. 680 pp, publ. by Sandia Corp., Albuquerque, N.M., 1974.

Druecker, M., and Fan, Pow-foong. Hydrology and geochemistry of groundwater in Puna, Hawaii. Groundwater. Sept-Oct. 1976 (in press).

A.S. Furumoto, Geophysical Exploration on the Structure of Volcanoes: Two Case Histories, in Utilization of Volcano Energy, Proceedings of a Conference Held at Hilo, p. 41-58, 1974.

A.S. Furumoto, Using Volcanoes. Physics Bulletin, vol. 25, p. 287, 1974.

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A.S. Furumoto, A Coordinated Exploration Program for Geothermal Sources on the Island of Hawaii. In Proceedings of Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, in press.

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A.S. Furumoto and K. Yuhara, On the Status of Research Leading toward Volcano Energy Utilization. Critical Reviews in Environmental Control. In Press.

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