Research Proposal to the Geothermal Division
Energy Research and Development Administration

from

University of Hawaii
Honolulu, Hawaii 96822

ANALYSIS OF HGP-A
REVISED PROPOSAL
Extension to Contract E(04-3)-1093

Amount Requested: $270,248
Proposed Duration: One Year
Requested Starting Date: October 1, 1976
Submittal Date: October 7, 1976

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Hawaii Geothermal Project - Phase II

Analysis of HGP-A

TABLE OF CONTENTS

Page

GEOSCIENCES

ENGINEERING

ENVIRONMENTAL

HAWAII GEOTHERMAL PROJECT - PHASE II

ANALYSIS OF HGP-A

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 conditions, develop correlations on the reliability of the various methods of prediction. Monitoring activities associated with emission of mercury and other toxic elements will be continued. 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 modelling, from drilling, from well testing -- will contribute to a more complete understanding of the geothermal regime associated with this well.

Progress has been initiated on the analysis of HGP-A, including preliminary well testing, during the three-month transition period with $104,464 in ERDA support. Tasks to be completed in the twelve-month FY 77 study described in this proposal, and a related budget for each, are listed below:

	ERDA Support	Direct State Support
Management and Support	$25,000	
Geosciences:		
2.1 Coordination	24,976	
2.2 Magnetics and Gravity Studies	10,015	
2.3 Seismic Studies	25,938	
2.4 Geoelectric Surveys for Geothermal Prospects	12,000	
2.5 Petrography, Petrology and Geochemistry	21,594	
2.6 Hydrology and Hydrothermal Geochemistry	16,408	
2.7 Physical Properties of Rocks	19,994	
Engineering:		
3.1 Numerical Modelling	23,000	
3.2 Well Test and Analysis	50,273	66,405
3.3 Reservoir Engineering	30,000	
Environmental:		
4.1 Geotoxicology	11,050	
TOTAL	$270,248	$66,405

The total budget requested for FY 77 to complete analysis of HGP-A is $336,653, with $66,405 of direct support -- as well as the salaries for many of the researchers and administrative staff contributing to the project -- coming from the State of Hawaii. This raises the total of direct State support to the HGP above $775,000.

Narrative summaries and complete budgets for each of the tasks follow.

TASK 1.1
MANAGEMENT

John W. Shupe

The Hawaii Geothermal Project (HGP) is a complex project, which has received financial support to date totaling $3,164,000 from six major funding sources within Federal, State, and County government and the private sector. Paid consulting services have been provided both by mainland experts and the New Zealand firm, KRTA. Uncompensated advice -- both solicited and unsolicited -- has come from many sources, and much of the advice in both categories has been of value. Conducting the research tasks have been over forty researchers and support staff from throughout the University of Hawaii system, involving faculty from campuses on both the islands of Oahu and Hawaii, and cutting across thirteen different academic departments, colleges, and institutes. An eighteen-person Hawaii Advisory Board was established and has played an active role in the Project, as has a ten-man National Liaison Board and a seven-man Executive Committee.

As Principal Investigator and Director of the HGP, my primary responsibilities and those of the Management Program during the first three years of the Project have been to serve as a communication link among all interested parties, both on and off campus; to coordinate and provide support services for the various research programs; and to identify sufficient funding to keep the Project moving. These activities will continue as the major responsibilities of the Management Program through FY 77.

From the beginning, the HGP has had not only a strong research orientation appropriate to a univeristy program, but also a definite promotional or developmental component. In endeavoring to fulfill the management requirements in these dual areas, examples of typical duties have included: 1. Resolving differences between University, State, and ERDA bureaucracies, as well as the New Zealand consultant and local drilling contractor in finalizing the drilling subcontract; 2. Serving as a "huckster" to promote additional funding both from public and private sources after each incremental "disaster" -- running out of drilling funds with 5/6ths of the depth of the hole left -- or "success" -- encountering high downhole temperatures; 3. Operating the master valve to control HGP-A, as one of four rather startled and very inexperienced University staff who first flashed the well on the night of July 2, 1976; and 4. Giving talks on the HGP in Washington, LASL, Palm Springs, Idaho Falls, Lake Tahoe, San Francisco, Honolulu (fourteen times), Hilo, and Kona.

In addition to speaking to these groups with energy related interest, I have also discussed various aspects of the project with many individuals -- particularly since the well began to look interesting in the early summer. Within the last five months, a partial list of representatives of organizations with whom I have discussed the HGP include:

ERDA - Washington (7)
ERDA - San Francisco (8)
ERDA - Las Vegas (2)
ERDA - Oak Ridge (2)
INEL (3)
LASL (3)
LBL
USGS (4)
Sandia (2)
Congressional delegates and staff (9)
State legislators and staff (8)
State Energy Resources Coordinator and staff (3)
Department of Land and Natural Resources -- regulations (3)
Director of Office of Environmental Quality Control
KRTA and their DSIR and MOW advisors (5)

Stanford University (3)
Colorado School of Mines
Water Resources International, Inc. (4)
Hawaiian Electric Company (4)
Hawaii Electric Light Company (2)
EPRI
Battelle Northwest (2)
Chevron (2)
Shell
Union (2)
Republic Geothermal
TRW (4)
Rogers Engineering
Banking, financial, and developmental institutions (5)
Miscellaneous visitors from the mainland U.S., Japan, Taiwan, the Philippines (13)
News media; radio, TV, and newspaper (8)
University Office of Research Administration (2)
University Office of Procurement and Property Management
Research Corporation of the University of Hawaii (2)
HGP associates (21)

In addition, there has been an exchange of correspondence with dozens of unsolicited inquiries running all the way from general information for help in writing an eigth-grade science term paper to applications for employment, catalogs of energy conversion options, interest in subsequent drilling, etc. There have been many periods over the past year when I have devoted essentially full time to this project, and conservatively have averaged 20 hours a week on the HGP. During FY 77 I intend to spend an equal amount of effort in the overall coordination and promotion of geothermal development, even though I am not listed on the ERDA budget. I can rationalize that the State and University have sufficient benefit to gain from the project to support my involvement. With the well and interest both warming up, the level of my involvement would have to increase except for the fact that this administrative load has begun to be shared with Dr. Helsley. I am most grateful that he has both the background and the interest to assist in this effort.

Specific duties of the Management Program include budget preparation, analysis, and monitoring; liaison between HGP researchers, University offices, and all off campus contacts; coordination, preparation, and dissemination of information on the HGP -- including reports and publications; and maintaining overall supervision and the flow of correspondence essential to a complex multimillion dollar research-development program. To assist in this effort is one able administrative assistant, who receives help during peak periods of budget or proposal preparation from staff of the Center for Engineering Research.

Management's proposed budget includes only this full-time administrative assistant, with related fringe benefits and indirect costs; two trips to the mainland for the Principal Investigator; the costs of printing two major publications -- a comprehensive report of the drilling program and a tentative final Project report; and miscellaneous expenses including supplies, communications, and xeroxing.

In addition to the analysis of HGP-A, parallel activity will proceed on: 1) The installation of a suitable wellhead generator at the HGP-A site; 2) The verification of the extent of the Pahoa geothermal field through additional drilling; and 3) Exploration of other potential geothermal sites on the Big Island, Oahu, and possibly Maui. I intend to continue to take an active role in the identification and implementation of appropriate alternatives for developing geothermal power in Hawaii.

BUDGET

Task 1.1 -- Management

1. Salaries and Wages	$10,380
Support Personnel:	
Administrative Assistant, 100% of time for 9 months @ $857/mo., 3 months @ $889/mo.	10,380
2. Fringe Benefits	2,387
3. Equipment	-0-
4. Travel (domestic only)	1,070
5. Other Direct Costs	6,388
Supplies and materials	360
Publications	4,000
Other: communications, xeroxing, miscellaneous	2,028
6. Indirect Charges: 46.00% of Salaries and Wages	4,775
TOTAL PROJECT COSTS	$25,000

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 understanding 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 attempted 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.

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.

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

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.

A.S. Furumoto, Geothermal Exploration on the Island of Hawaii. Jour. of the Japan Geothermal Energy Assoc., vol. 12, no. 4, p. 29-36, 1975 (in Japanese).

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

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

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

McMurtry, G., Fan, Pow-foong and Copelen, T., Chemical and isotopic investigation of groundwater in potential geothermal area in Hawaii. Am. Jour. Sci. 1976 (in press).

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

Technical Reports

D.P. Klein and J.P Kauahikaua. Geoelectric-geothermal exploration on Hawaii Island; preliminary results. Hawaii Inst. of Geophys. Report, HIG-75-6, 23 pp, 1975.

Hawaii Geothermal Project, Summary Report for Phase I, May 1975.
- A.S. Furumoto: A narrative of the exploration prog. p. 16-29.
- A.T. Abbott: Photogeologic Survey; Imagery from infrared scanning of the rift zones of Kilauea and Mauna Loa, p. 29-32.
- D.P. Klein: Geoelectric surveys on Hawaii 1973-75, p. 32-47.
- A.S. Furumoto: Electrical resistivity survey conducted by G.V. Keller, p. 48-49.
- A.S. Furumoto and D. Klein: Gravity survey to determine dike complex size, p. 50-53.
- R. Norris and A.S. Furumoto, Puna magnetics, p. 54-59.
- J. Halunen and D. Epp, Well temperature survey, p. 59-62.
- W. Suyenaga: Results of the microearthquake survey and seismic studies of the lower east rift, p. 62-66.
- R. Norris and W. Suyenaga: Ground noise survey, p. 66-68.
- P.F. Fan: Geochemical studies, p. 68-74.
- A.S. Furumoto: Integration of geophysical data, p. 74-80.

Hawaii Geothermal Project, Initial Phase II Progress Report, Feb. 1976.
- A.S. Furumoto, R. Norris, M. Kam and C. Fenander: Gravity profile and the intrusive zone, p. 26-31.
- R. Norris: Puna magnetics, p. 32-35.
- W. Suyenaga and M. Broyles: Puna seismology, p. 36-38.
- D. Epp and J. Halunen: Well temperature survey, p. 39-44.
- R. Buddemeier, P. Kroopnick, and L.S. Lau: Hydrology, p. 45-49.
- M.H. Manghnani, C.S. Rai and T. Hanada, Physical properties of rocks, p. 50-62.
- D.P. Klein, J. Kauahikaua, E.T. Sakoda, Geoelectric surveys, p. 63-71.

Manuscripts

G.V. Keller "An electrical resistivity survey of the Puna and Kau Districts Hawaii County, Hawaii". 100 pp.

W. Suyenaga, The shallow seismic structure of the east rift zone of Kilauea, Hawaii.

W. Suyenaga, Microearthquake survey in Puna, Hawaii.

W. Suyenaga, Microearthquake survey at Waimanalo, Oahu, Hawaii.

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

Task 2.1 - Coordination

A.	Salaries and Wages		
	1. Support personnel		
	a. Research Associate (8 mos.)	$7,112	
	b. Electronics Technician (5 mos.)	5,130	
	TOTAL SALARIES AND WAGES		$ 12,242
B.	Fringe Benefits		2,693
C.	Equipment		-0-
D.	Travel		
	1. Domestic (East coast meeting)		760
E.	Supplies		-0-
F.	Publications		
	1. Six volumes @ $400 ea.	2400	
	2. Drafting charges	450	
	TOTAL PUBLICATION COSTS		2,850
G.	Other Costs (Communications, xerox, car rental, etc.)		800
H.	Total Direct Cost		19,345
I.	Indirect Costs (46% of Salaries and Wages)		5,631
J.	Total Costs		$ 24,976

TASK 2.2

Magnetics and Gravity

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 two parts to this task, the magnetic part is in the stage of manuscript writing. The gravity part is presently incorporating data from the logs and core samples of HGP-A to obtain more constrained interpretation.

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 has been prepared for a journal article.

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 subsurface 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

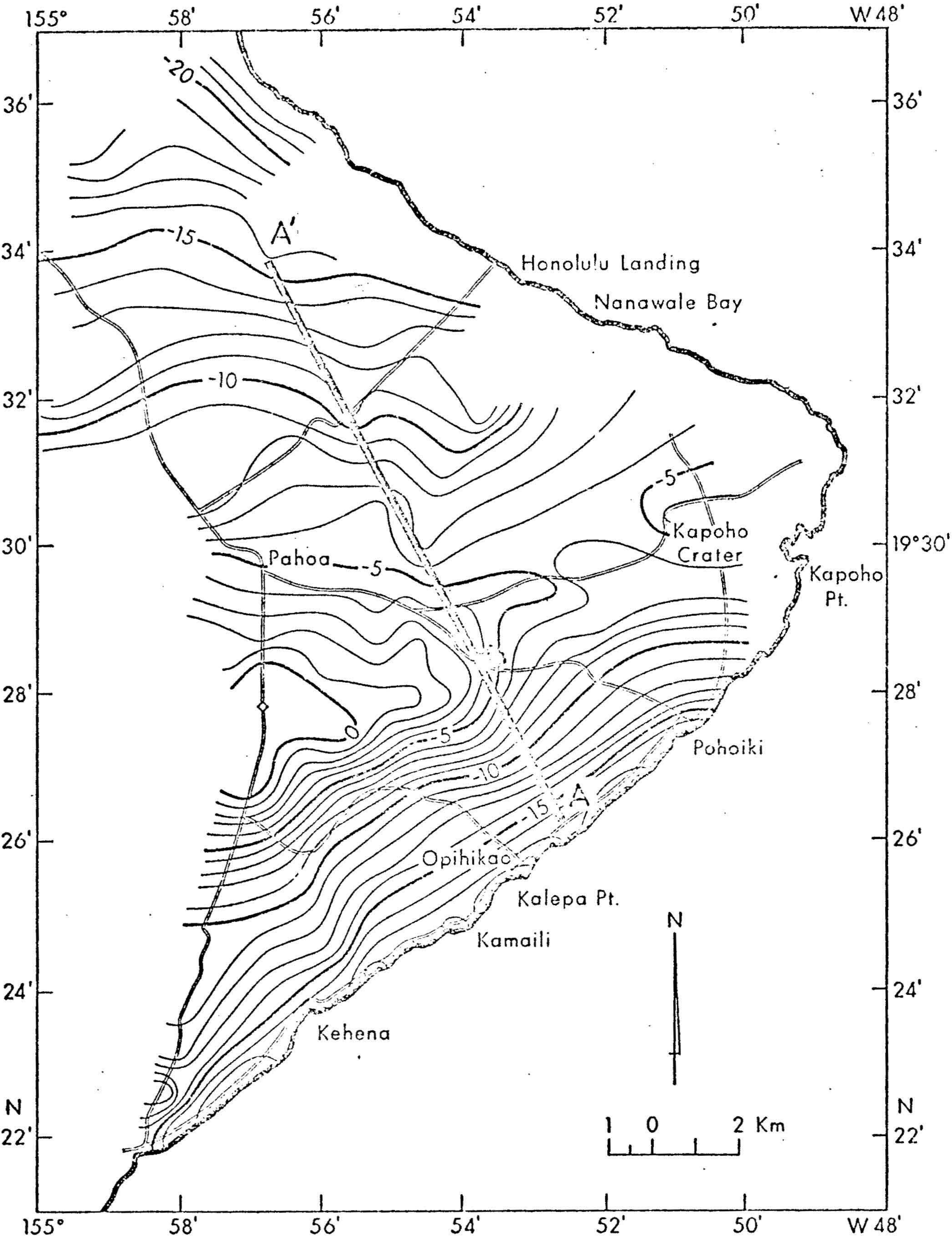


Figure 1. Bouguer gravity map of Puna area island of Hawaii. The highest value has been arbitrarily set at zero. Triangle shows site of HGP-A well.

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 interpreting 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

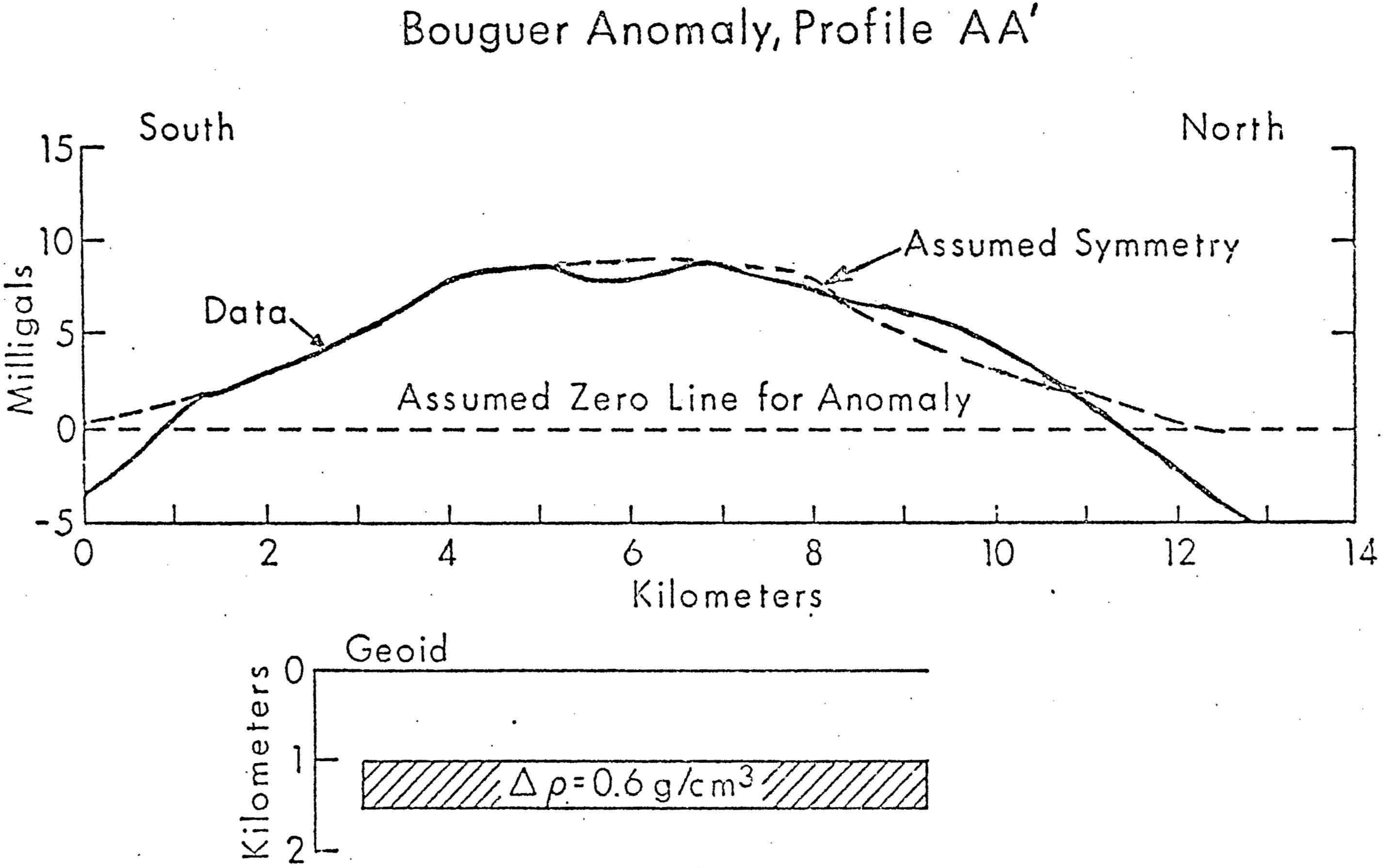
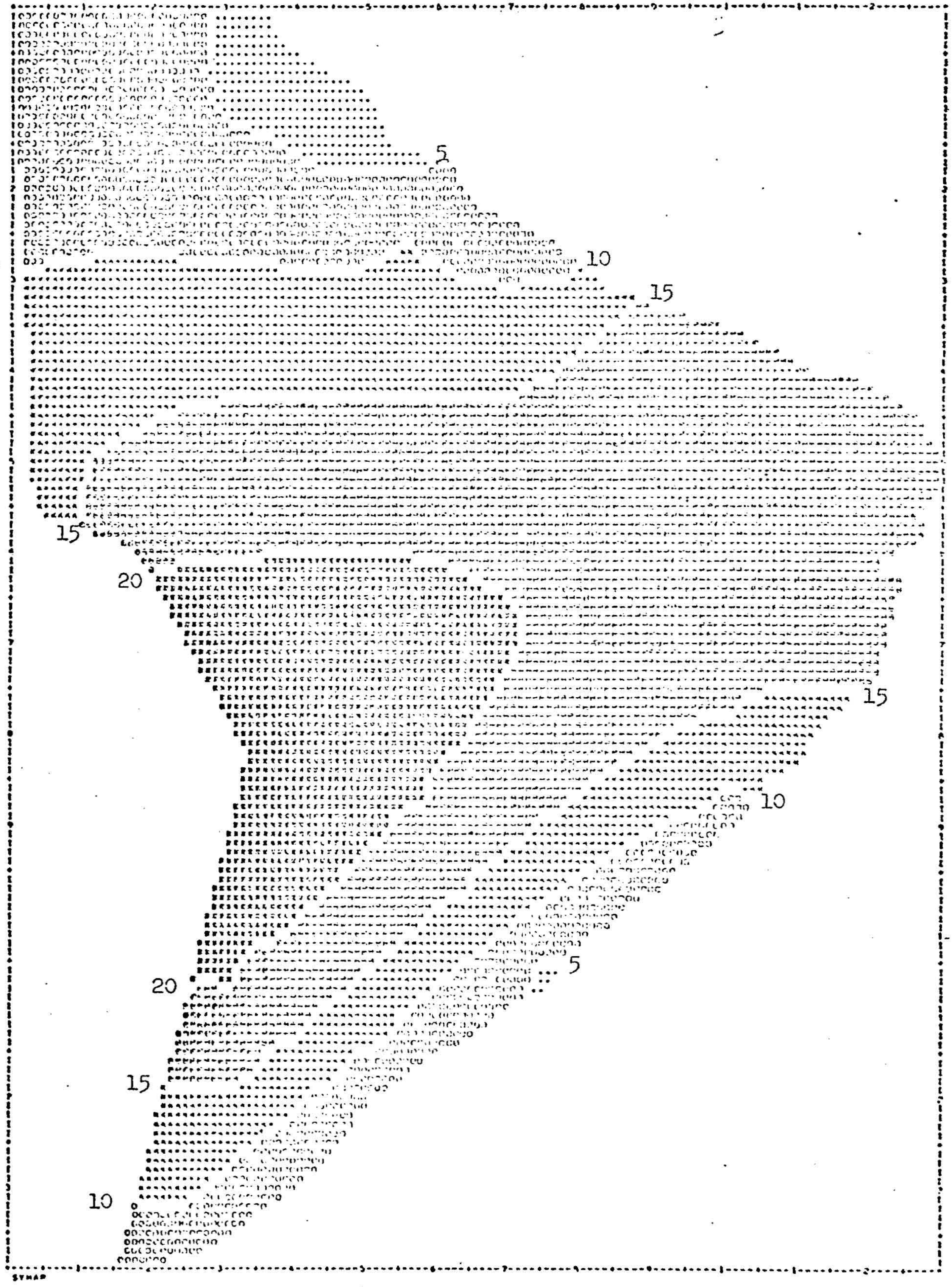


Figure 2. Profile along AA' of previous figure and its associated anomaly.



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SYMAP

C    TREND SURFACE CONTOUR MAP OF BOUGUER II - HAND CONTOURED GRID
C    THIRD ORDER POLYNOMIAL
C    GRAVITY SURVEY - JUNE, 1975 BY A. S. FURUMOTO ET AL.
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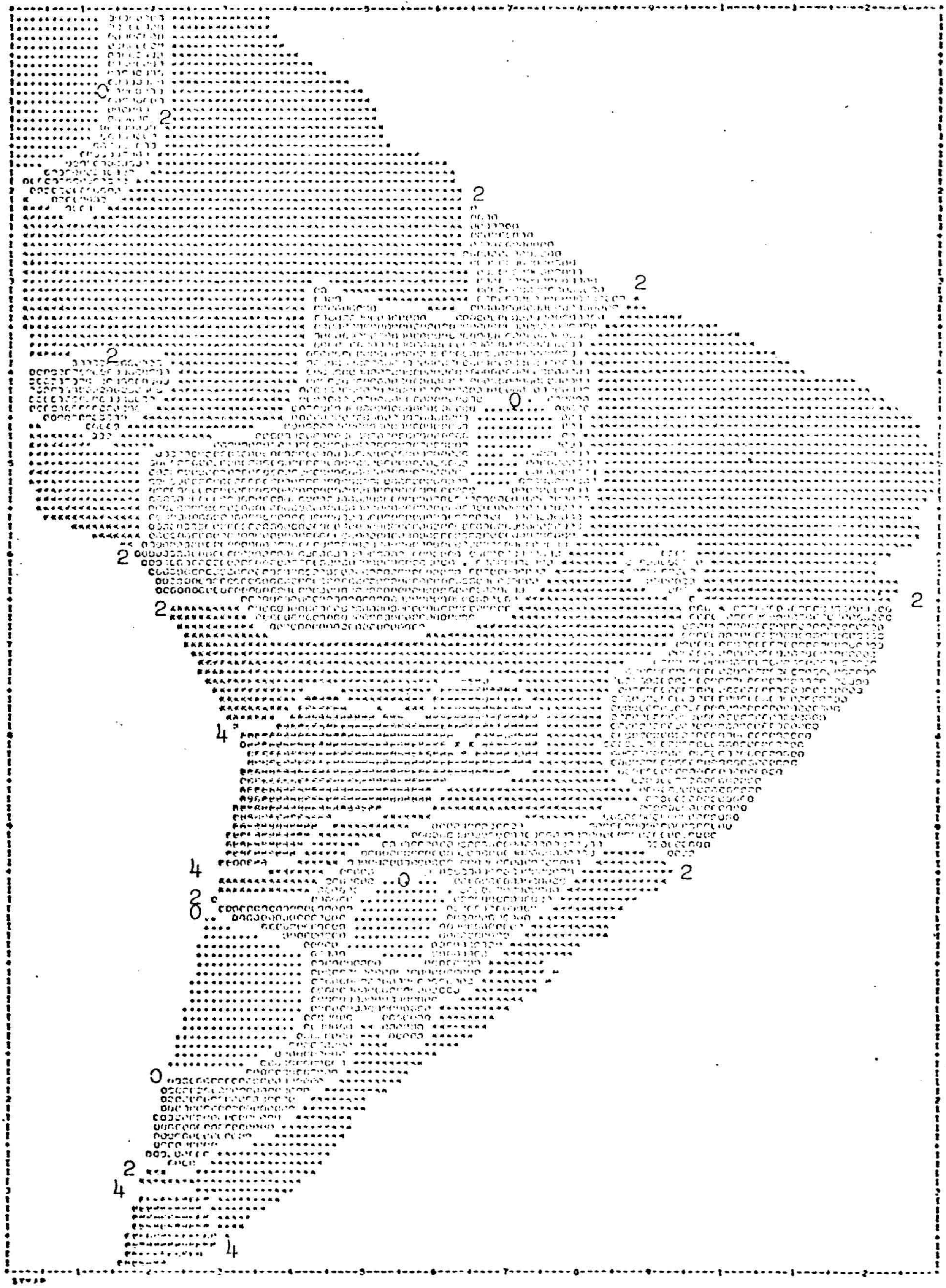
Figure 3. Contour of the third order polynomial trend surface of the Bouguer gravity data. The contours are in 5-milligal intervals.



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C    RESIDUAL SURFACE CONTOUR MAP OF BOUGUER II - HAND CONTOURED GRID
C    THIRD ORDER POLYNOMIAL
C    GRAVITY SURVEY - JUNE, 1975 BY A. S. FURUMOTO ET AL.
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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.

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 characteristic 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.

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BUDGET

Magnetics, Gravity and Thermal Budget Studies - Task 2.2

A.	Salaries and Wages		
	1. R. Norris, Research Assoc. (4-1/2 mos. @ $1227/mo.)		$ 5,521
B.	Fringe Benefits		1,214
C.	Equipment		-0-
D.	Travel		
	1. Domestic (West coast meeting)		390
E.	Other Costs		
	1. Supplies and materials	200	
	2. Publication, drafting	150	
	TOTAL OTHER COSTS		350
F.	Total Direct Costs		7,475
G.	Indirect Costs		
	(46% of Salaries and Wages)		2,540
H.	Total Costs		$ 10,015

Task 2.3

Seismic Studies

A. S. Furumoto

Seismic methods, both active and passive, have been used to estimate the subsurface structure of the intrusive zone or dike complex under the east rift of Kilauea. In the period 1974 to 1976 three types of seismic studies were carried out: (1) microearthquake monitoring using a network of seven stations, (2) a ground noise survey, (3) short traverse seismic refraction surveys. During the coming year we propose to make a long traverse seismic refraction survey to determine the deeper subsurface structure of the Puna rift zone.

I. RESULTS OBTAINED TO THE PRESENT

(1) Microearthquake monitoring.

Summaries of the microearthquake monitoring project with details on field procedure, instrumentation and methods of analysis have been presented by W. Suyenaga in the Hawaii Geothermal Project, Summary Report for Phase I and the Initial Report for Phase II. We shall repeat here only the essential parts of these results. Figure 1 shows the deployment of seismic stations (black dots) and the epicenters of the microearthquakes that were located (numbers indicate depths of foci). Observations were made over a 3 week interval in which thirty nine earthquakes were located by the network in the nearby area.

A plot of foci distribution of the earthquakes against the plane AA' of Figure 1 is shown in Figure 2, together with the velocity structure which was used to determine the foci of the earthquakes. The velocity structure was published by Hill (1969), and although it probably represents the flank of the volcano just to the south of the rift zone, it was used in the absence of any other information. In the careful analysis for epicenter and foci determinations, Suyenaga did make allowance for higher velocities along the trend of the east rift (see Suyenaga's comments in Summary Report Phase I and Initial Report Phase II).

As seen in Figure 2, the majority of earthquakes are confined to a narrow zone (5 km) paralleling the surface expression of the east rift zone and occurs at depths shallower than 5 km. Deeper earthquakes tend to align themselves along a plane dipping to the south. Geophysicists from Microgeophysics Inc., who carried out a similar seismic survey in the general area for a commercial firm have informed us that earthquakes deeper than 5 km have a first motion compatible with a normal faulting mechanism along a plane dipping 45° to the south or faulting along its conjugate plane, and that the shallower earthquakes have a different mechanism. We infer that the shallower earthquakes are associated with the dike complex and we notice that all shallow earthquakes fit within the area of the dike complex derived from gravity data of Task 2.2. The earthquakes deeper than 5 km are associated with a tectonic process that may or may not be related to the dike complex. One possible hypothesis is that the deeper earthquakes are indications of gravity slumping of the south flank of Kilauea. On the other hand, the magnitude (7.2) of the Kalapana earthquake of November 29, 1975, (19°20'N, 155°02'W) which had similar mechanism as the deeper

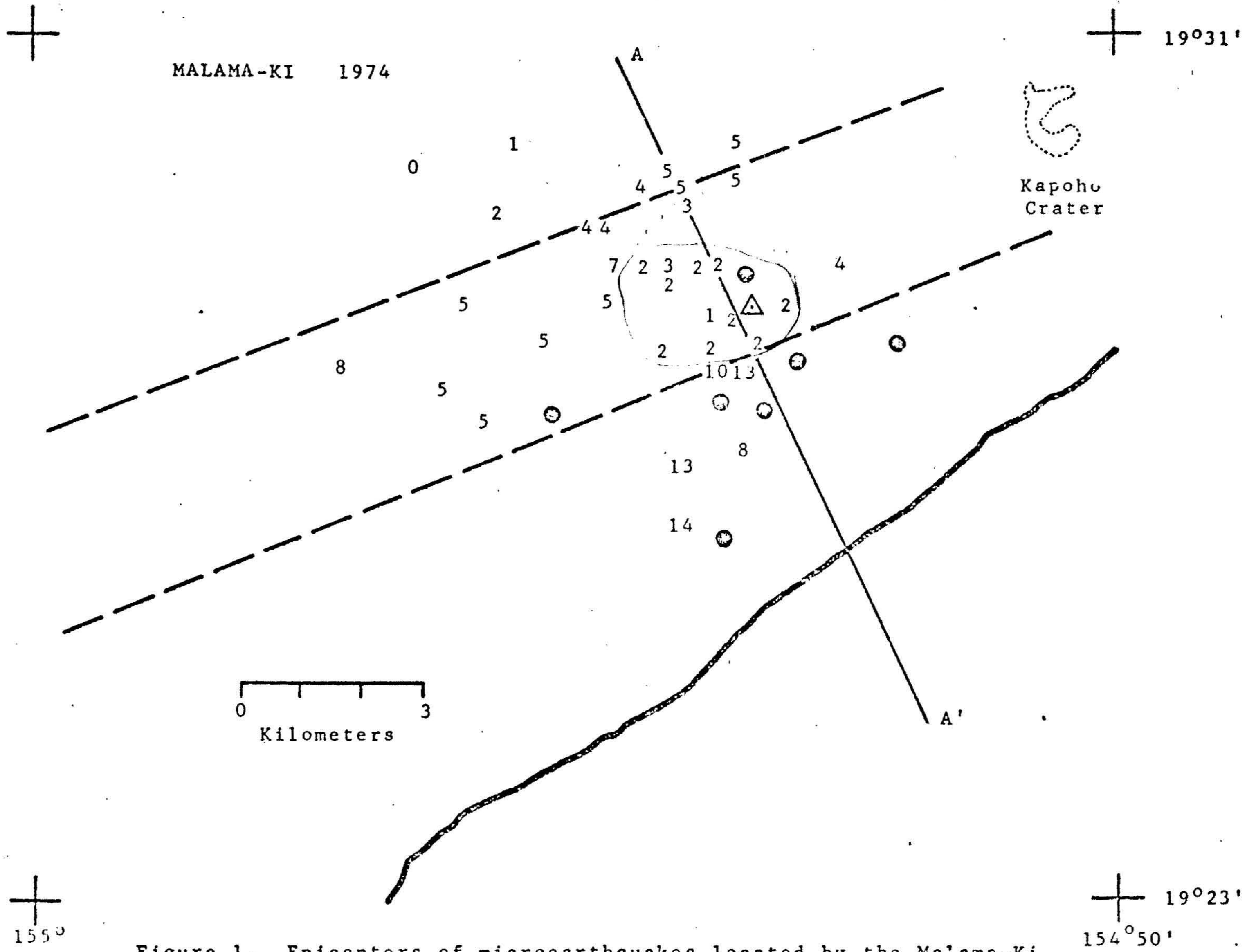

Figure 1. Epicenters of microearthquakes located by the Malama-Ki array, August-September, 1974. Dots are seismometer locations. Numbers on epicenters indicate depth in kilometers. Dashed lines indicate approximate boundary of the surface expression of the rift zone. Triangle shows site of the HGP-A well.

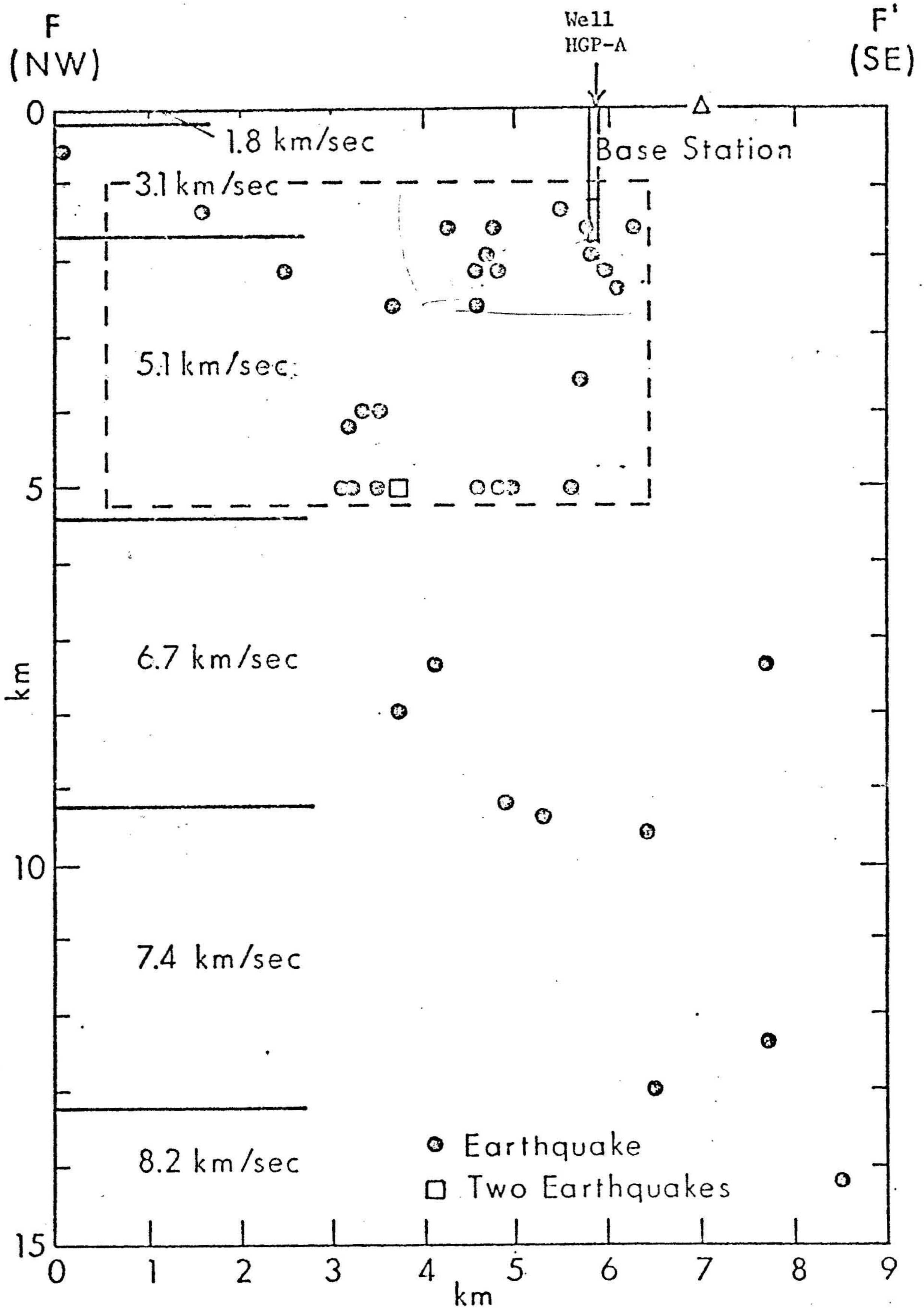

Figure 2. Foci of earthquakes projected on plane AA'. Broken line shows dike complex by gravity data.

earthquakes, strongly suggests a tectonic process far more powerful than mere gravity slumping of a mountain flank.

The earthquakes with depths shallower than 3 km tend to cluster in the vicinity immediately to the west of the site of HGP-A. The clustering suggests a region of shallow activity, perhaps associated with the geothermal reservoir penetrated by the well.

In summary the microearthquake project contributed to the delineation of the structure of the dike complex under the east rift. It strongly supports the hypothesis that a dike complex is present beneath the east rift and suggests that the base of this zone is at a depth of about 5 km. Moreover, it revealed a region of shallow activity that may be associated with the geothermal reservoir.

(2) Ground Noise Survey.

Field work for the ground noise survey was done in 1974 and a report of the results has been presented in the Summary Report for Phase I of the Hawaii Geothermal Project, pp. 66-68. In brief a mobile unit occupied 59 measurement stations through out the Puna area while the microearthquake monitoring was in continuous operation. Recordings from the microearthquake stations were used as a reference to eliminate transient phenomena such as wind and surf effects. Cultural noise was a minimal annoyance, as the Puna area is sparsely populated.

In data processing, attempts were made to eliminate all conceivable transient effects so that the spatial variations in the time invariant background noise could be understood. In analysing the data, we subjected the tape recorded signals to narrow band pass filtering and measured the mean square vertical velocity of the ground motion within each band pass.

Although many bands of filtering were tried, and the results will be published as a series of maps for each band pass filtering, we shall limit our presentation to the 4 hz band, as shown in Figure 3. Reasonably defined moderate high areas of 9 db were found which surround the drill site of GHP-A. The ground noise high areas also overlap the low resistivity area found by electrical studies and the cluster of very shallow earthquakes located by the microearthquake team.

(3) Short Traverse Seismic Refraction Survey

A short seismic refraction survey was carried out in the Puna area to outline the shallow structure of the dike complex under the east rift (Suyenaga, 1976). Because of environmental considerations, the charge size of the explosives were kept small, this in turn limited the length of the traverses. One traverse was done along the trend of the east rift, the other was normal to it. The locations of the traverses are shown in Figure 4.

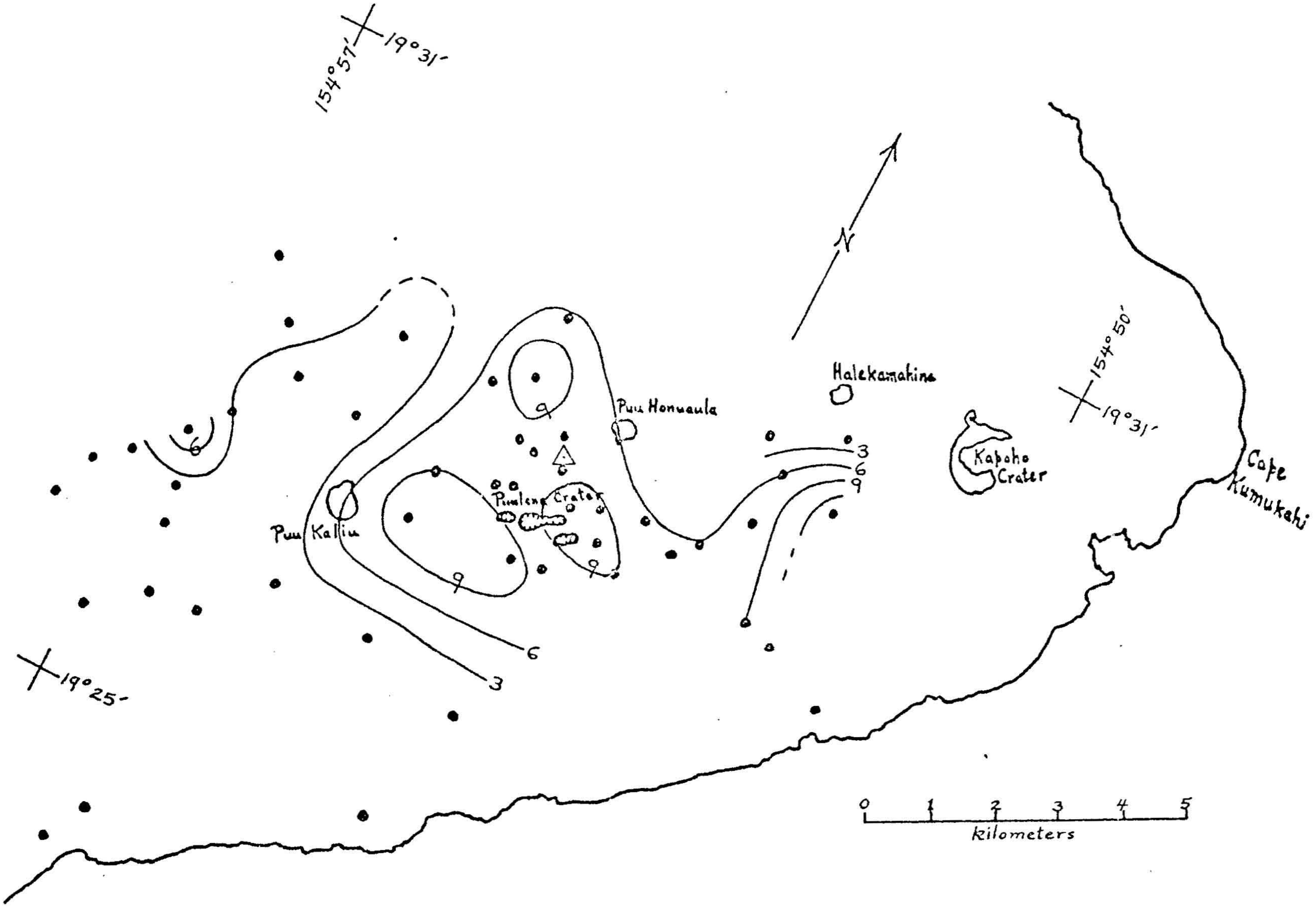

Figure 3. Ground noise level contours in the 4 hz band. The contours are in 3 db levels. The triangle indicates the HGP-A well site. Dots indicate ground noise station locations.

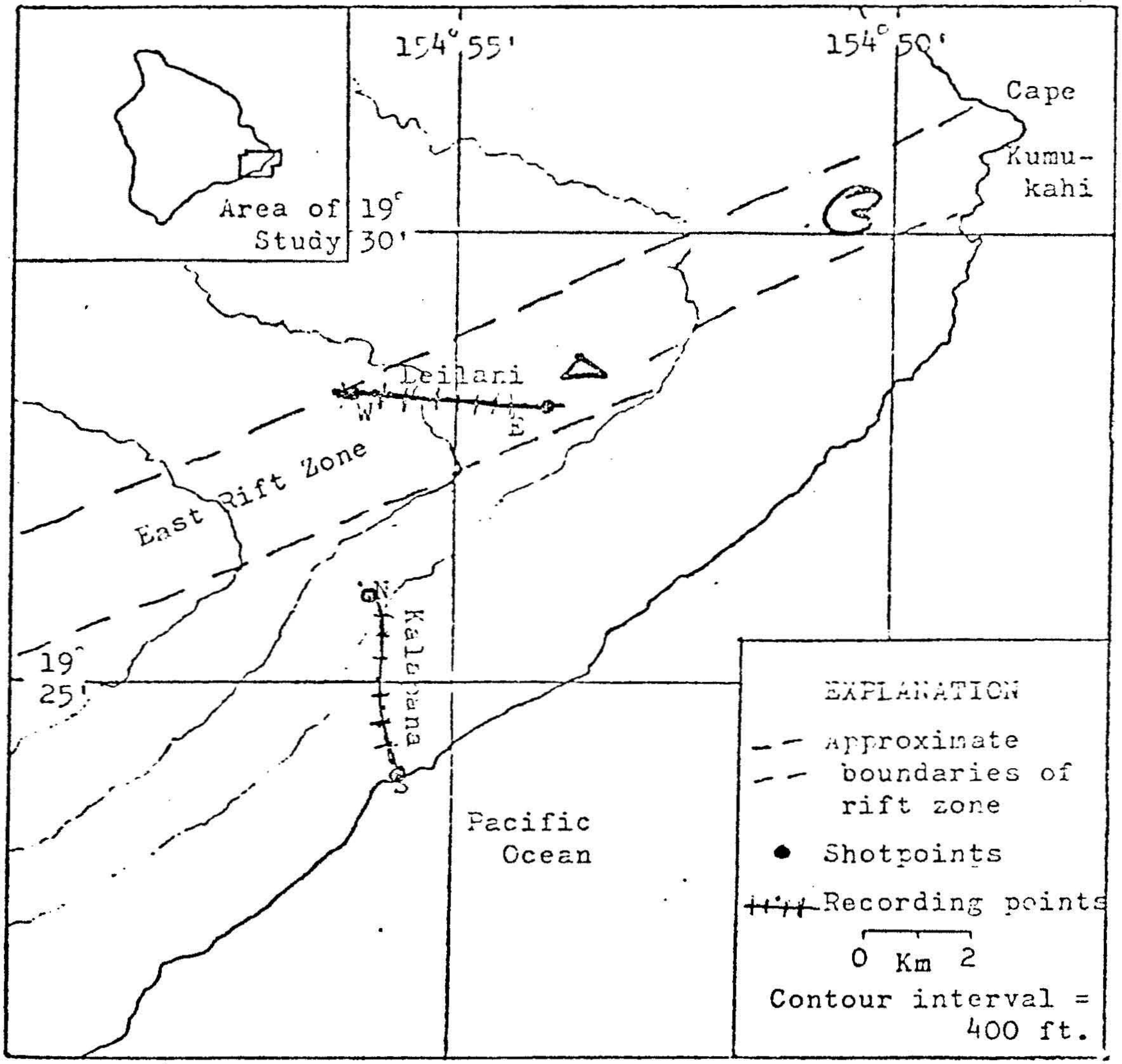

Figure 4. Locations of short traverse seismic refraction lines. Leilani and Kalapana. The triangle indicates HGP-A well site.

The traverse over and along the east rift was named "Leilani" as it was located in a housing subdivision by that name. The travel time plot is shown in Figure 5. The recordings close to the shots show very low velocities, indicative of high porosity of surface layers. The branches of 2.51 km/sec and 3.86 km/sec were put together to give a layer velocity of 3.1 km/sec. No attempt was made to interpret the arrivals on the eastward branch at 3 km for these arrivals are probably due to lateral structural changes, perhaps the encountering of a dike.

The traverse normal to the rift zone was called "Kalapana", its travel time plot is shown in Figure 6. The curves look more conventional than those of the Leilani line.

Velocity depth profiles of the two lines are shown in Figure 7. The Leilani profile shows a steeply dipping 3.1 km/sec layer. Since the traverse was over a dike zone, this result is not unexpected. The Kalapana line shows plane layers. The deepest layer, the 2.9 km/sec layer is probably the same as the 3.1 km/sec layer detected by Hill (1969). Hill placed the layer at a depth of about 200 m, because he had chosen 1.8 km/sec arbitrarily as the velocity of the first layer. Our survey shows that the first layer of Hill is

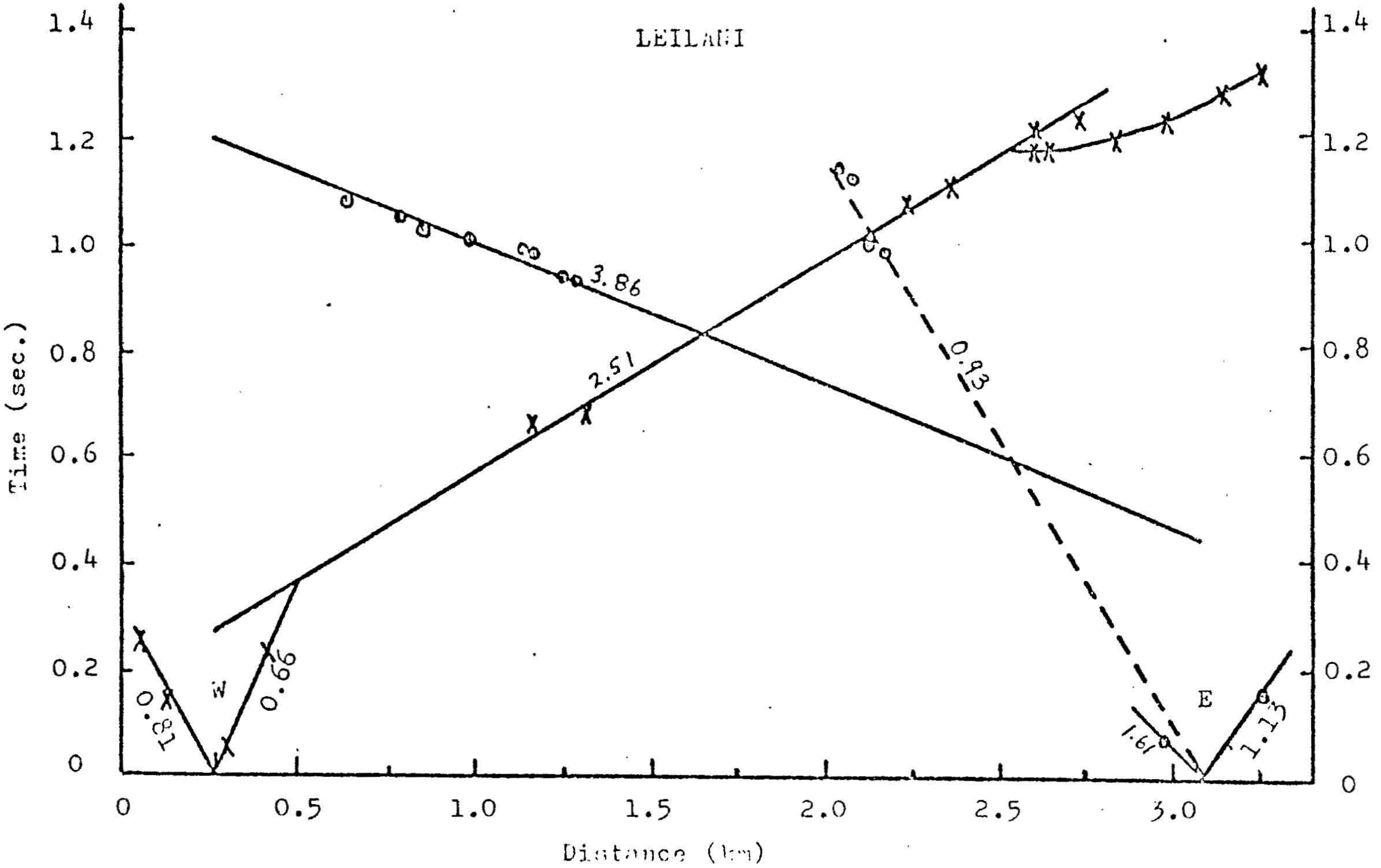

Figure 5. Travel time plot of line Leilani.

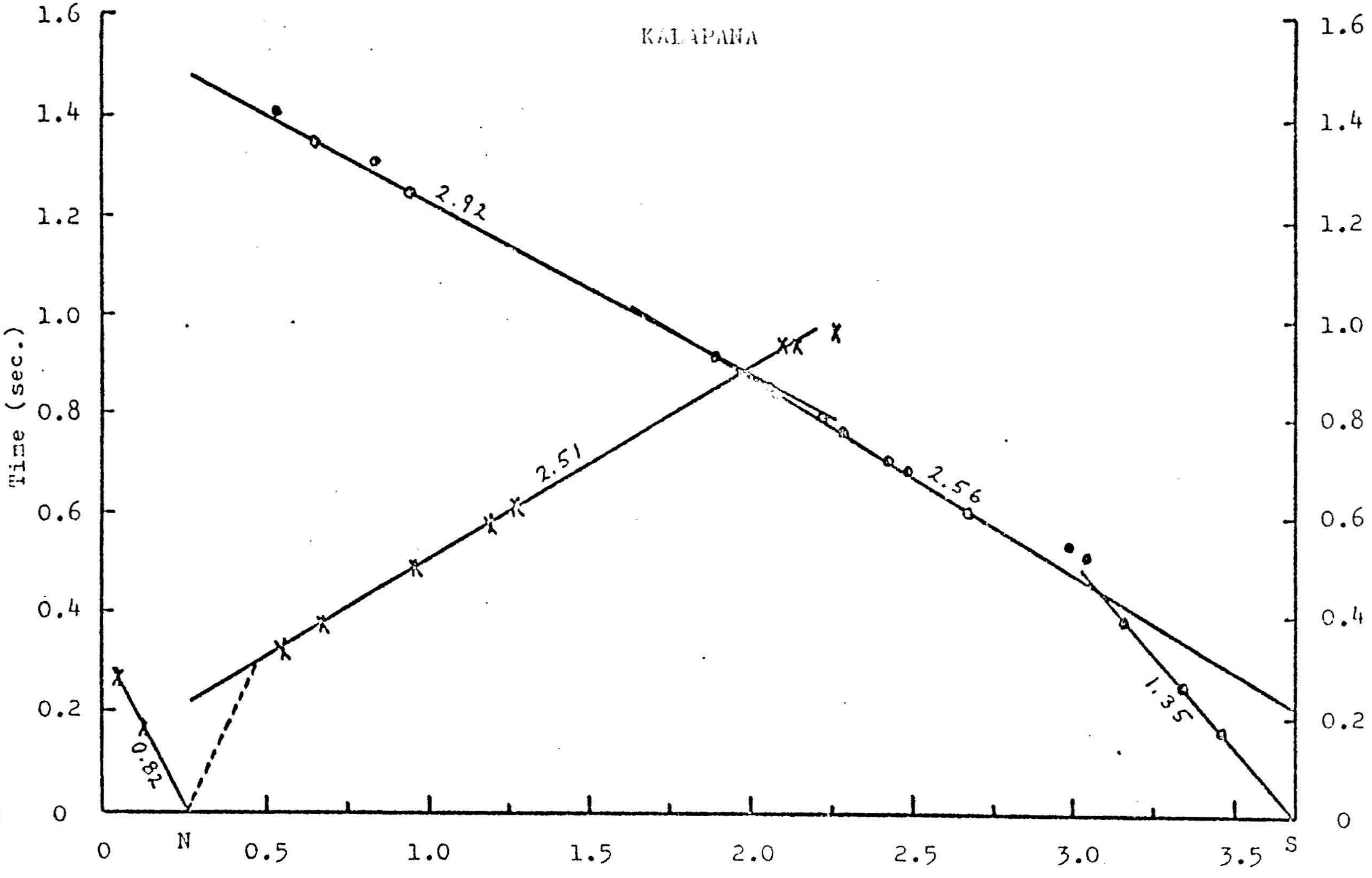

Figure 6. Travel time plot of line Kalapana.

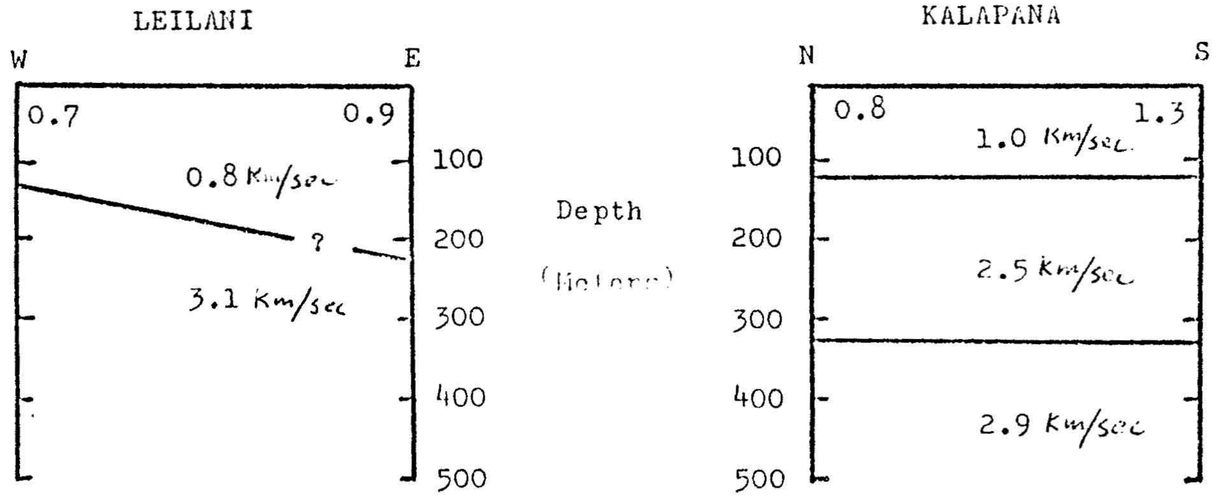

Figure 7. Velocity depth profiles from the travelt ime plots.

actually made up of two layers. This puts the 2.9 km/sec (or 3.1 km/sec) layer at a depth of about 320 meters.

From these short traverse refraction surveys, at least the velocities of the shallow layers were resolved. These parameters are helpful in the interpretation of gravity data, as we are able to locate the depths at which density contrasts take place.

II. PROPOSED WORK

The proposed seismic studies will consist of an active seismic experiment using traverses of up to 20 km.

We intend to use a long recording analog format seismograph, which is modified form of the ocean bottom seismograph which is being routinely built for the marine geophysics program at the Hawaii Institute of Geophysics. This seismic system can run for 12 days on a 120 minute type cassette tape and has a frequency response that is flat between 4.5 hz to 20 hz. We can extend the lower end of the frequency response to 1 hz by substituting a 1 hz geophone in place of the 4.5 hz geophone used in the ocean bottom system. In finding events on a tape recorded by this instrument, the playback is accomplished first on a regular cassette deck connected to an audio system to locate the whereabouts of the events by ear. After the tape is marked, the events will be put on a visual format recorder or digitized on an HIG computer.

IV. LONG TRAVERSE SEISMIC REFRACTION EXPERIMENT

From gravity data, we have estimated the structure of the dike complex under the east rift. The seismic refraction survey of Hill (1969) provided the structure of the flank south of the rift. The short traverse refraction studies, mentioned earlier in this task, defined the velocity in the shallow layers along the east rift, but it was not intended to penetrate to the bottom of the dike complex. All of these data combined still do not give us a clear picture of the structure of the dike complex. We propose a long traverse seismic refraction survey to outline the nature of the dike complex under the east rift in a more unambiguous way.

Over a decade ago, a seismic refraction traverse was carried out over the northwest rift of the ancient volcano of Koolau on the island of Oahu (Furumoto, Thompson, Woollard, 1965). In that survey, under a 4.6 km/sec layer were two layers, a 6.1 km/sec layer at 3 km depth and a 7.6 km/sec layer, at 5 km depth (Fig. 8). These high velocities are unusual and are not generally found at such shallow depths. If the Puna rift is like the Koolau rift, we should expect the east rift dike complex of Kilauea to have two or more layers, each with high velocities.

In the experiment we shall carry out, one traverse will be along the trend of the east rift and another perpendicular to the trend. The locations of the planned shot points and the geophone stations are shown in Figure 9. For the traverses along the trend of the rift, the shot point will be located offshore from the eastern tip of the island. In addition to

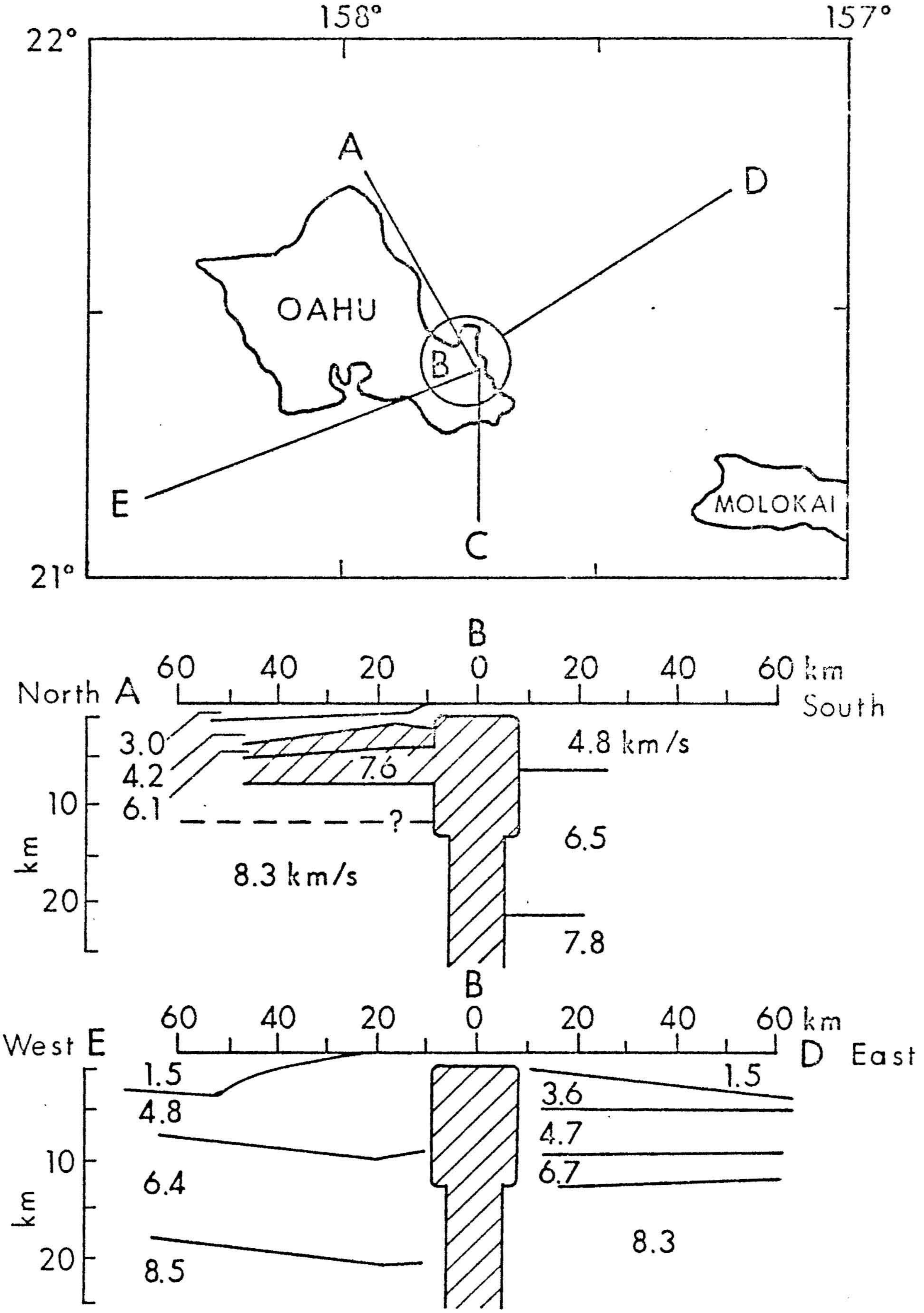

Figure 8. Internal structure of Koolau Volcano as inferred from geophysical data. Values are in kilometers per second.

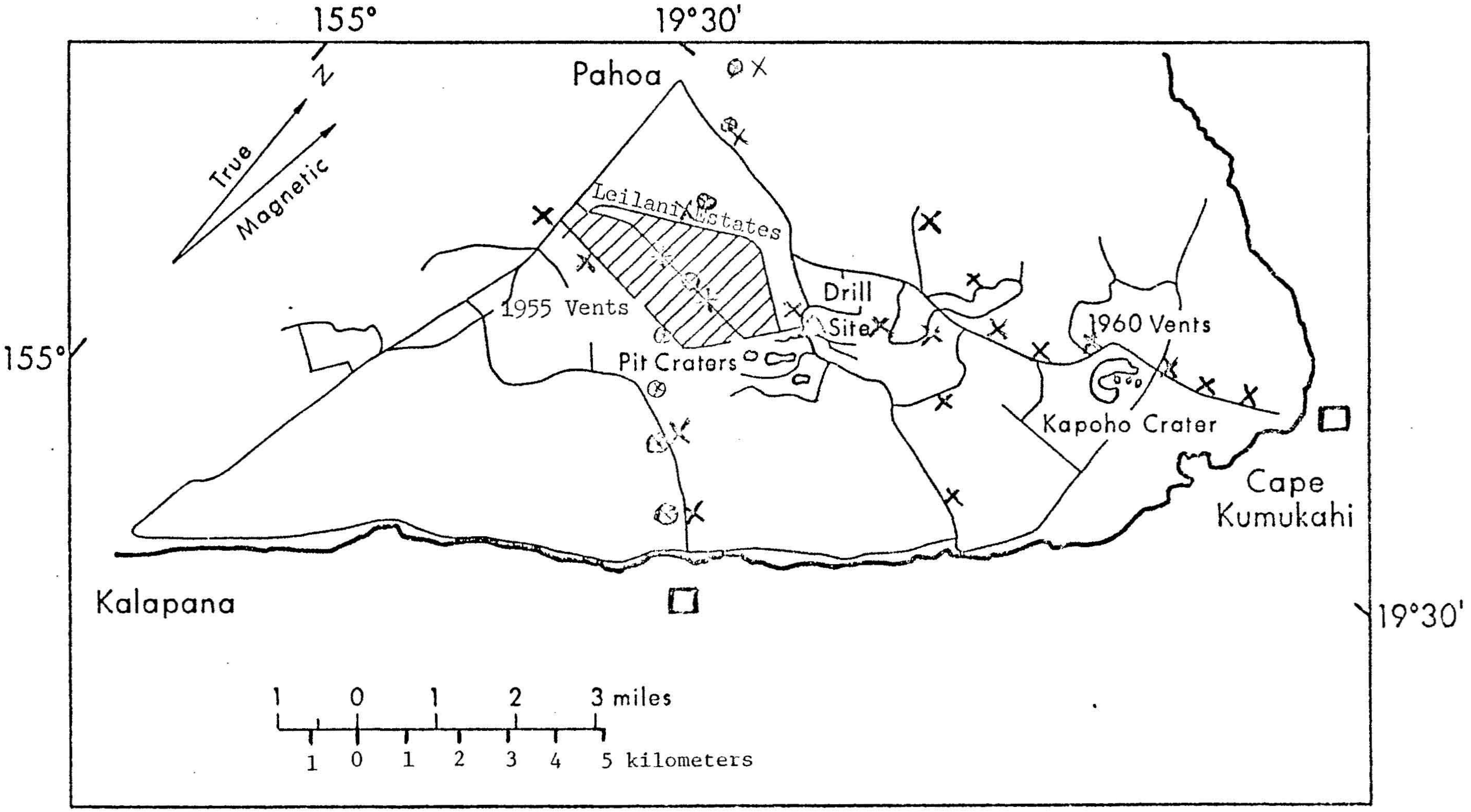

Figure 9. Planned seismic refraction traverses. The traverse along the trend of the is shown by crosses,. the traverse normal to the trend is shown by encircled crosses. The triangle indicates the site of HGP-A.

setting up geophones over the trend, shorter recording traverses will be made at different angles to obtain a fan shooting effect. For the traverse perpendicular to the trend, the shots will be fired off the south coast.

The shots will be 50 lb size, which have been found to be adequate for offshore onshore experiments of this type.

There will be several mobile recording teams in the field. Three of the teams will use our regular refraction gear which records on FM mode on tape. One team will use our long recording seismograph packages and move them along the traverse lines.

In further drilling for exploratory or production wells, a knowledge of the structure of the intrusive dike complex under the east rift will be very helpful. At the present time, gravity data can estimate the structure but with a measure of ambiguity inherent in gravity data. If a seismic refraction program is successful, this ambiguity will be significantly reduced.

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TASK 2.3

Seismic Studies

A.	Salaries and Wages		
	1. Senior personnel, C. Helsley overload	$3,395	
	2. Grad. asst. (5 mos., $491/mo.)	2,455	
	3. Technicians (ship, field)	2,500	
	4. Student help	1,200	
			$ 9,550
B.	Fringe Benefits		755
C.	Equipment		
	1. Radio buoy (hydrophone and accessories)	560	
	2. Readjusting seismic gear, parts	600	
	3. Ship outfitting	860	
			2,020
D.	Expendable Supplies and Equipment		
	1. Explosives 1200 lbs	675	
	2. Scientific supplies	780	
	3. Office supplies	160	
	4. Field accessories	725	
			2,340
E.	Travel		
	1. Airfare to Hawaii	420	
	Per diem 6 x $30 x 7	1,260	
	Car rental 3 x 7 days	450	
	2. Travel, meeting, west coast	380	
			2,510
F.	Computer cost		-0-
G.	Publication Cost		
	1. Page charges	520	
	2. Drafting	150	
			670
H.	Other Costs		
	1. Ship charter	3,500	
	2. Communications	200	
			3,700
I.	Total Direct Costs		21,545
J.	Indirect Costs (46% of Salaries and Wages)		4,393
K.	Total Costs		$ 25,938

Task 2.4

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

Douglas P. Klein

Objectives, Financial Grants, Accomplishments

The objectives 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.

These objectives, 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

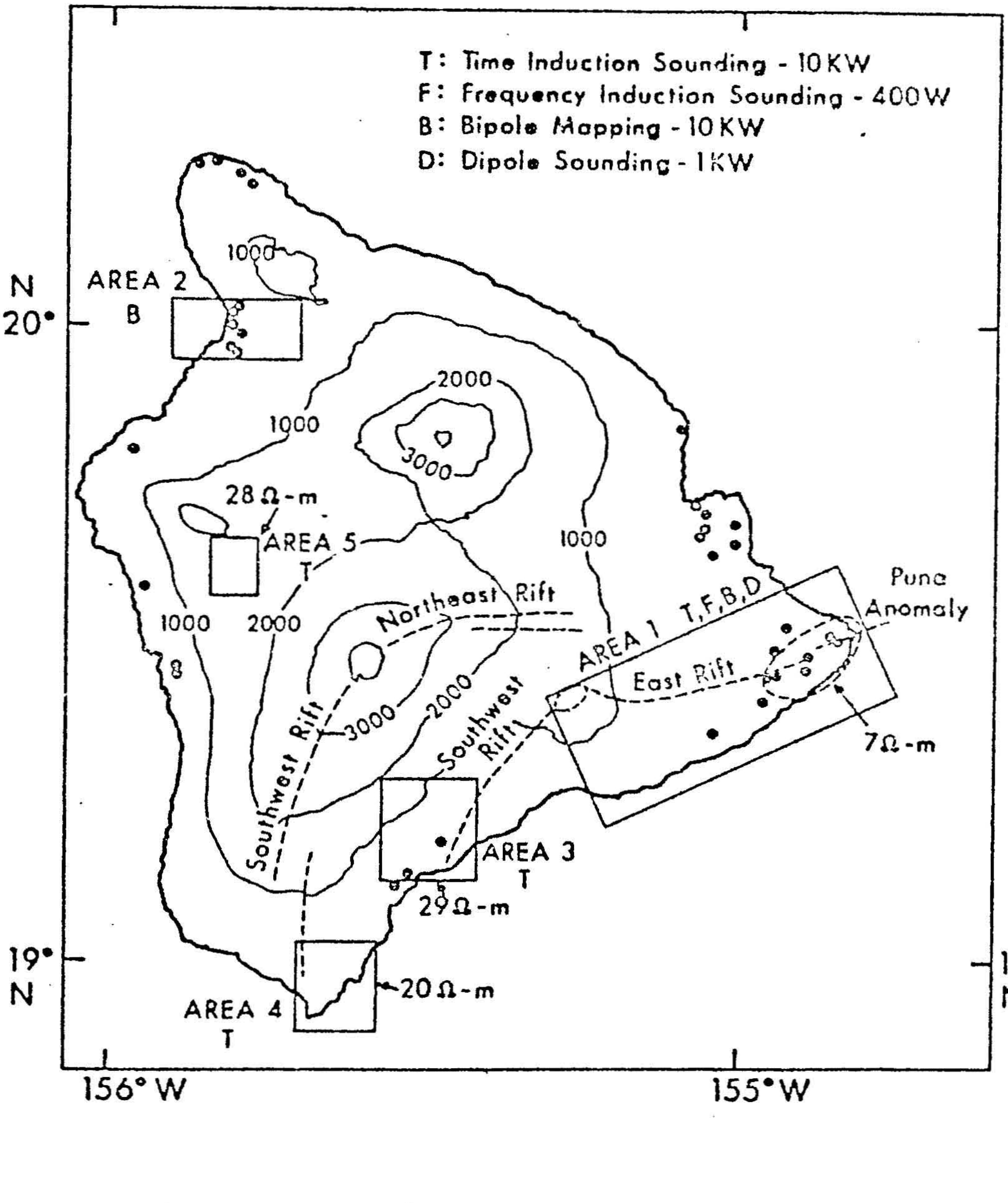

Figure 1. Regions of resistivity reconnaissance surveys. Generalized resistivities are shown as mean values of preliminary reductions for the transient soundings. Circles are locations of shallow drill holes.

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.

Figure 2, modified from Klein 1975, shows the zones of lowest resistivity deduced from the Puna dc mapping surveys.
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.

The geoelectric data synthesis up to the time of drilling is reported in Klein, 1975; Furumoto, 1975; and Klein, et al., 1976.

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 Puna inductive data set.

Present Objectives

Our primary priority for the last half of 1976 is to prepare a publication on the principle aspects of the geoelectric surveys on Hawaii Island leading up to the drilling. This 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 $12,000.

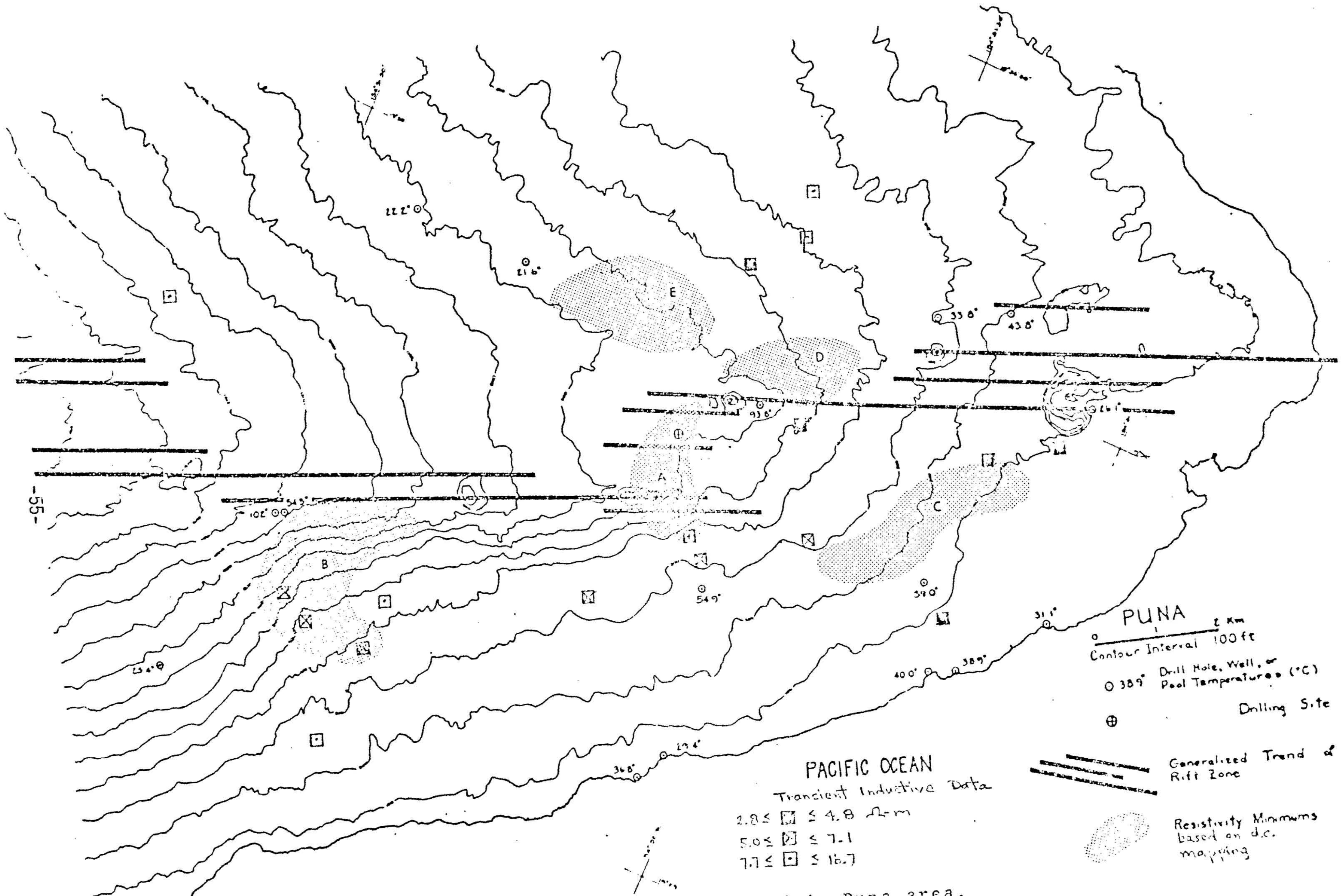

Figure 2. Resistivity lows located in Puna area. The Spatial distribution of transient inductive results is also shown.

The transient inductive method was our primary data aquisition method and it is a demonstratably 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.

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.

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 report. Secondarily, if time permits, we will take a more detailed look at the initial reconnaissance data in order to quantitatively compare the "normal" and "anomalous" areas on Hawaii.

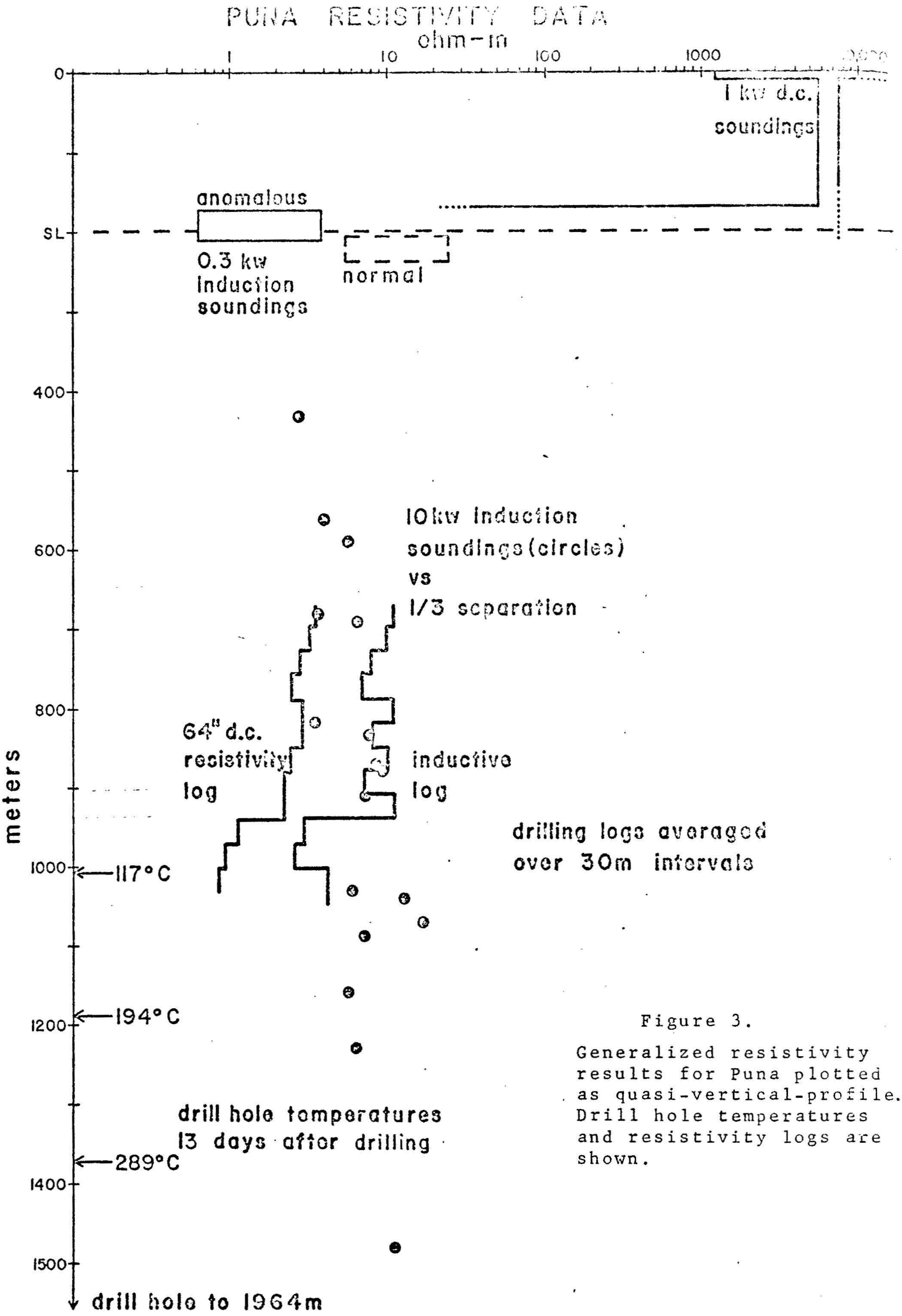

Figure 3.

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

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BUDGET

Task 2.4 - Geoelectric Surveys

A.	Salaries and Wages		
	1. Scientific Personnel		
	a. Post-doctorate (D. Klein) 3 mos. @ $1284/mo.	$3852	
	b. Professional (J. Kauahikaua) 3 mos. 50% @ $552/mo.	1656	
	c. Professional (E. Sakoda) 1.5 mo. 100% @ $880/mo.	1320	
	TOTAL SALARIES AND WAGES		$ 6,828
B.	Fringe Benefits		1,570
C.	Equipment		-0-
D.	Expendable Equipment and Supplies		61
E.	Travel		-0-
F.	Publication Costs		
	1. Publication charges: drafting, photography, xerox reprod., page charges, etc.		400
G.	Total Direct Costs		8,859
H.	Indirect Cost (46% of Salaries and Wages)		3,141
I.	Total Cost		$12,000

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 groundwater 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.

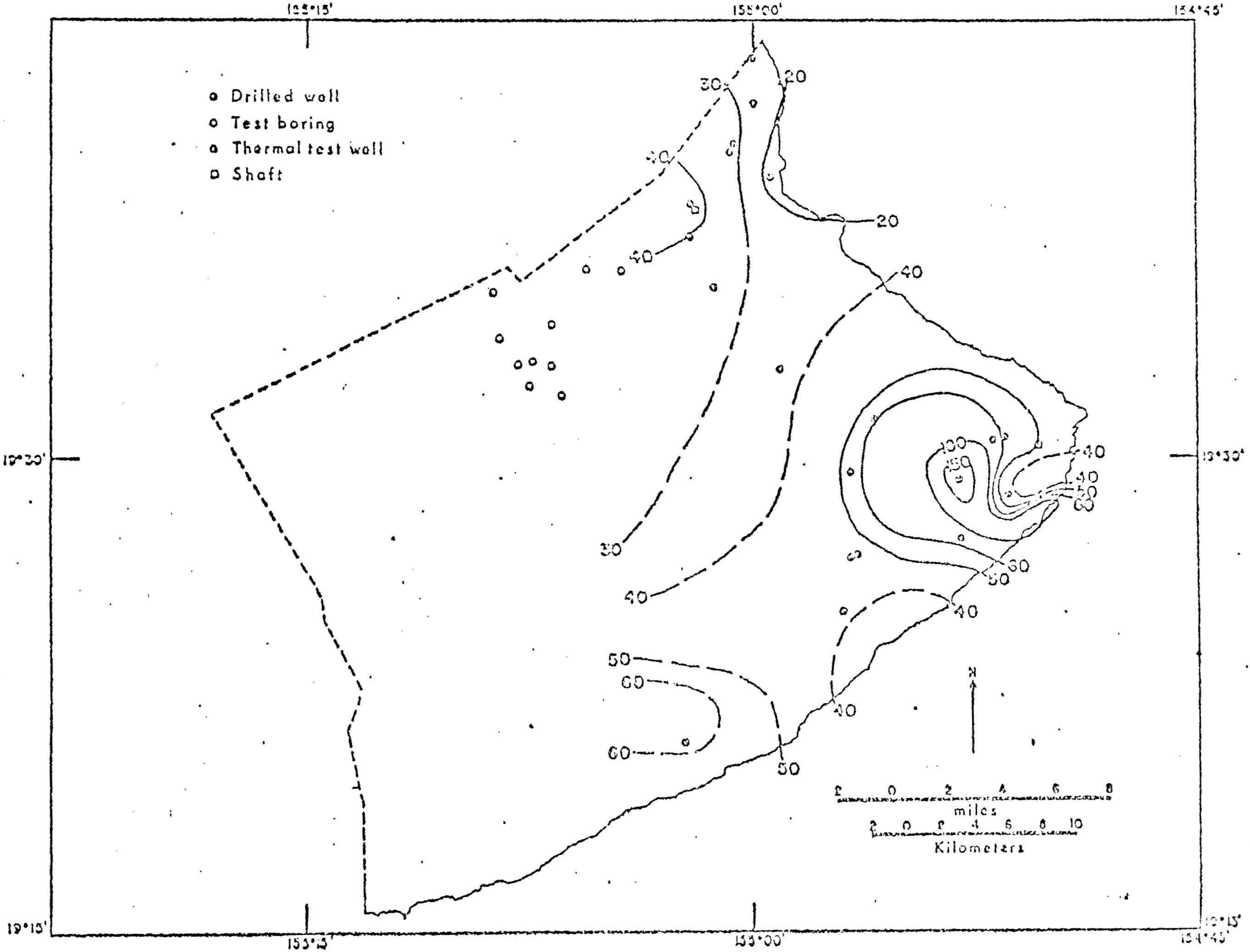
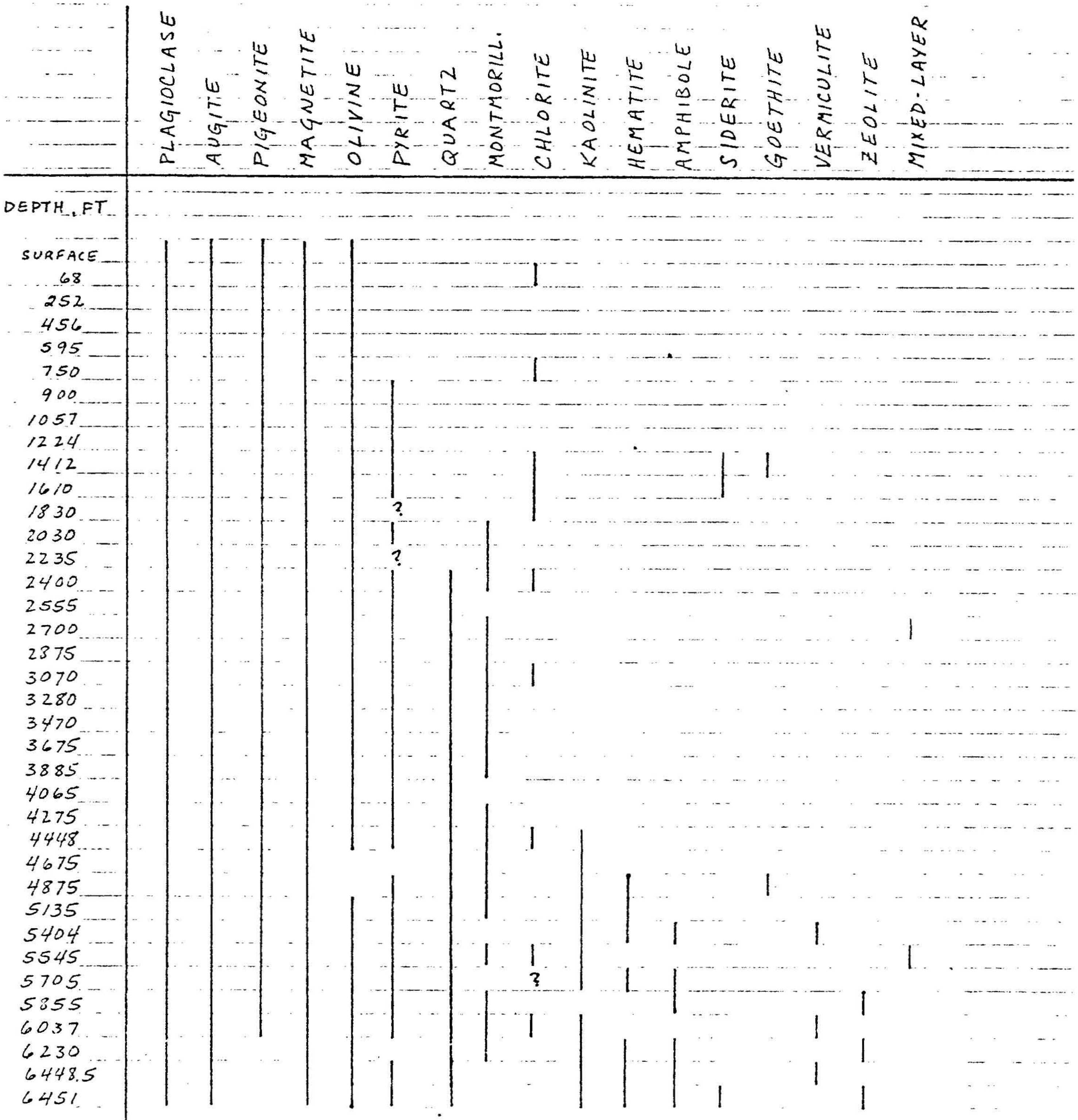


FIGURE 1.
Lines of equal silica concentration, in milligram per liter (mg/l) of the Puna District, island of Hawaii.

FIGURE 2.

INITIAL X-RAY IDENTIFICATION *
HGP A



* WHOLE - ROCK ANALYSES

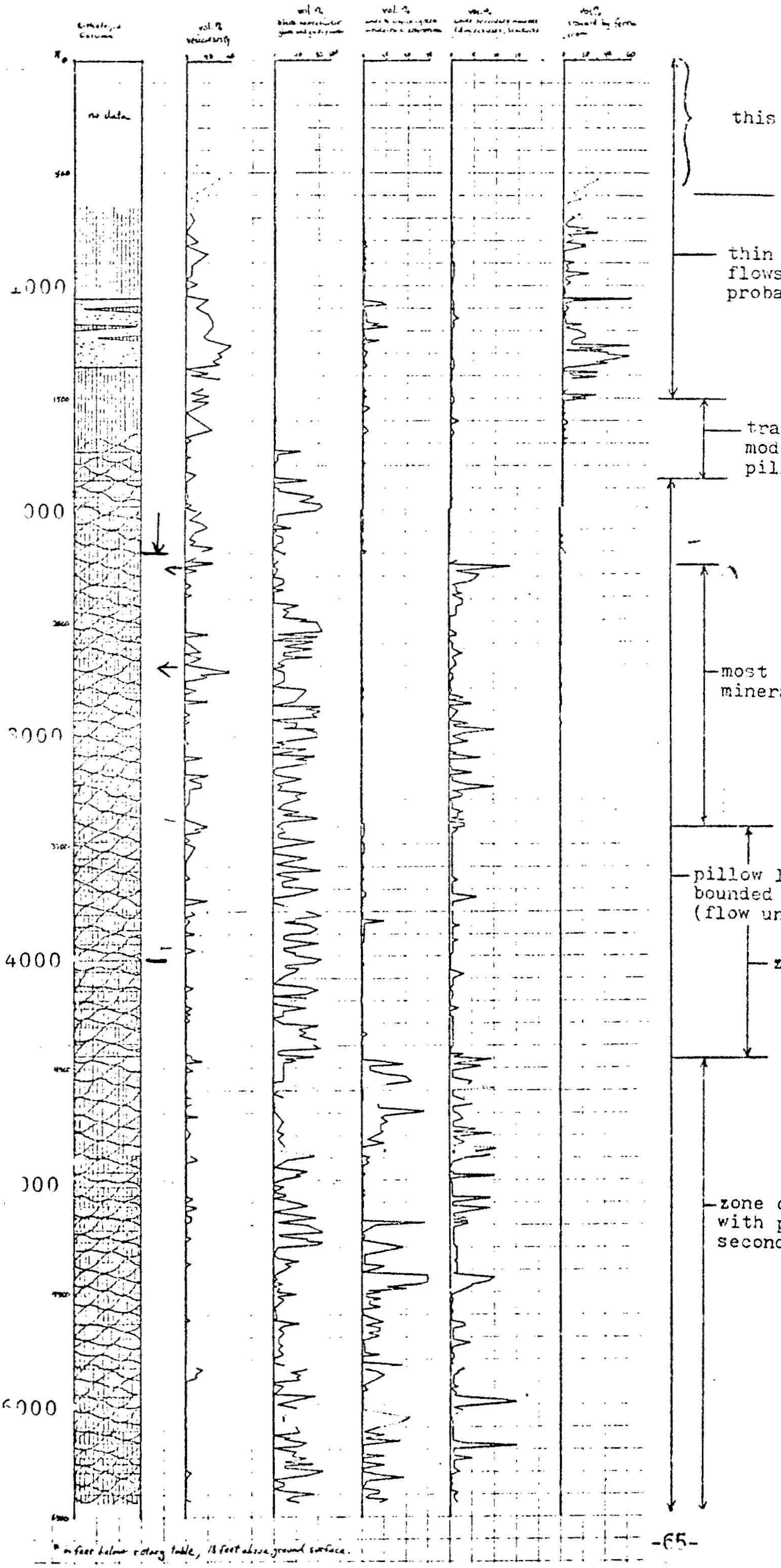
Macroscopic study reveals that the hole penetrates a sequence of subserial pahoehoe and as basalt flows to about 1700 feet below the surface, and submarine pillow lavas, also basaltic, from 1700 feet to the bottom (see Fig. 3). From the 4500-foot level to the bottom of the hole, intense whole-rock alteration 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.

GEOLOGY OF [illegible]

(Compiled by Daniel B. Palmiter, 1976)

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

* in feet below rotary table, 18 feet above ground surface.

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 discussed 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		671
C.	Equipment		-0-
D.	Expendable Equipment and Supplies		2,300
E.	Travel		
	1. Domestic		750
F.	Publication Costs		400
G.	Total Direct Costs		16,089
H.	Indirect Costs		
	(46% of Salaries and Wages)		5,505
I.	Total Costs		$ 21,594

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.

TABLE OF CONTENTS

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 expansion 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 temperatures in New Zealand geothermal areas to within about $\pm 2°C$ (Mahon, 1966). Moreover, the measurement is made while drillholes discharge, 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 investigated during future studies.

The Na/K ratio in natural hot waters is controlled by a reversible 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:

$$t = \frac{1647}{\log\frac{Na}{K} + \frac{1}{3}\log\frac{Ca}{Na} + 2.24} - 273.$$

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 basalts 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 $E = \frac{RH_1 - rH_2}{R-r}$ where E is the enthalpy, R the ratio of concentrations 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.

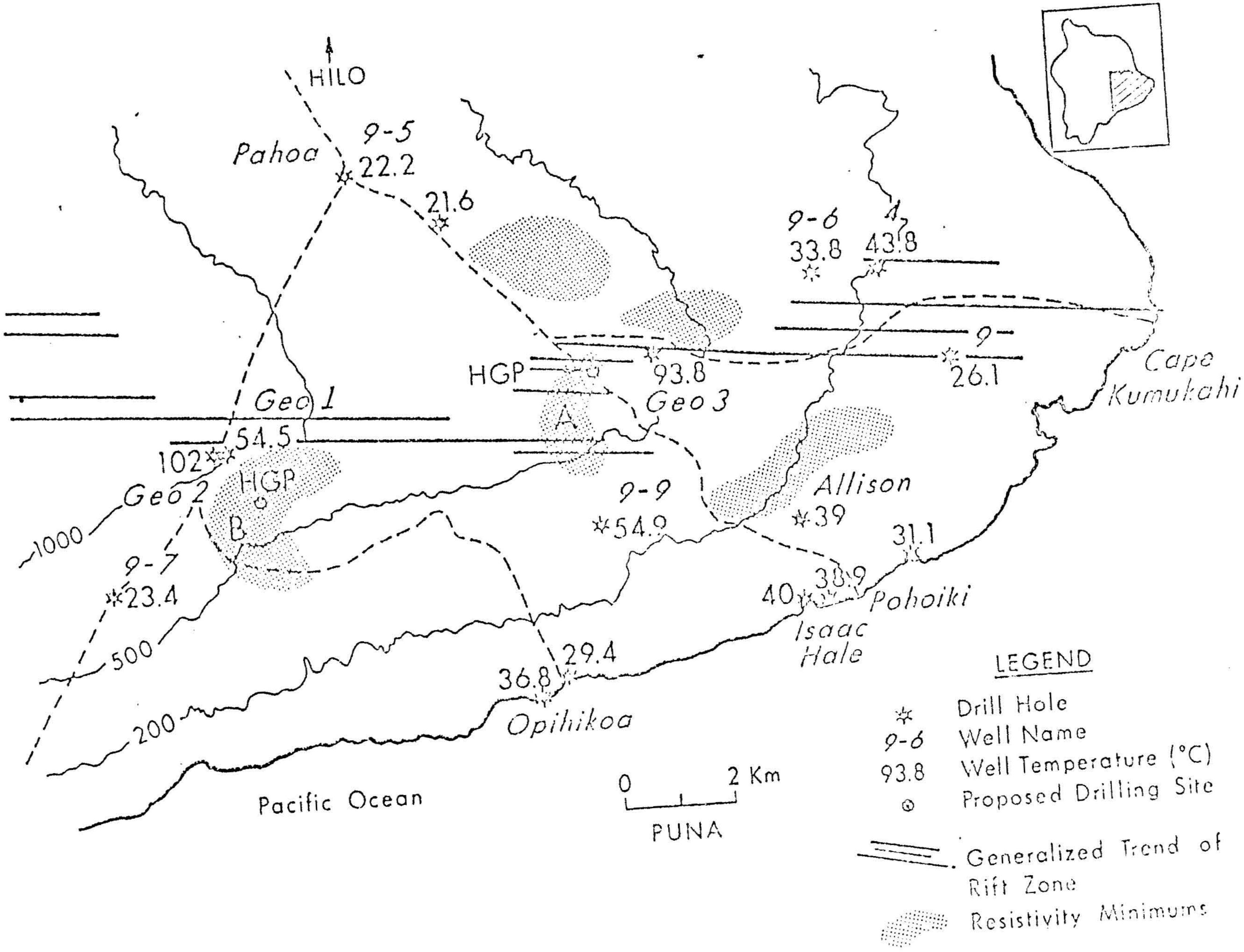
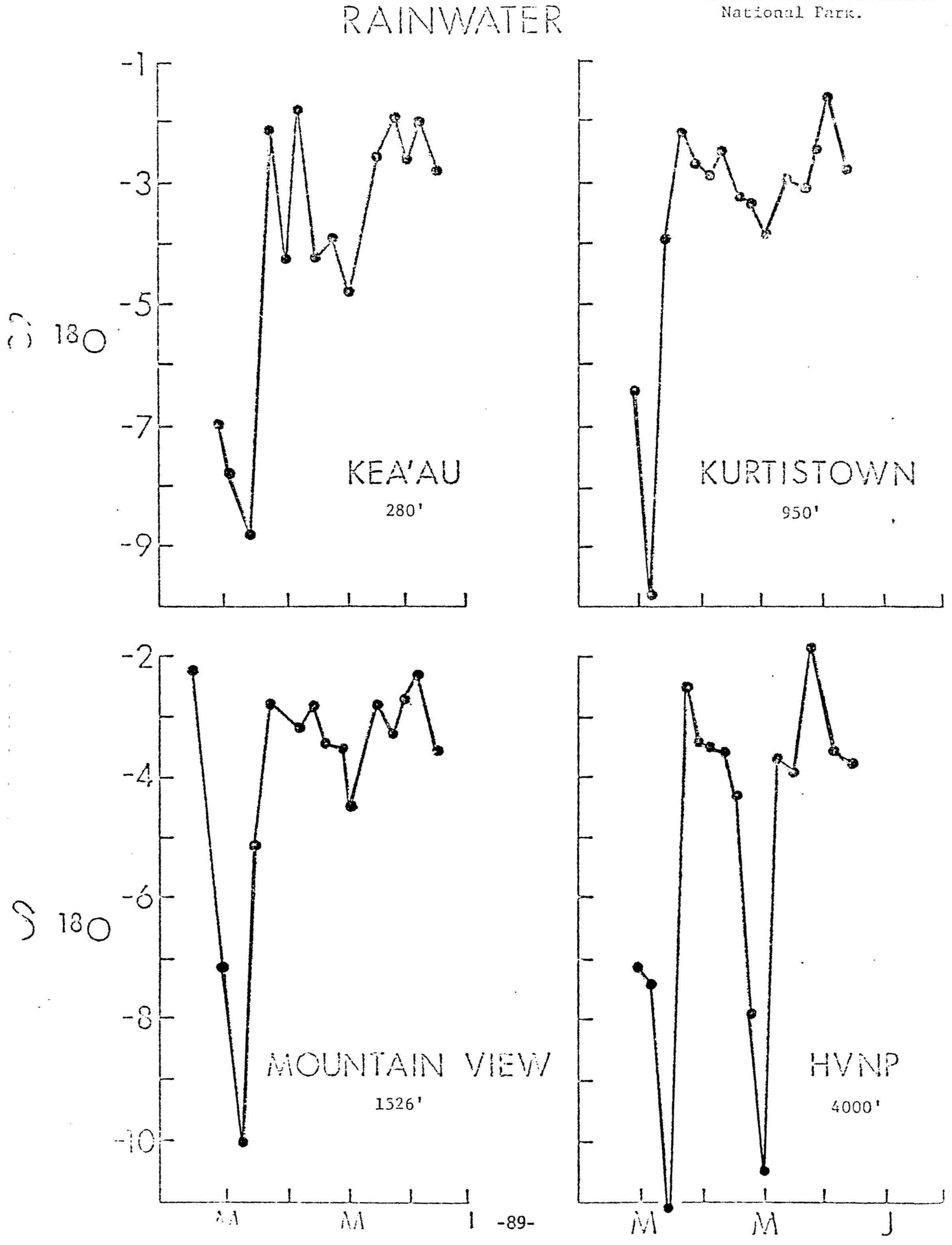


Figure 1. Map of the Puna area of the Island of Hawaii.

Figure 2. 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.



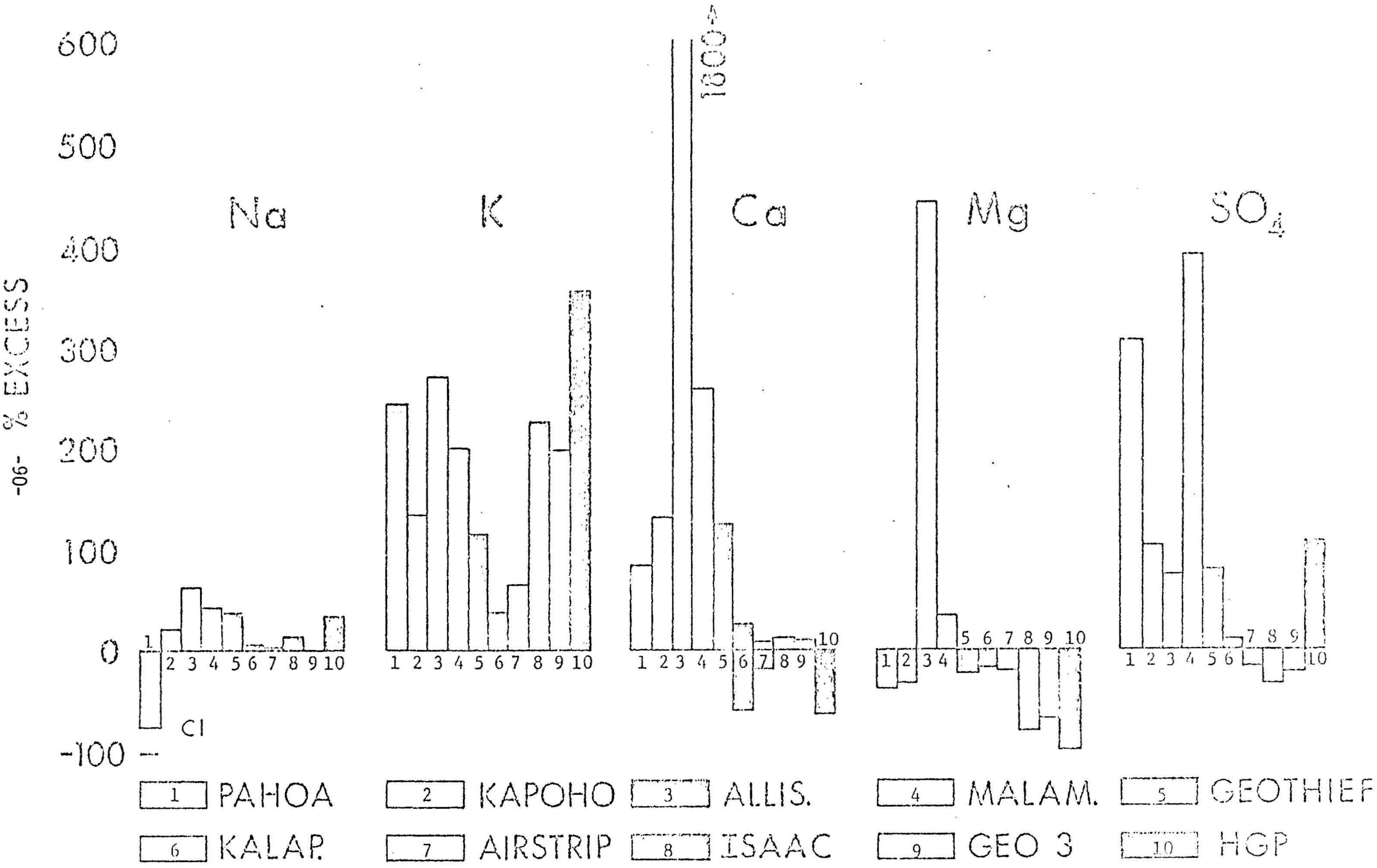


Figure 3. Major ion concentrations of Puna area wells expressed at the % excess (or depletion) over that expected if they were formed by mixing fresh water with sea water. The wells (numbered 1-10) are arranged in approximate order of increasing temperature.

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		

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*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	-5.5	-5.4	01/21/75
		10/28/75	-5.9		
Kapoho Shaft	38	01/06/75	-6.6	-2.3	02/12/76
		10/28/75	-6.6		
Allison Well	140	01/07/75	-5.8	-4.8	07/21/75
Airstrip	287	01/06/75	-5.3, -5.3	-4.0	
		07/21/75	-6.1	-6.2	
				-5.7	01/13/76
Malami Ki	274	01/06/75	-4.6	-3	
		07/21/75	-5.1		
Geothermal #3	600	01/07/75	-4.7, -4.6		
		07/21/75	-5.3		
Pahoa	705	01/06/75	-6.7	-3	
		07/21/75	-6.7		
Kalapana	752	01/06/75	-5.4, -5.5	-4.6	01/03/75-01/06/75
		07/21/75	-6.3	-4.6	06/04/76-06/06/76
				-3.4, -3.4	
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	

TABLE 4

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

		$\delta\ ^{13}C$ (PDB)	$\delta\ ^{18}O$ (SMOW)
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			
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 $\delta^{18}O$ 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°/∘∘). 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	HCO_3	SO_4	SiO_2	N (b)	P	Sr
2986-01	Pahoa Station	1-6-75		7.30	36.0	2.72	1.58	2.7	13.5	48	21.1	50.0	0.252	0.078	
	(Well 9-5)	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	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	
	(Well 9-7)	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	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	
	(Well 9)	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	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
	(Well 9-6)	7-22-75	33.5	7.75	223	16.8	12.5	27.2	316	44	211		0.39	0.076	
2681	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	1-7-75	36.0	7.75	2020	86.0	32.4	200	3534	56	507	81.5	1.218	0.016	
	Spring	10-27-75			2140	87.5	98.0 (c)	239	3660	61.0	552		<0.01		1.3
2783-01	Malama Ki Well	1-7-75	52.2	7.02	2105	109	66.8	210	3811	144	471	100.7	0.280	0.006	
	(Well 9-9)	7-22-75		7.45	2890	149	117	293	5120	128	598		0.41	0.013	2.2
	Geothermal 03	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 03 (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

Groundwater Samples	Date	^{3}H (T.U.)[a]	δ^{18}O (‰)[b]
Pahoa Station (Well 9-5)	1-6-75 7-21-75	9.9 ± 1.1 10.6 ± 1.2	 -6.70
Kalapana Station (Well 9-7)	1-6-75 7-22-75	16.7 ± 1.8[c] 18.0 ± 2.0	-5.42[d] -6.33
Kapoho Shaft (Well 9)	1-6-75 7-21-75	14.1 ± 1.5 10.5 ± 1.2	 -6.33
Airstrip Well (Well 9-6)	1-6-75 7-22-75	 11.1 ± 1.2	-5.29[d] -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 7-21-75	15.6 ± 1.6 8.6 ± 1.0	-4.57 -5.08
Geothermal #3	1-7-75 7-21-75	10.3 ± 0.8 7.3 ± 0.9	-4.66[d] -5.33
Rainwater Samples			
Kalapana	1-6-75 7-22-75	9.1 ± 1.2	-5.01 -5.80
Airstrip	1-6-75 7-22-75		-4.04 -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%)	$6,980	
	2. Student Help (Undergrad.)	2,240	
			$ 9,220
B.	Fringe Benefits		447
C.	Equipment		-0-
D.	Expendable Equipment and Supplies		1,000
E.	Travel		
	1. Domestic		1,100
F.	Publication Costs		400
G.	Total Direct Costs		12,167
H.	Indirect Costs		
	(46% of Salaries and Wages)		4,241
I.	Total Costs		$16,408

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 ∿ 6,455 ft as well as from the Keller [1974] hole to ∿ 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 temperature (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 thermal 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 program in geophysical exploration. It is anticipated that the laboratory data will provide useful parameters for the exploration 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 quantities 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 exploitation 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 knowledge of the physical properties of *in situ* rocks, therefore, has values from viewpoints of successful exploration and modeling of potential geothermal systems.

The purposes of this task are oriented toward (1) understanding how the physical properties of the Hawaiian basaltic rocks (including the drill hole samples) relevant to electrical, thermal, 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 (∿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 (∿5 ohm-meter) observed in the Puna district at a depth of ∿1 km [Klein and Kauahikaua, 1975] could be due to the presence of porous (ϕ ∿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 diffusivity (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 ∿ 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 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 (ϕ < 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

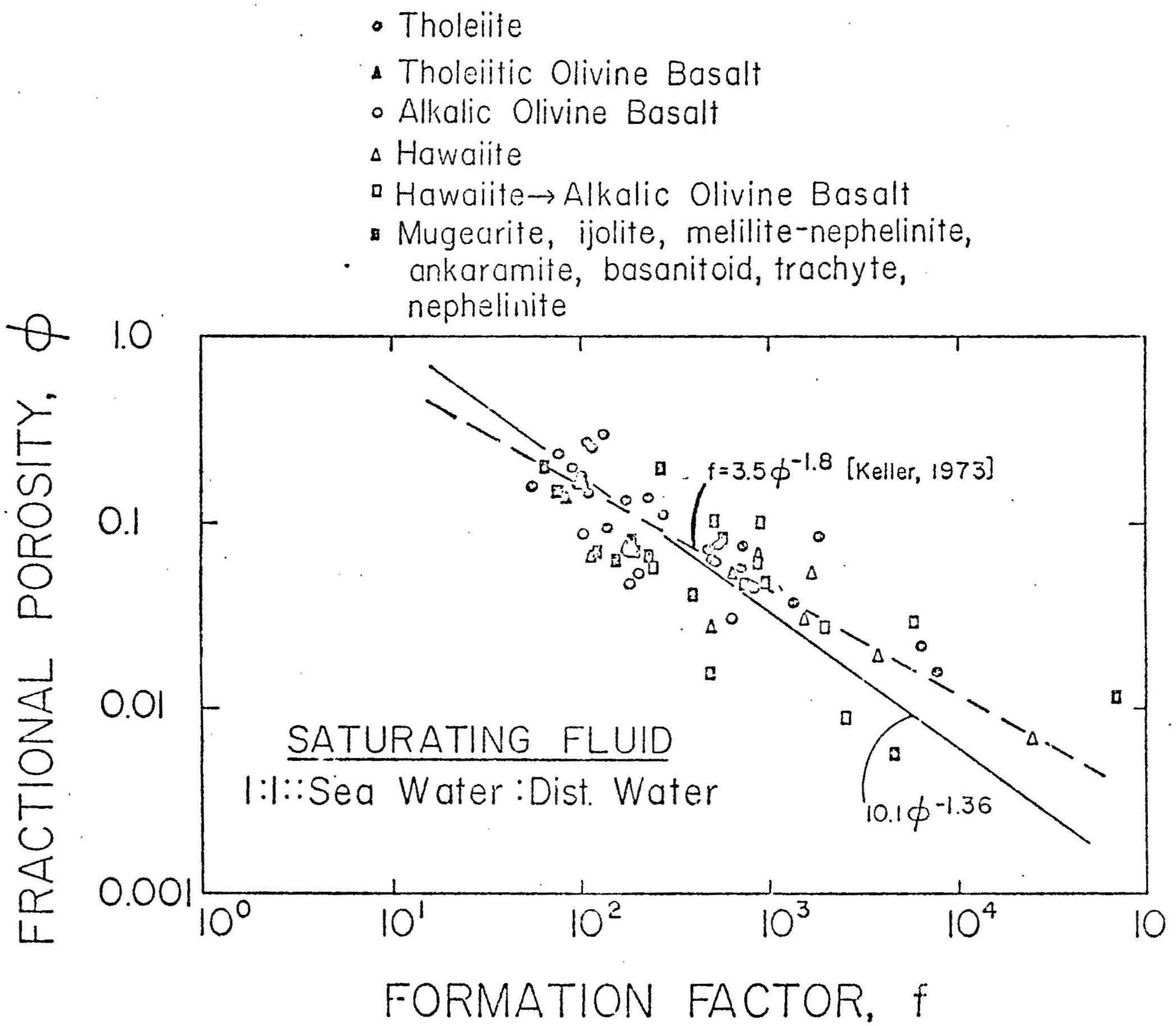

Figure 1. The relationship between "effective" (connected) fractional porosity ϕ and formation factor f for various types of Hawaiian basalts saturated with fluid 1:1:: sea water:distilled water. The best-fit line $f = 10.1\ \phi^{-1.36}$ represents the Archie's law.

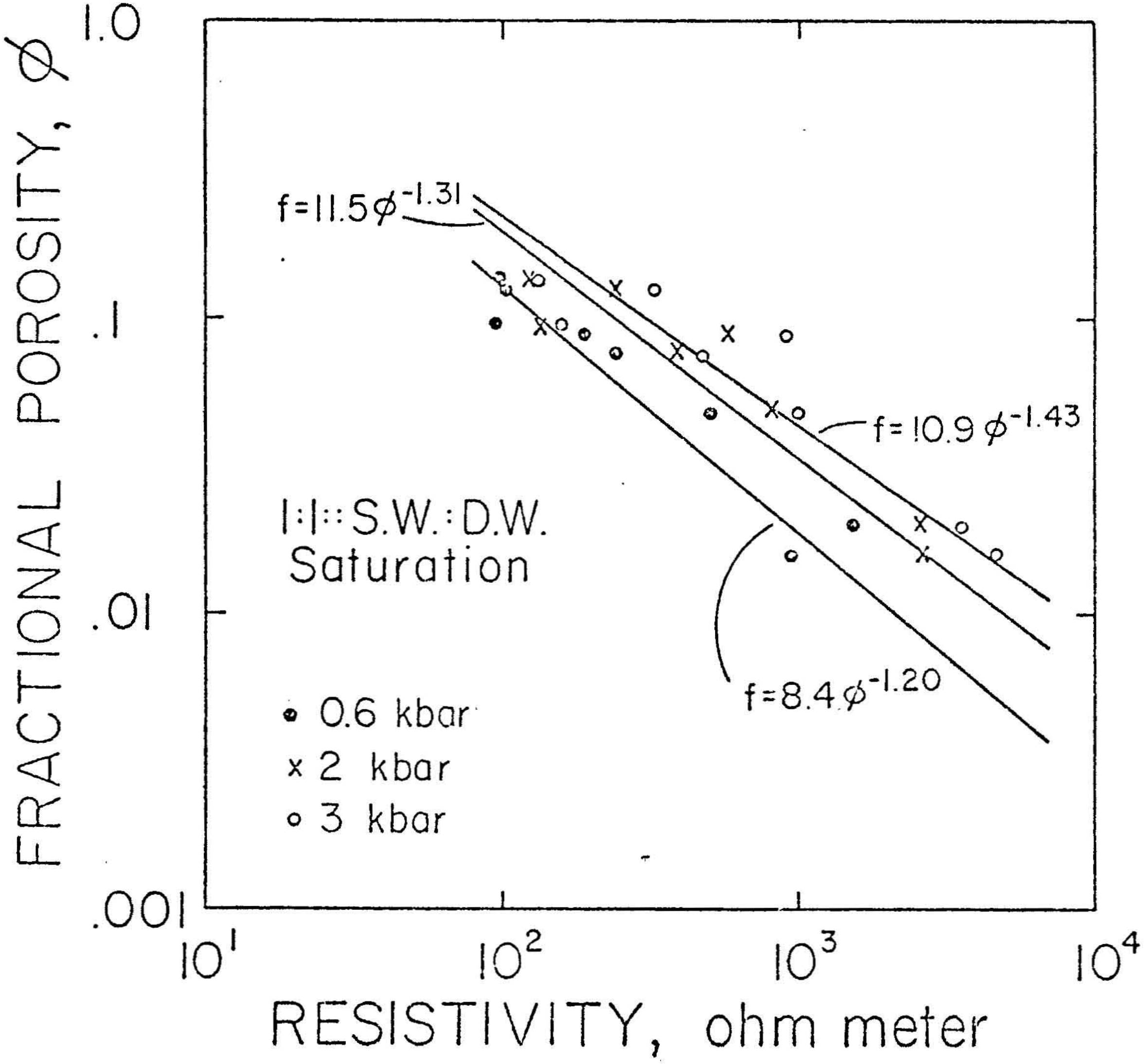

Figure 2. The relationship between "effective" porosity vs. resistivity for Hawaiian basalts saturated with fluid 1:1::seawater: distilled water at different pressures. The "effective" porosity is that at l bar and has not been corrected for pressure here.

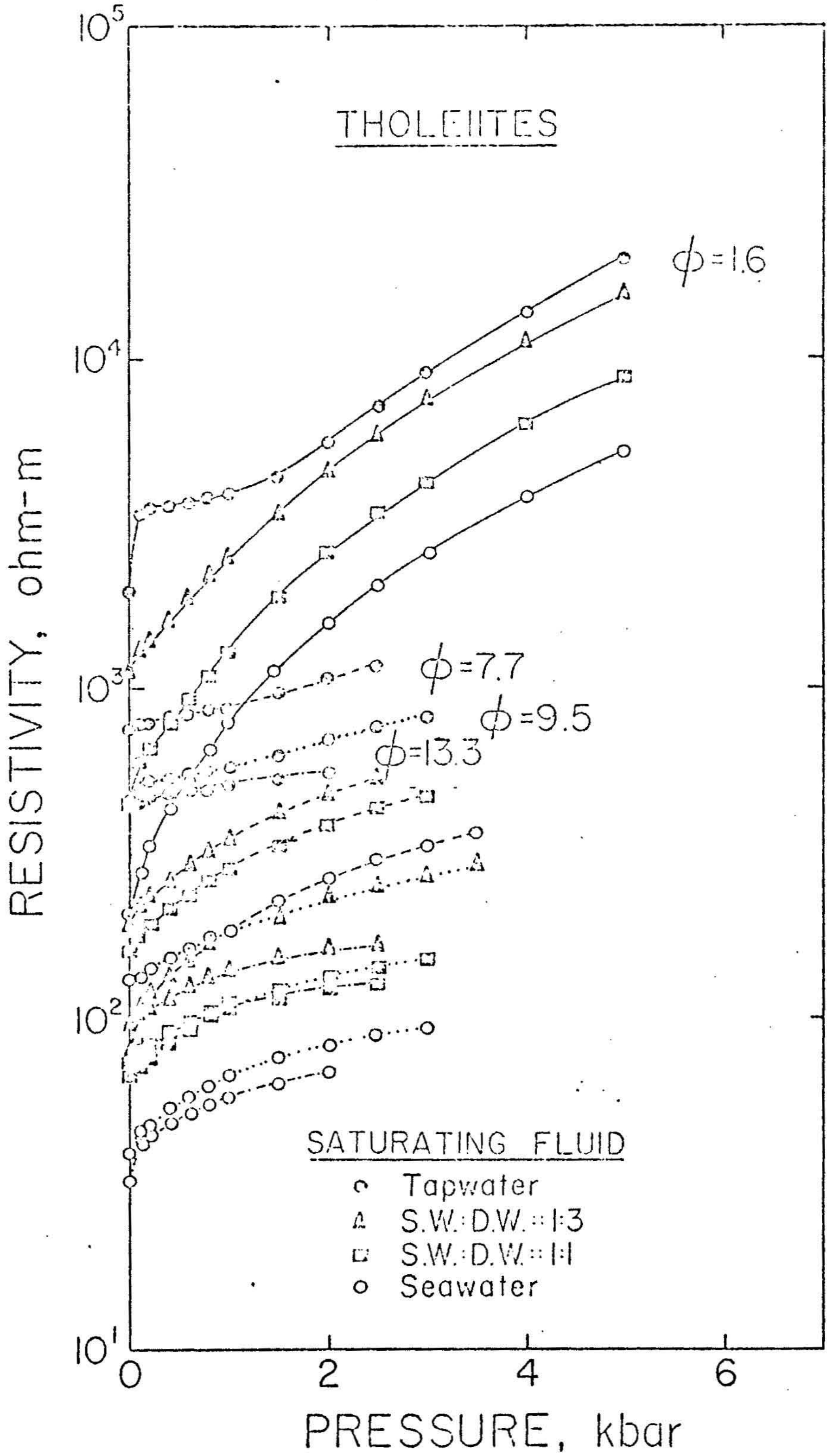

Figure 3. Pressure dependence of resistivity of four tholeiites of varying porosity and saturated with different fluids.

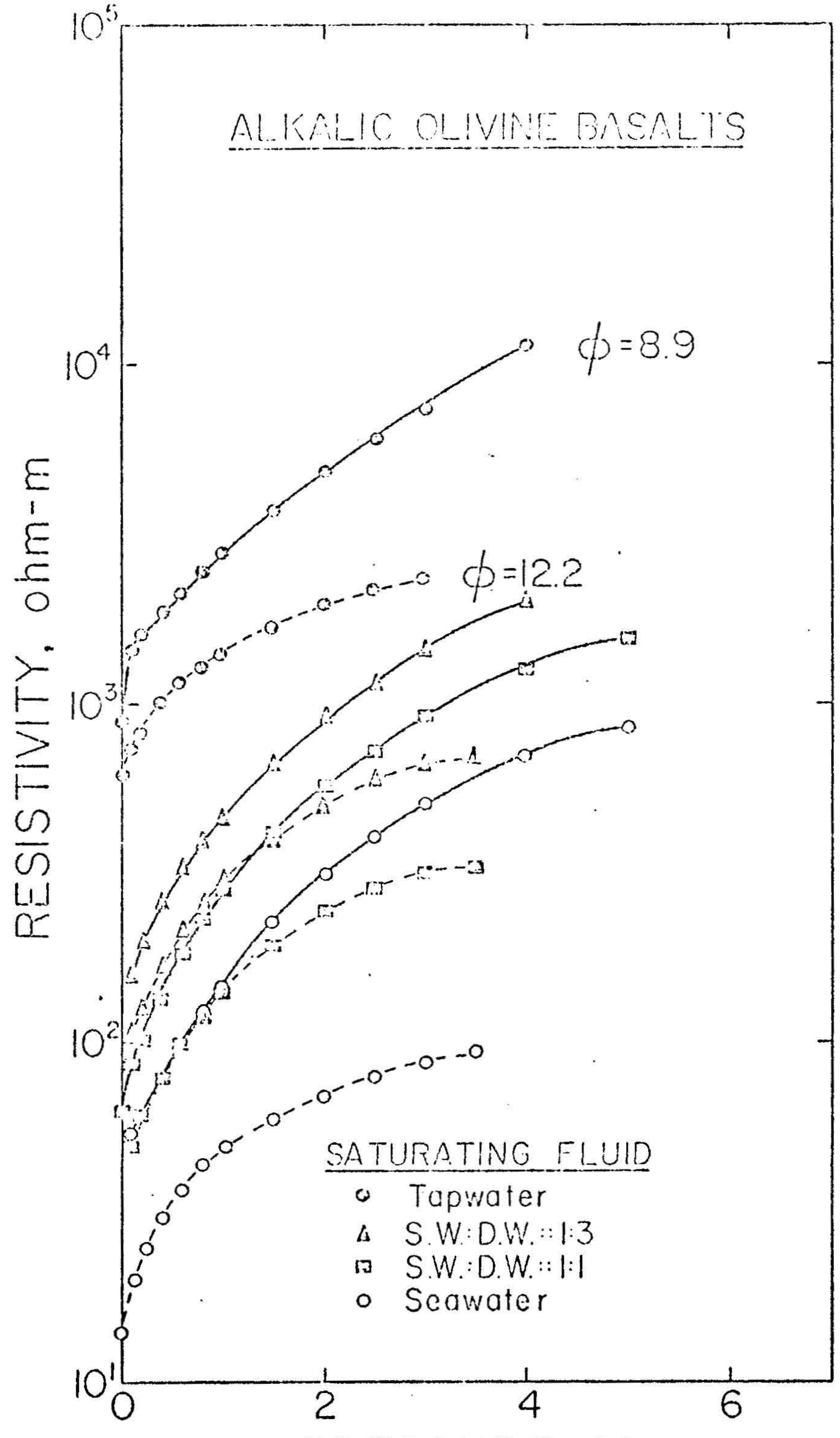

Figure 4. Pressure dependence of resistivity of two alkalic olivine basalts of varying porosity and saturated with different fluids.

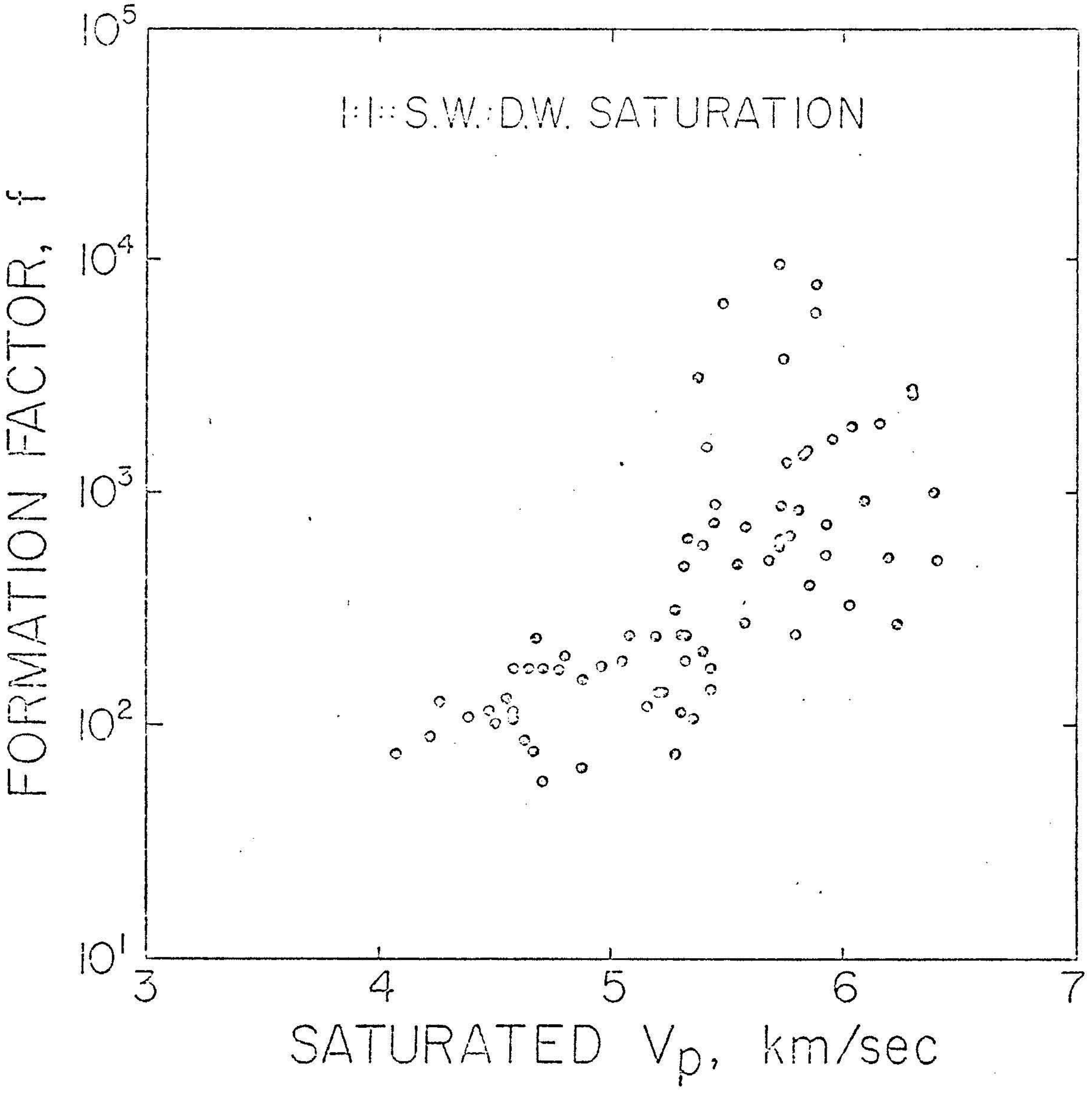

Figure 5. Formation factor vs. V_p in various types of basalts having variable "effective" porosity and saturated with fluid 1:1:: sea water: distilled water.

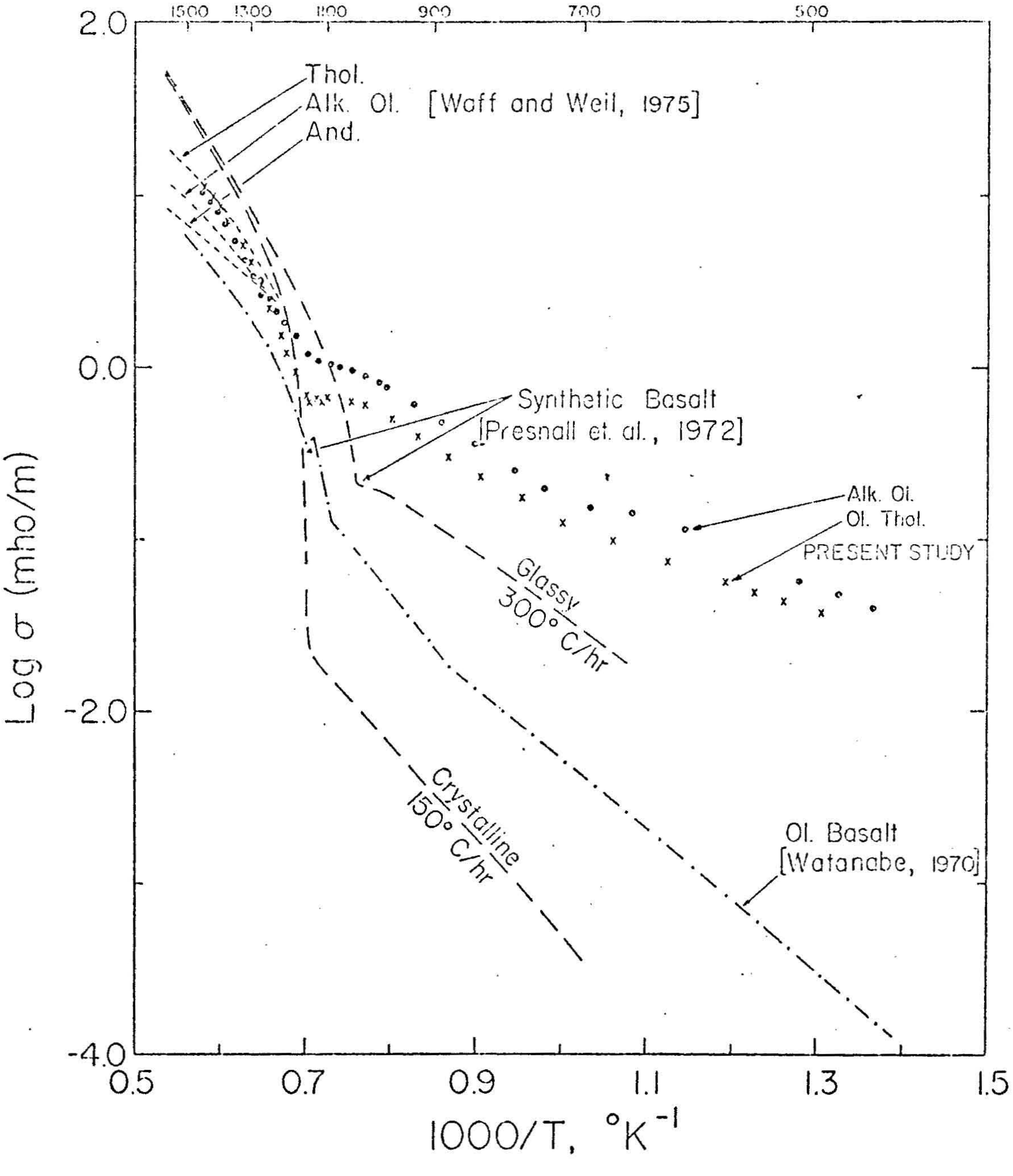

Figure 6. Preliminary electrical conductivity measurements on two Hawaiian basalts (alkalic olivine and olivine tholeiite) to melting temperatures under controlled f_{O_2}. Note the abrupt change in conductivity at the onset of melting. The results are compared with conductivity data on the other types 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

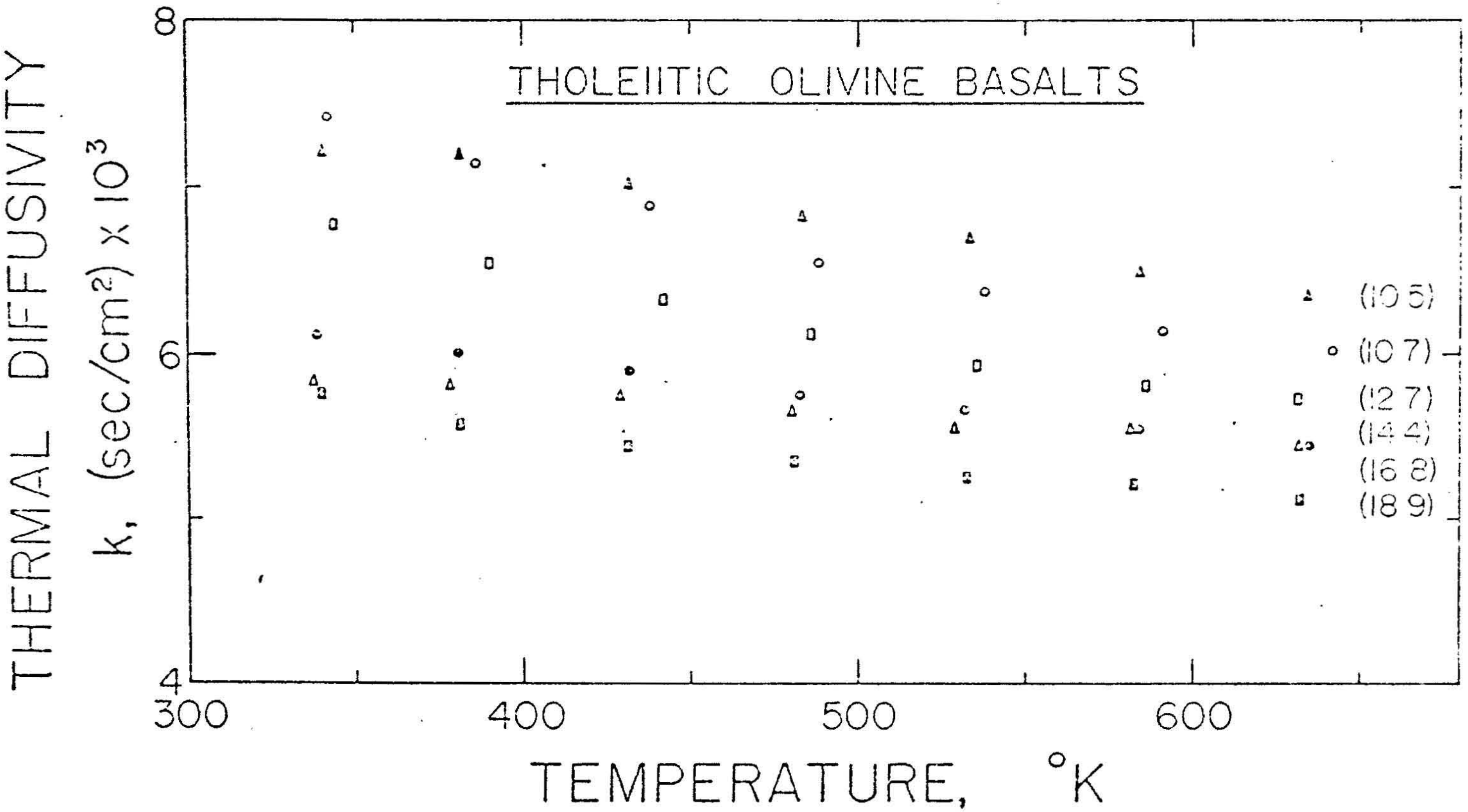

Figure 7. Temperature dependence of thermal diffusivity k of 6 tholeiitic olivine basalts of varying porosity (10.5-18.9%).

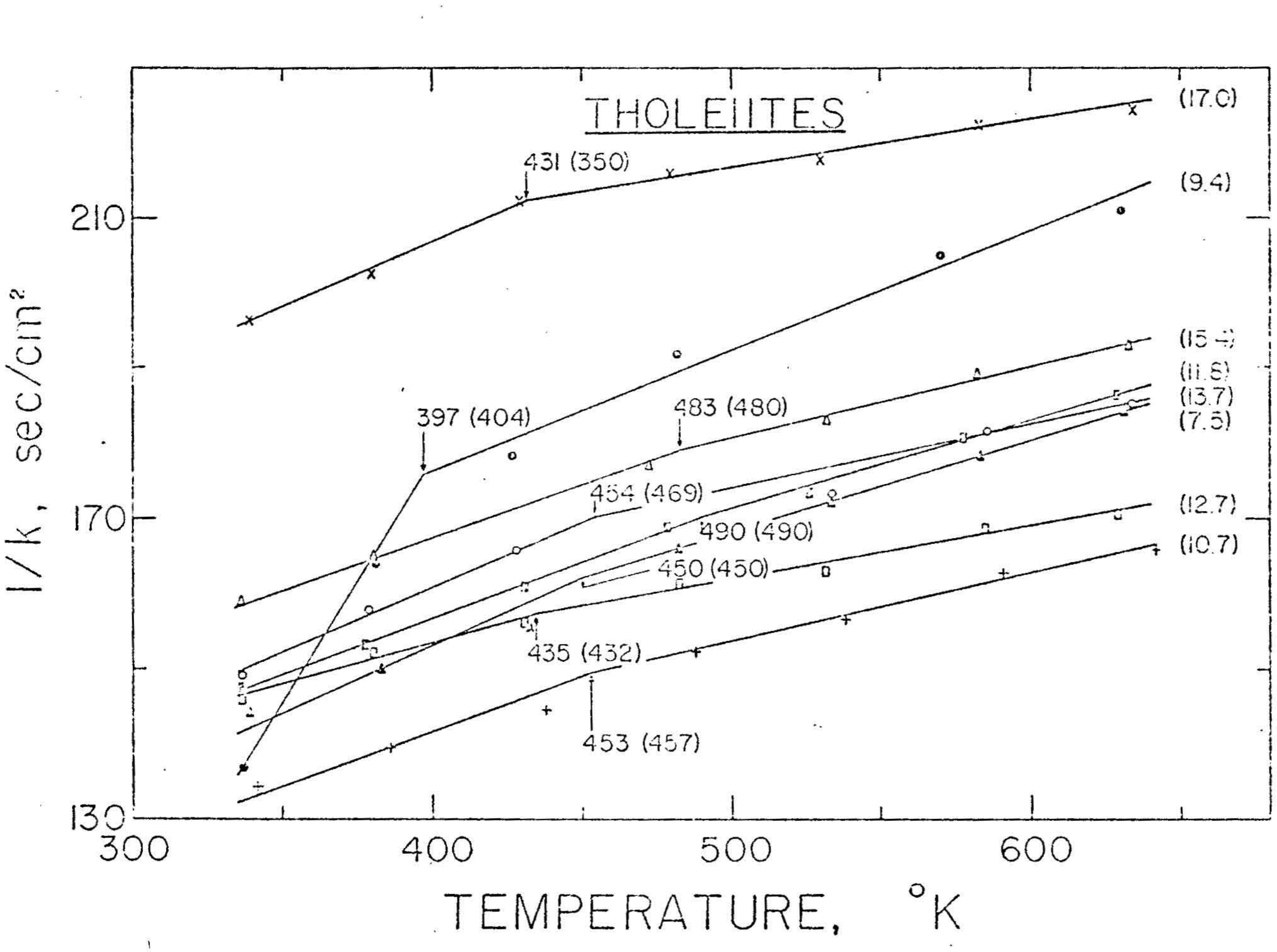

Figure 8. 1/k vs. T for tholeiites. The values of θ_D, estimated from the change in slope, are indicated by arrow (designated as $\theta_{thermal}$) and those calculated from the elastic data are shown in parentheses (designated as $\theta_{acoustic}$).

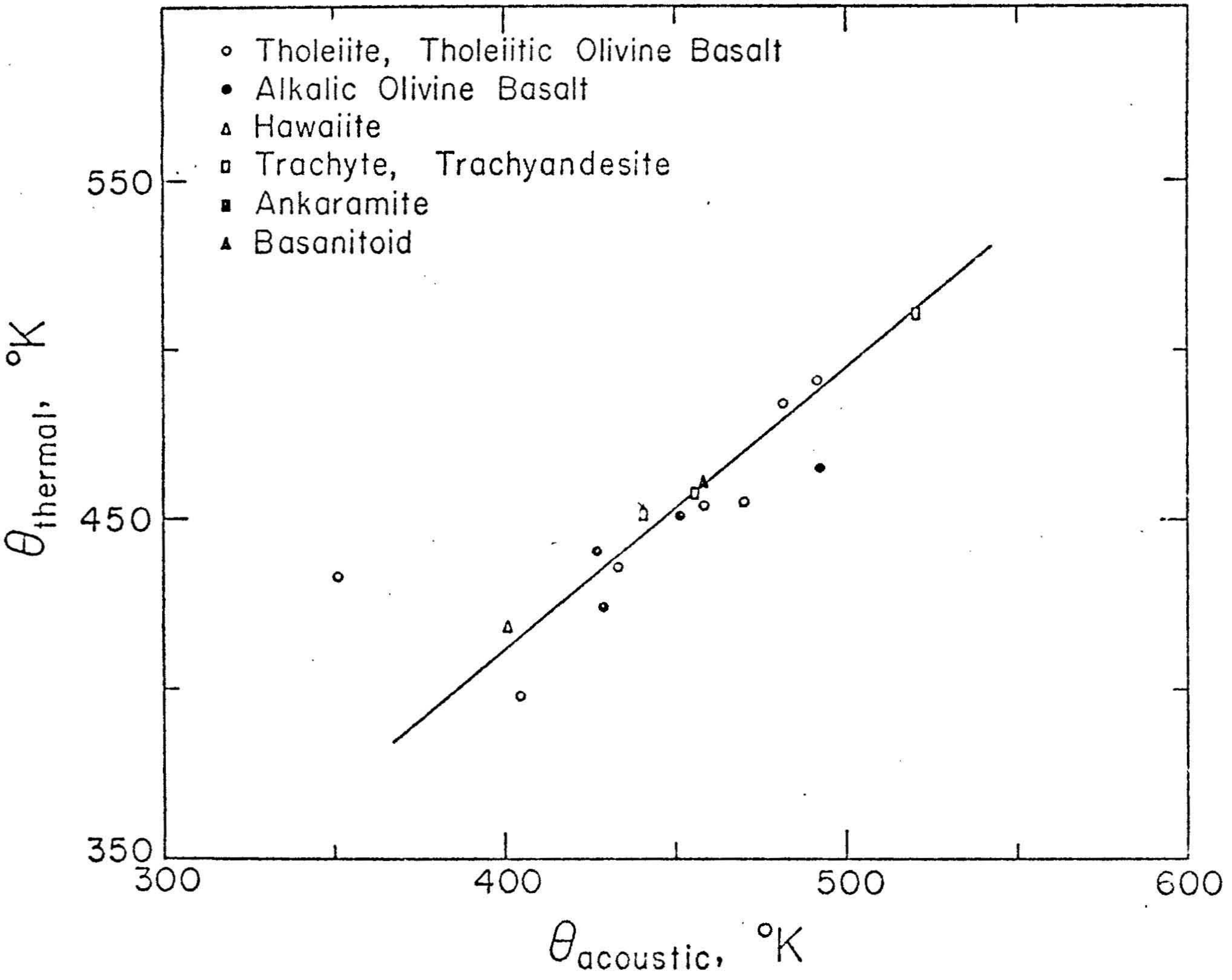

Figure 9. Comparison of the Debye temperature values estimated from thermal and elastic measurements, respectively.

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 properties 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) at 1 kbar.

(b) V_p and V_s and Q^{-1} measurement in dry and saturated samples as a function of pressure (The experimental work related to Q^{-1} measurements on basalts will be conducted in collaboration with Dr. B. Tittman, Rockwell International, Thousand Oaks, California; some laboratory work will be conducted at the Rockwell International laboratory for crosschecking results.).

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

(d) correlation among the above physical properties.

(ii) To correlate the laboratory and logging data available for both geothermal holes.

B. Laboratory Studies of the Hawaiian Basalts

It is planned to complete the ongoing laboratory investigation 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.

(iii) 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 diffusivity and elasticity of Hawaiian basalts, in preparation.

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BUDGET

Physical Properties of Rocks - Task 2.7

A.	Salaries and Wages		
	1. Post-doctorate Assist., 75% (2.5 mos. @ $9,607/yr.)	$2,001	
	2. Grad Assist., 50% for 8 mos., @ $441/mo., 100% 3 sum. mos.	6,294	
	Total Salaries and Wages		$ 8,295
B.	Fringe Benefits		818
C.	Equipment		
	1. Digital Recorder (Hewlett Packard, Model 7210A) for thermal diffusivity and Q^{-1} measurements		3,750
D.	Expendable Equipment and Supplies		1,900
E.	Travel		
	1. Domestic		900
F.	Publications		100
G.	Other Direct Costs		
	1. Computer and xerox services	115	
	2. Communications	200	
	3. Freight charges	100	
	TOTAL OTHER DIRECT COSTS		415
H.	Total Direct Costs		16,178
I.	Indirect Cost (46% of Salaries and Wages)		3,816
J.	Total Cost		$ 19,994

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

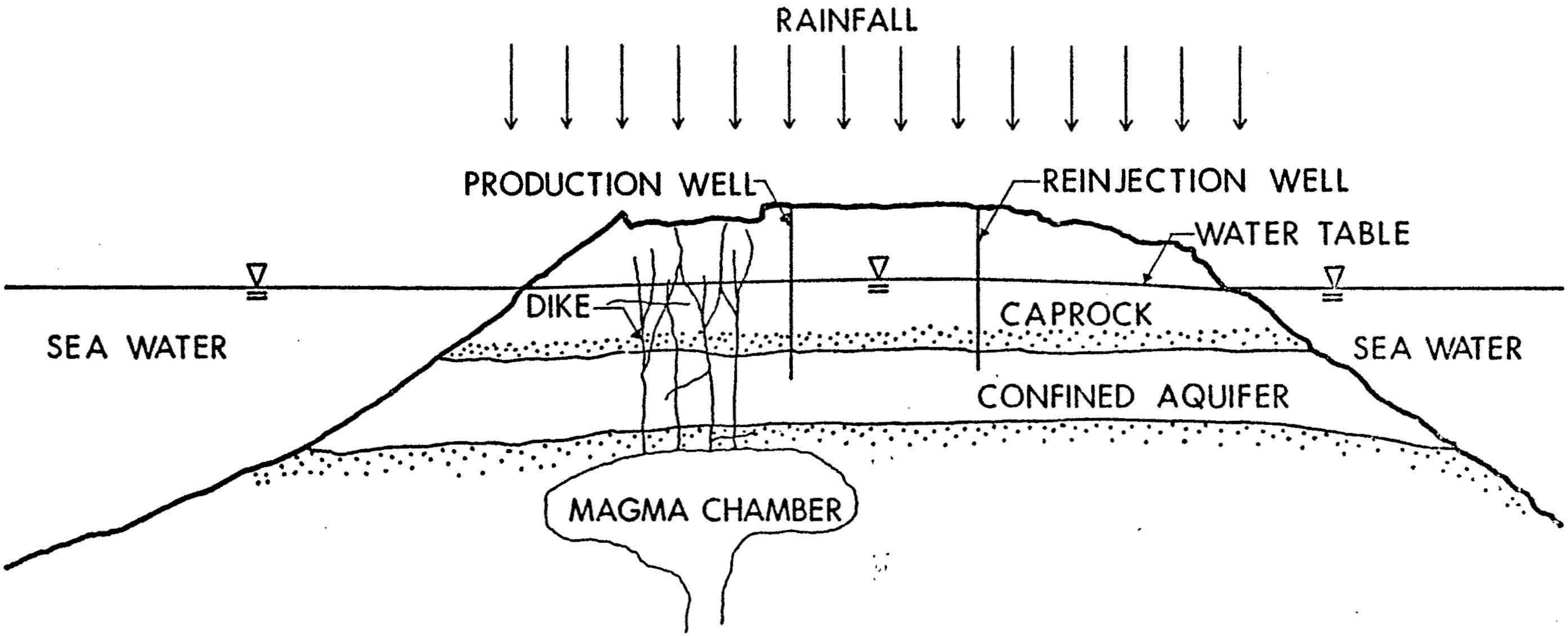

Fig. 1 Island Aquifer with Geothermal Heat Source

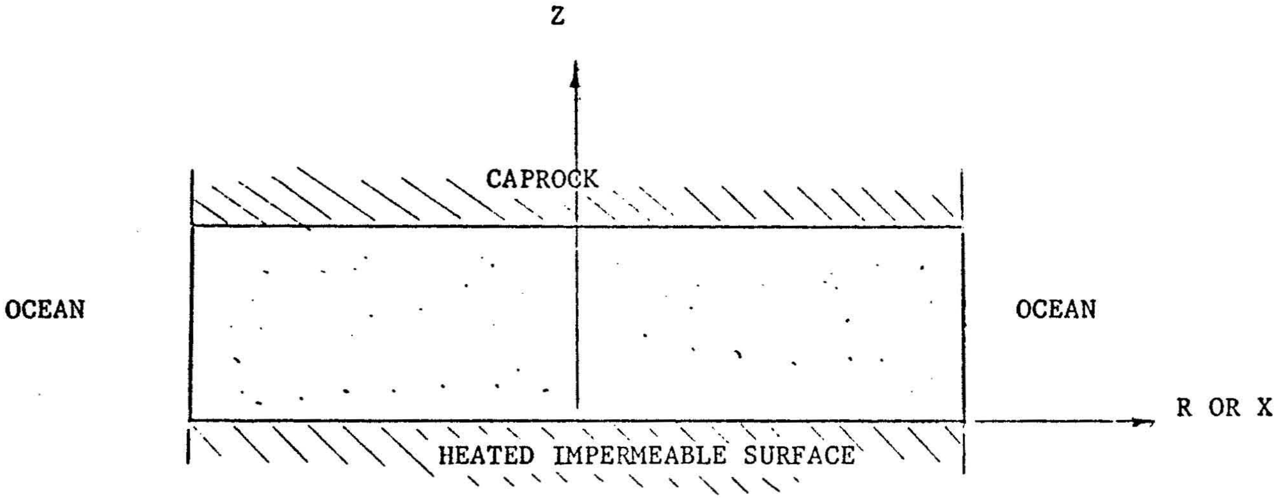

FIG. 2 ISLAND AQUIFER HEATED FROM BELOW

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

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

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

where

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

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

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 $\tau = 0.001$ 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 $\tau = 0.035$ 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

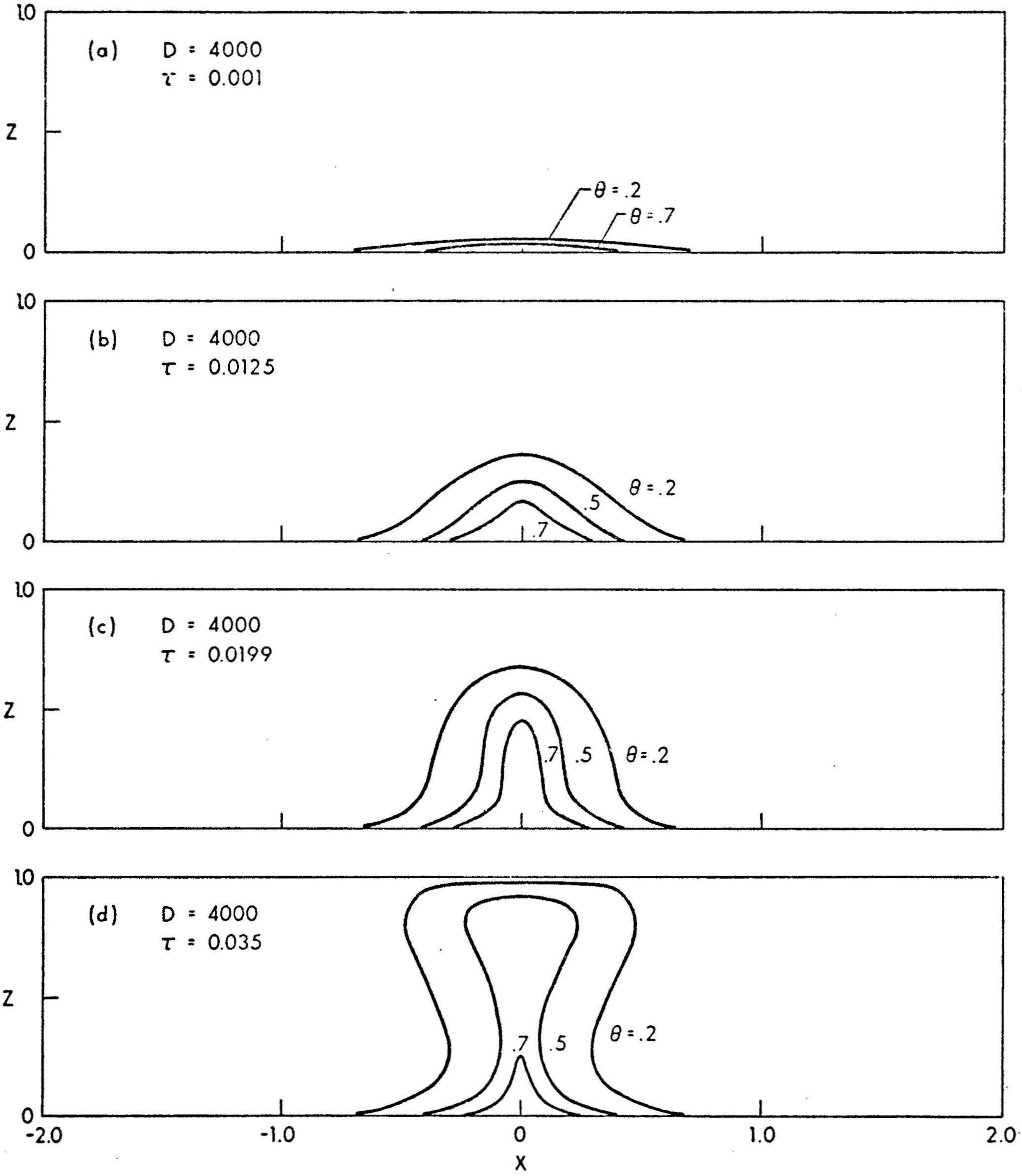

FIG. 3 DEVELOPMENT OF ISOTHERMS IN A GEOTHERMAL RESERVOIR AT D = 4000

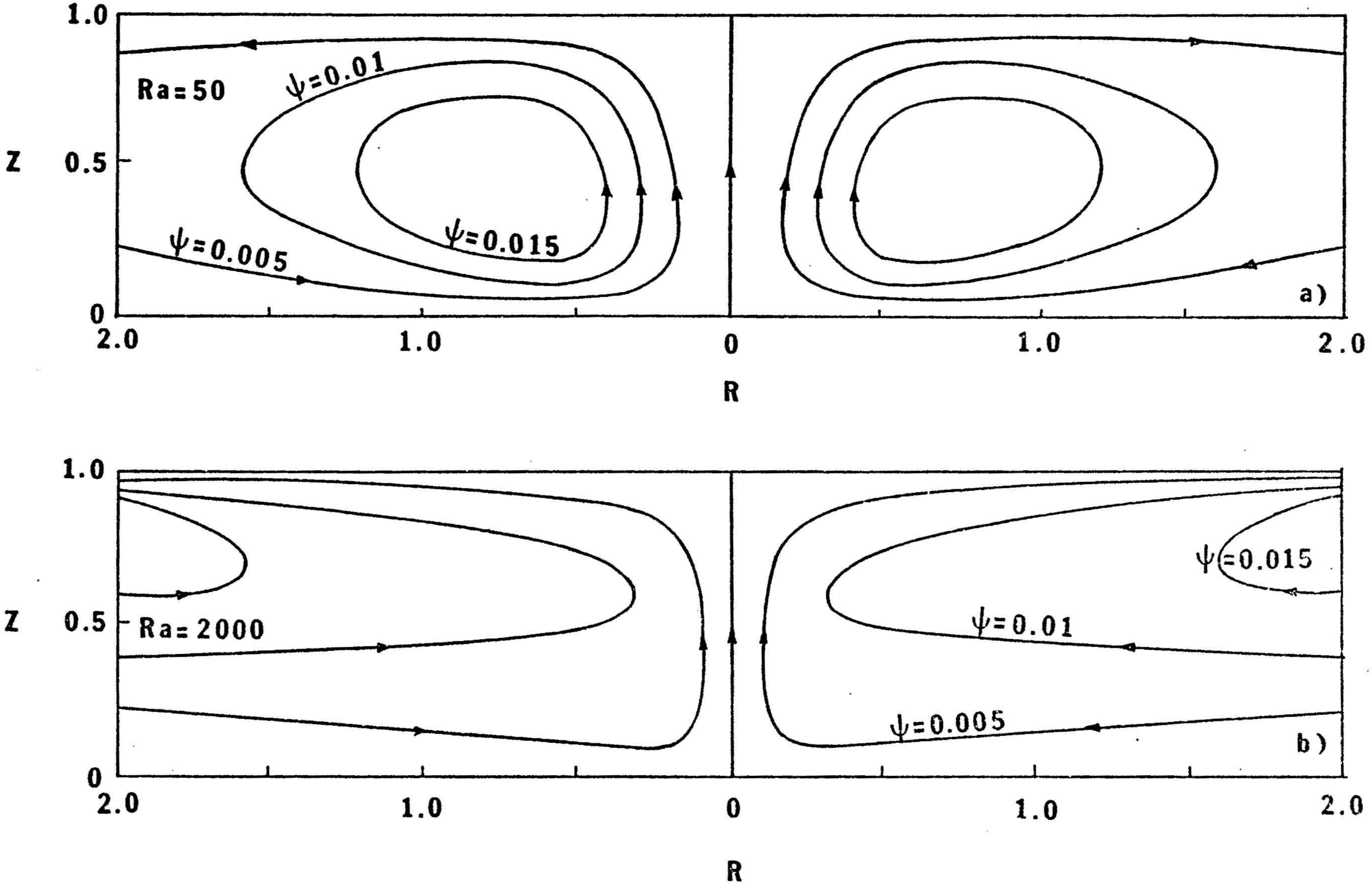

FIG. 4 STREAMLINES FOR A CYLINDRICAL ISLAND AQUIFER

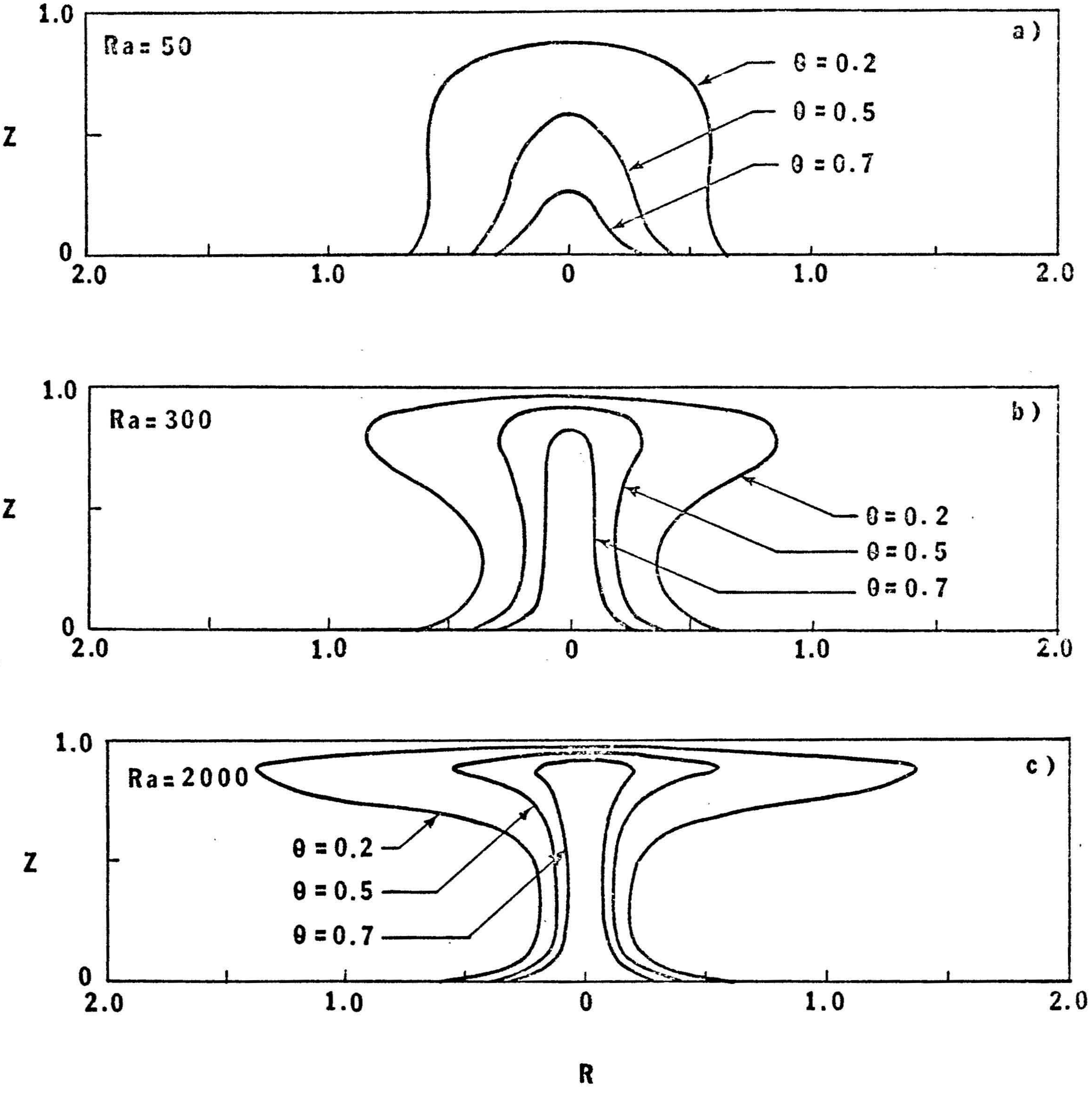

Fig. 5 Temperature Contours in a Cylindrical Island Aquifer with Caprock Temperature Specified

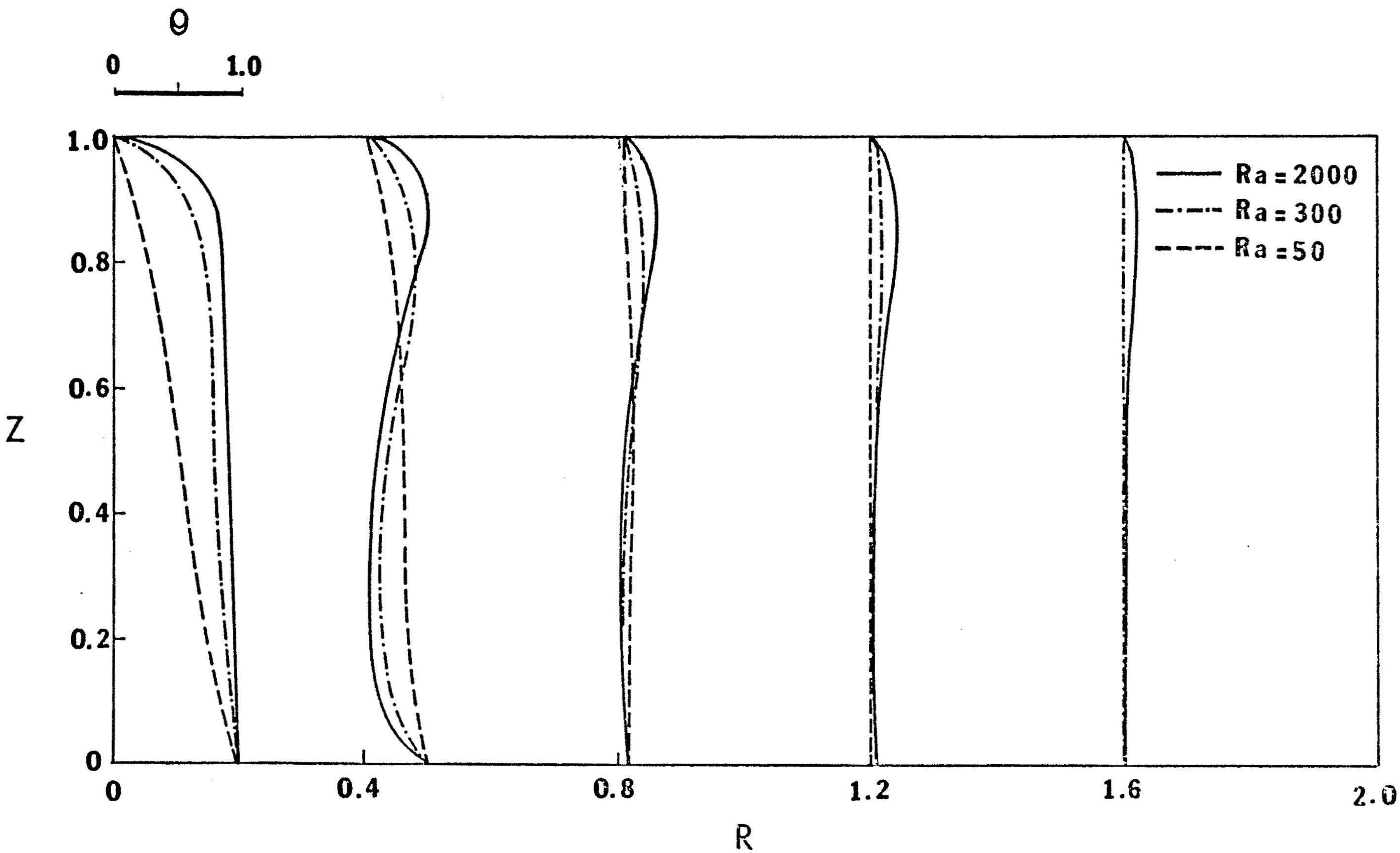

Fig. 6 Vertical Temperature Profiles in a Cylindrical Island Aquifer with Caprock Temperature Specified

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

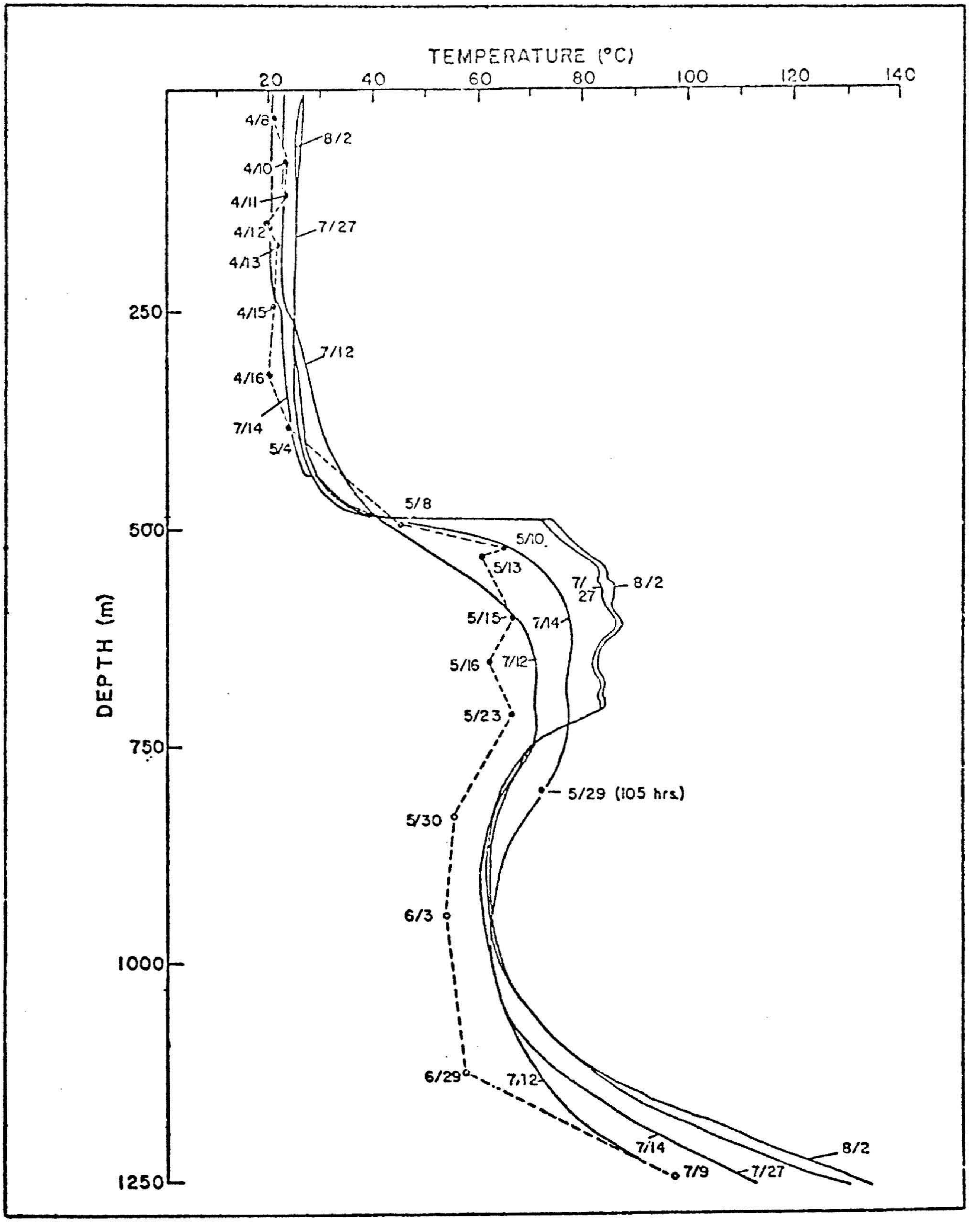

FIG. 7 TEMPERATURE PROFILES IN THE KILAUEA DRILL HOLE MEASURED BY KELLER

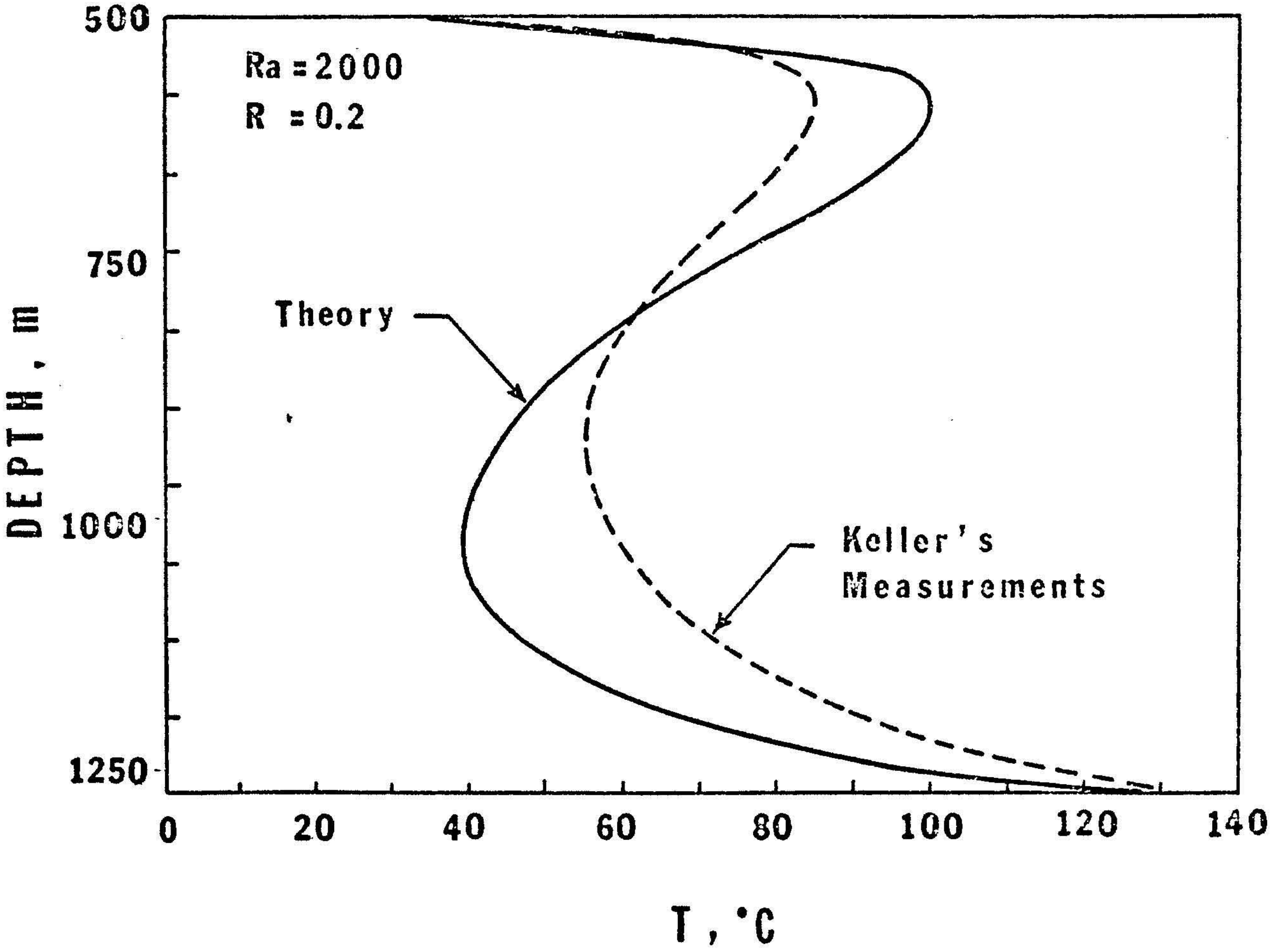

FIG. 8 COMPARISON OF THEORY AND MEASUREMENTS

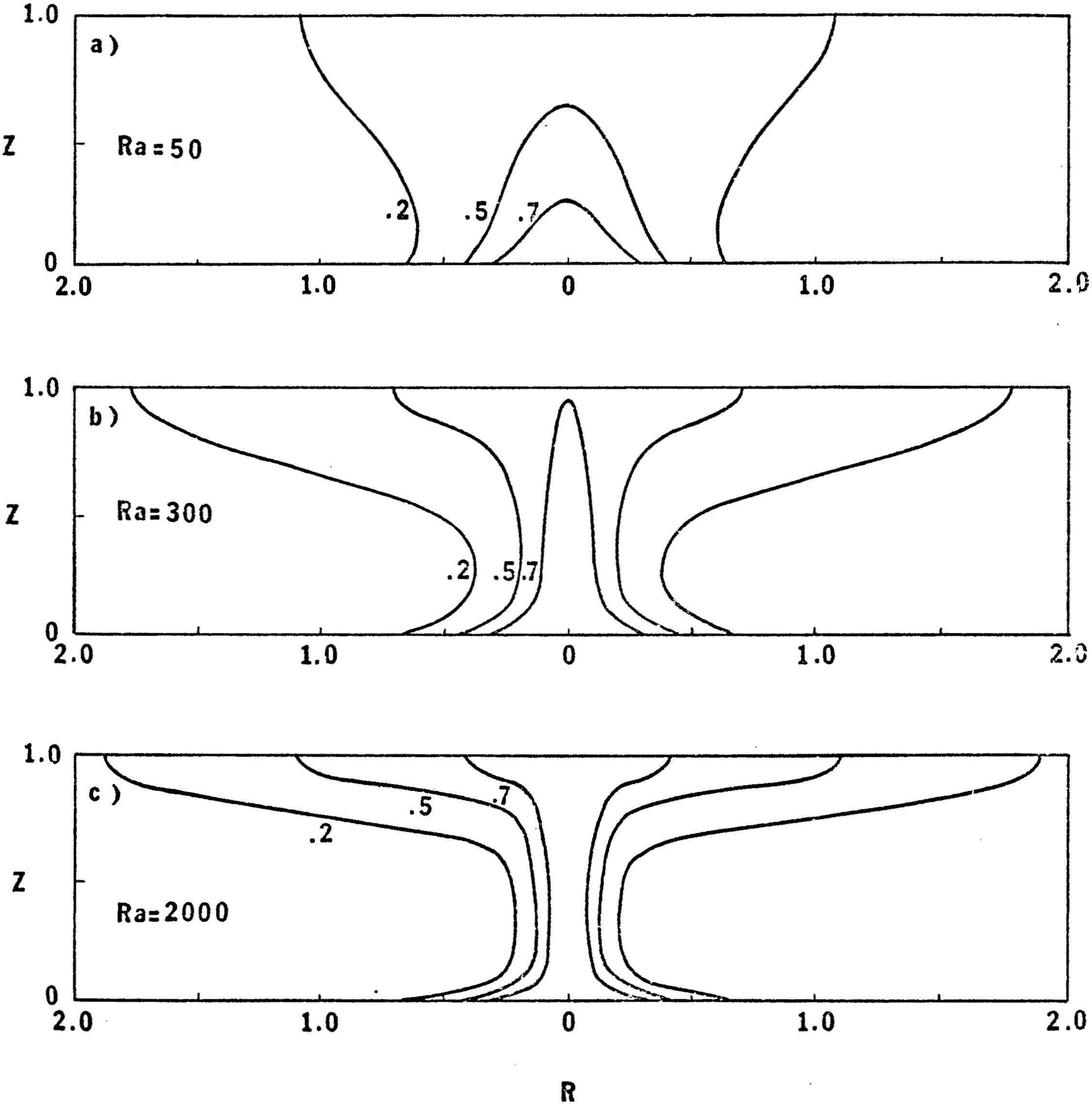

Fig. 9 Temperature Contours in a Cylindrical Island Aquifer With Adiabatic Caprock

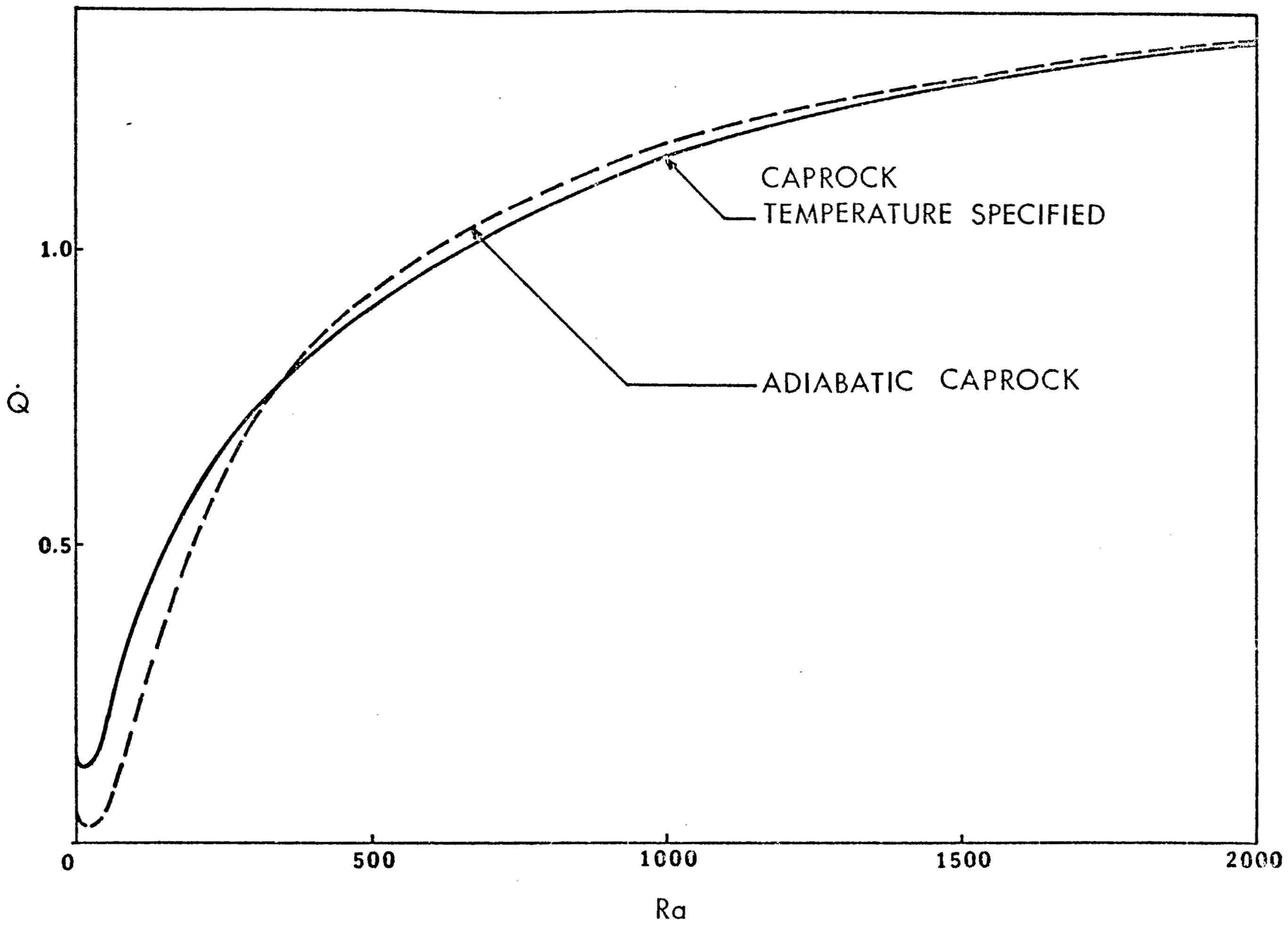

FIG. 10 EFFECT OF THERMAL BOUNDARY CONDITION OF CAPROCK ON SURFACE HEAT TRANSFER RATE OF THE BEDROCK

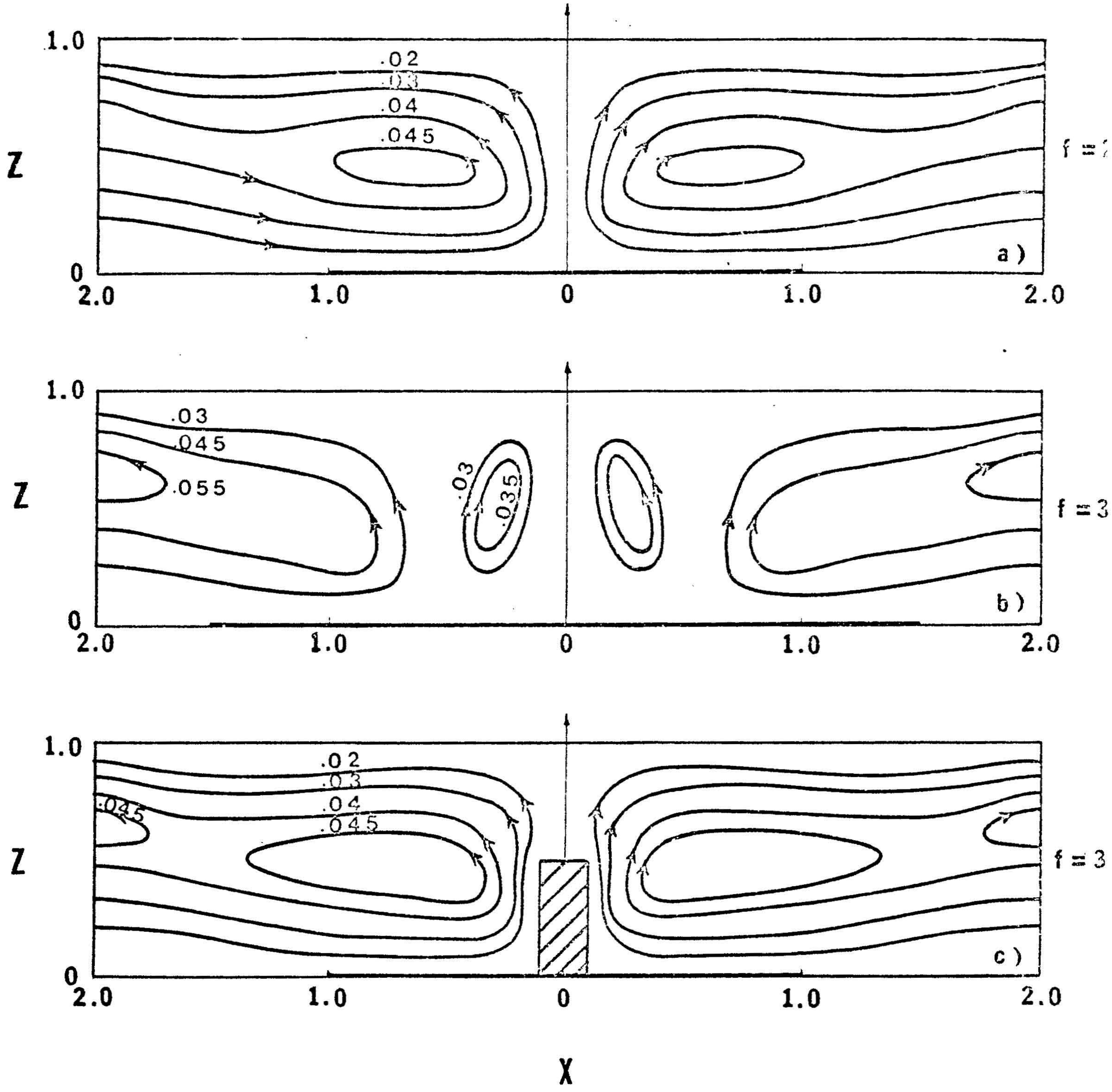

Fig. 11 The Effects of Heating Length and Magmatic Intrusion on Streamlines in a Rectangular Reservoir with Heat-Conducting Caprocks

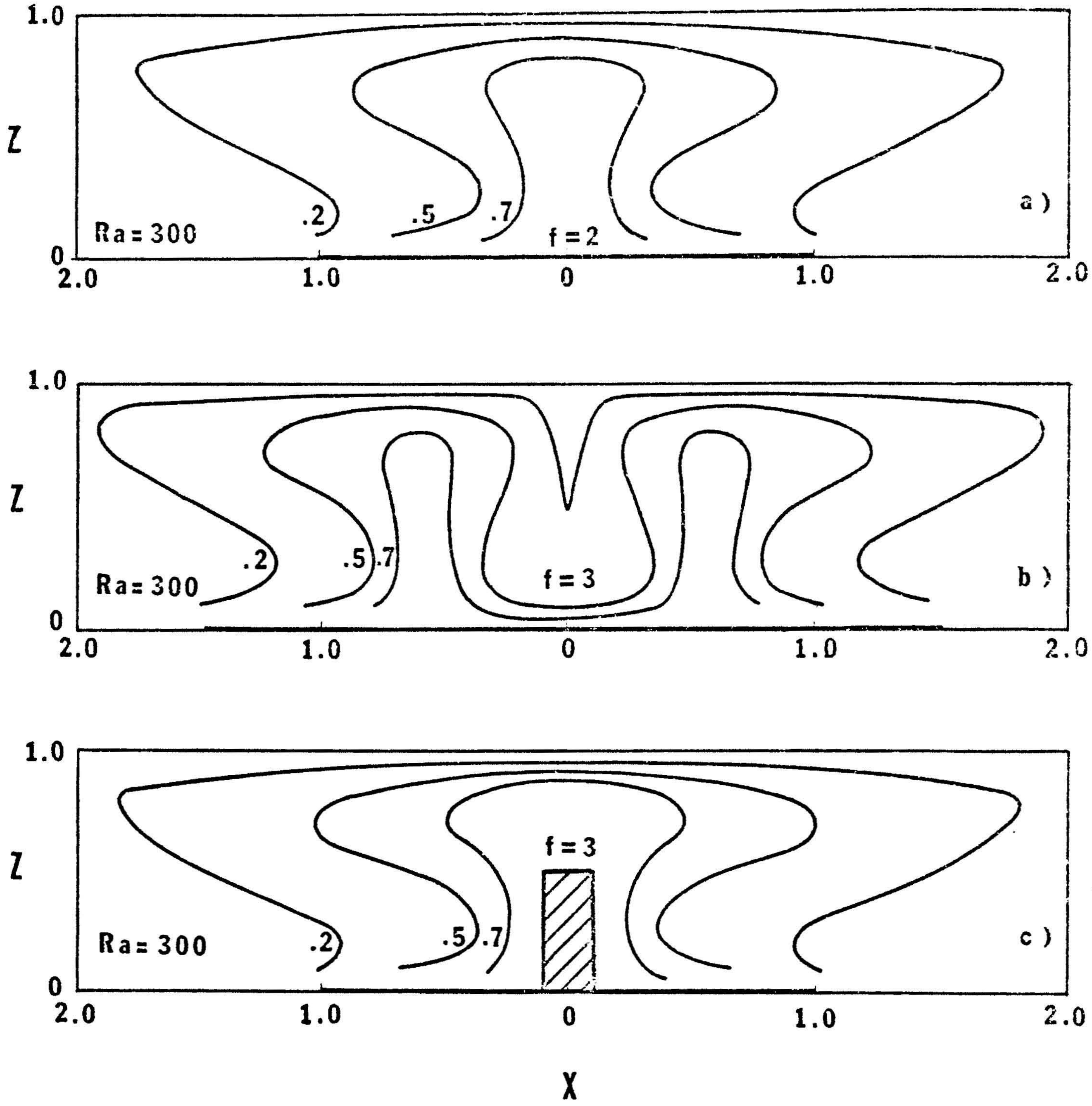

Fig. 12 The Effects of Heating Length and Magmatic Intrusion on the Isotherms in a Rectangular Reservoir with Heat-Conducting Caprocks

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

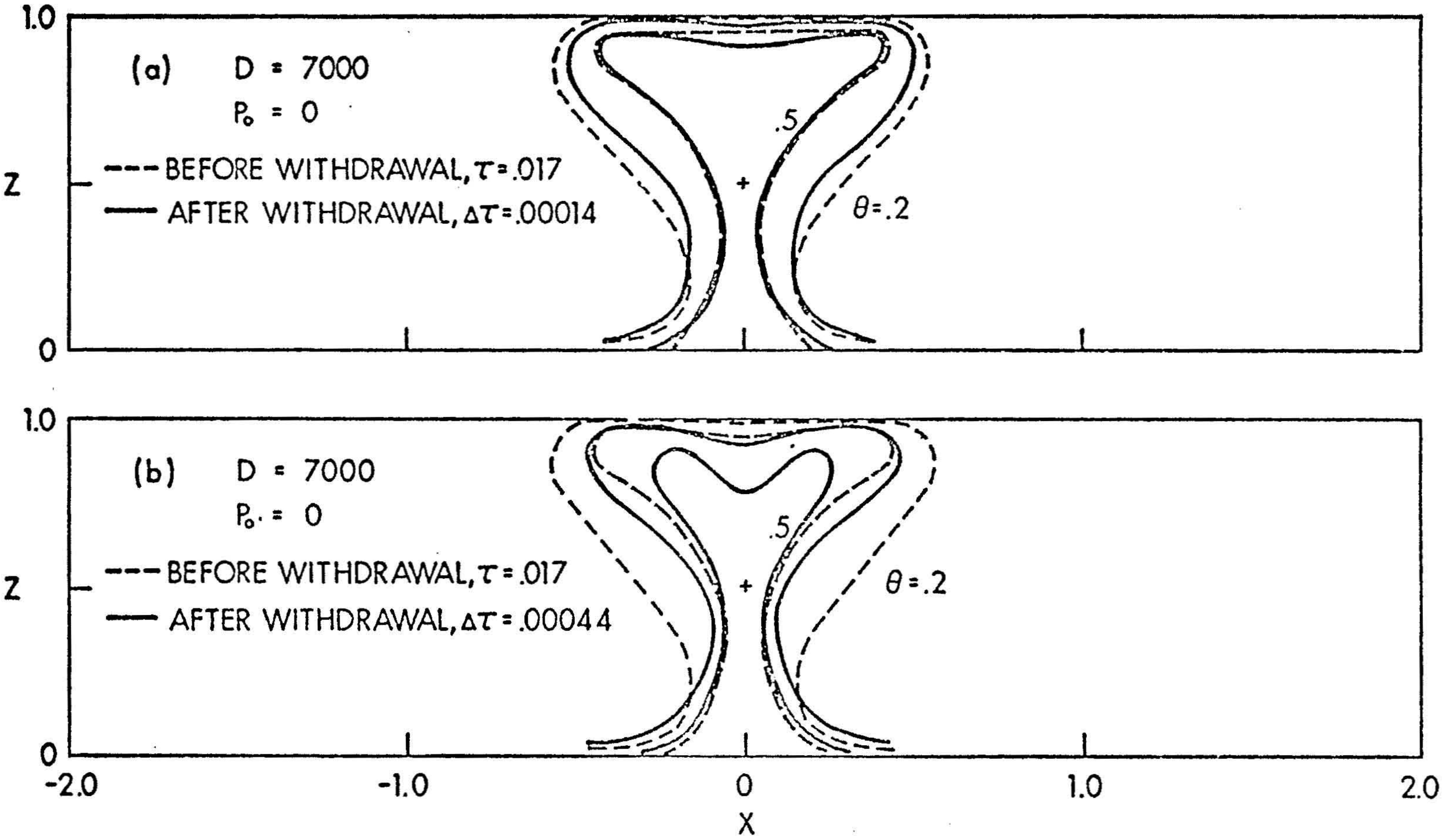

FIG. 13 CONTRACTION OF ISOTHERMS IN A GEOTHERMAL RESERVOIR RESULTING FROM WITHDRAWAL OF FLUIDS FROM A POINT SINK

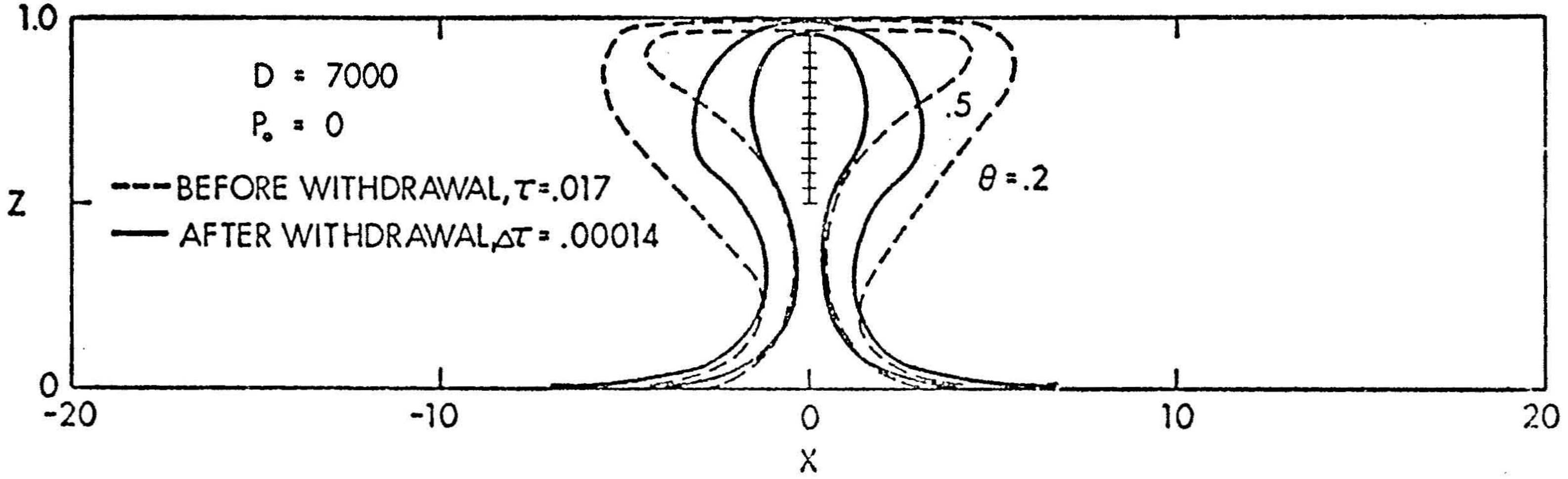

Fig. 14 Contraction of Isotherms in a Geothermal Reservoir Resulting from Withdrawal of Fluids from a Line Sink

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]

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

and

$$q_1 = 0.88Sk(T_w - T_\infty)^{3/2}\left[\frac{\rho_\infty g\beta KL}{\mu\alpha}\right]^{1/2} , \tag{4}$$

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]

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

and

$$q_2 \cong 1.4 S k (T_w - T_\infty)^{4/3} \left[\frac{\rho_\infty g \beta K L}{\mu \alpha} \right]^{1/3} . \tag{6}$$

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 modifications 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.

Budget

The program plan discussed in this proposal is based upon an initital request of $44,947. The attached budget totals only $23,000, and reflects the cut-back prescribed by the Program Manager, following the September 8 review. However, the Program Manager also indicated a willingness to endeavor to identify the additional $21,947 elsewhere within ERDA. If the additional funding becomes available, the program plan as outlined will be completed. If only $23,000 is available, the scope of the study will be reduced accordingly.

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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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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

Task 3.1 -- Numerical Modelling

1. Salaries and Wages		$12,937
Scientific Discipline Personnel		
Faculty Associate, P. Cheng, Professor-100% of time for 1-1/2 summer months @ $2658 per month	3,987	
Faculty Associate, K.H. Lau, Associate Professor-100% of time for 3/4 summer months @ $1912 per month	1,434	
1 Graduate Assistant, D. Epp @ $982 per month-100% of time for 3 months	2,946	
1 Graduate Assistant @ $914 per month-50% of time for 10 months	4,570	
2. Fringe Benefits		655
3. Equipment		-0-
4. Travel		1,000
Domestic	1,000	
Foreign	-0-	
5. Other Direct Costs		2,457
Supplies and Materials	357	
Publications	500	
Computer Services	1,600	
6. Indirect Charges: 46.00% of Salaries & Wages		5,951
Total Task 3.1 Costs		$23,000

Task 3.2

WELL TEST AND ANALYSIS PROGRAM

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

With the completion of the drilling of HGP-A, installation of a slotted liner, and indications of extremely high bottom hole temperatures, the next major phase in the Hawaii Geothermal Project is a test and analysis program designed to determine the properties of the well, the fluid, and the reservoir. The program described below was formulated as a first step to obtain this information.

The objectives of the well test and analysis program are:

1. Determine well and reservoir characteristics
2. Obtain data useful for drilling future wells
3. Determine problem areas relative to well production
4. Determine possible environmental problems
5. Remedy possible skin damage in well

Figure 1 gives the casing plan for HGP-A, and Figure 2 is a listing of the slotted and plain liner locations in the bottom 4,000 ft. of the well. Figure 3 contains a detailed drawing of the slotted liner section.

A brief record of important events which have happened to the well since the completion of drilling on April 27, is given in Table 1. As noted there, the slotted liner at the bottom of the well was installed during the period May 27 to June 1, Water.injection tests were completed on June 6 using the mud pumps that were still present at the drill site. HGP-A has been flashed four times for varying periods, once on July 2, a second time on July 19, a third time on July 21 to check instrumentation, and then a longer period of four hours on July 22 to obtain preliminary values for wellhead pressure and temperature, and total mass flow rate. Beginning April 29, temperature

FIGURE 1
HGP-A CASING PROGRAM

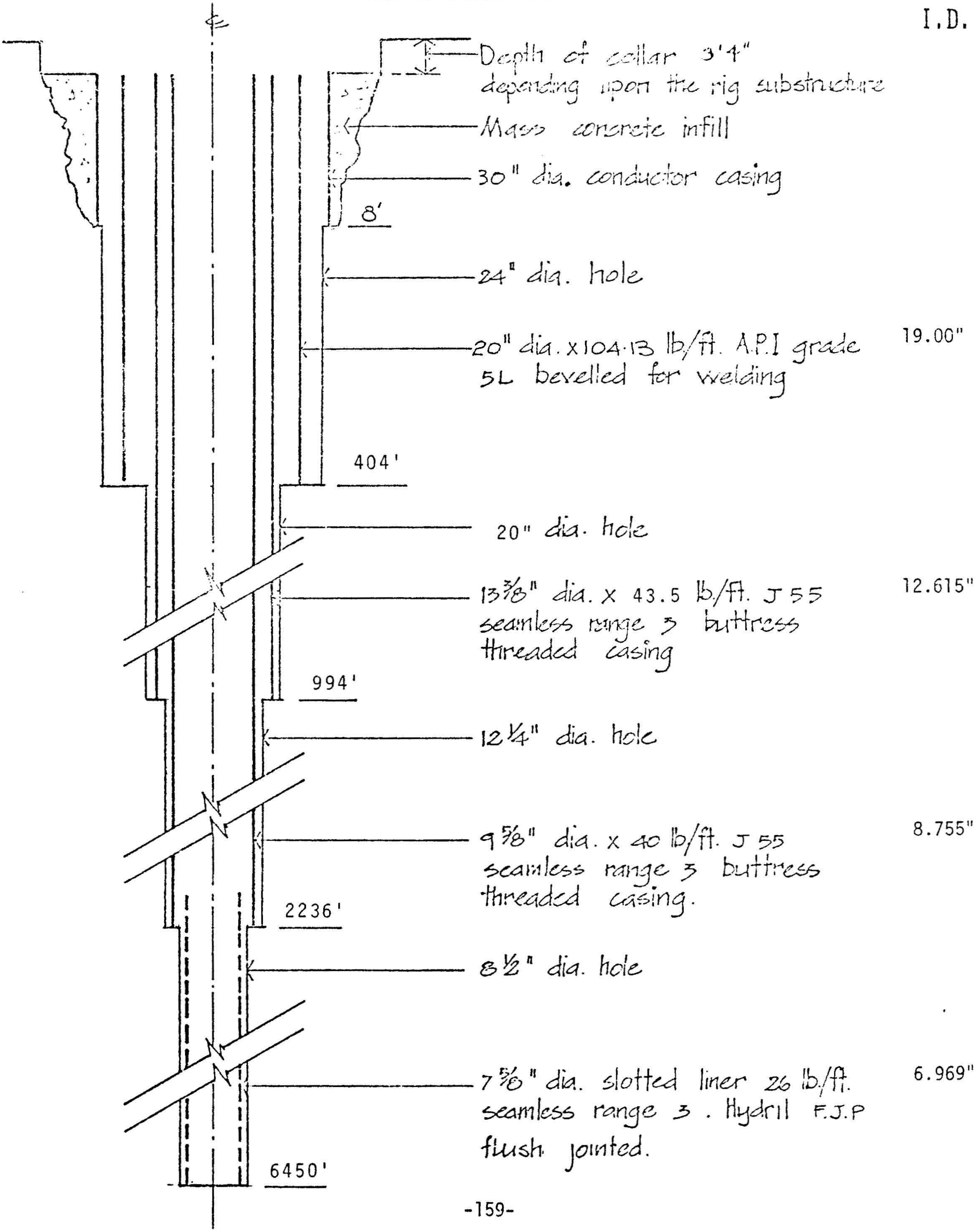


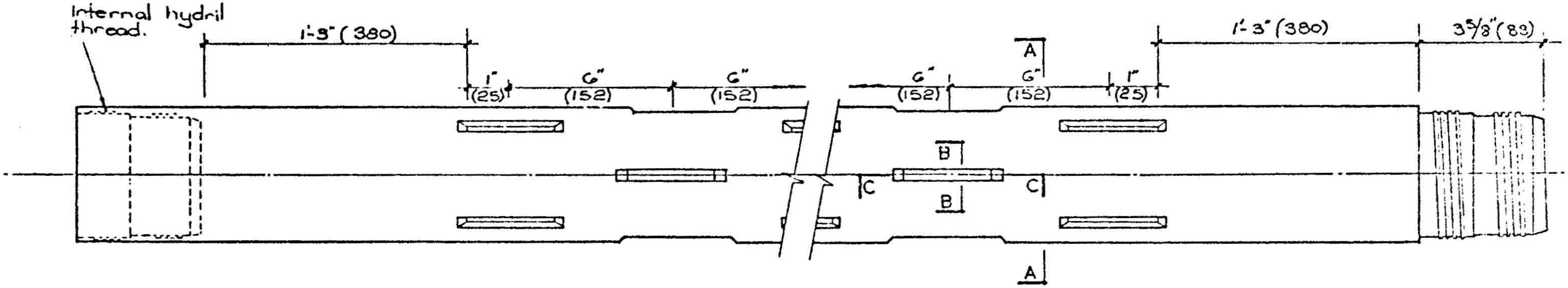
FIGURE 2
HGP-A SLOTTED/PLAIN LINER LOCATIONS

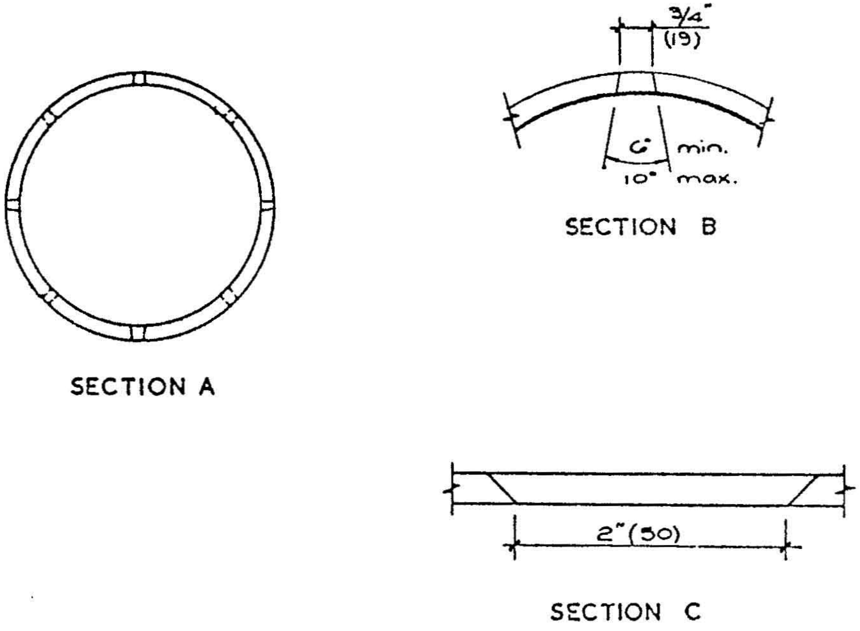
	2146.70'								
109		87		65	X	43		21	
108		86	X	64		42	X	20	X
107		85		63		41		19	
106	X	84		62	X	40	X	18	X
105		83		61		39		17	
104		82		60	X	38	X	16	X
103		81	X	59		37		15	
102		80		58	X	36	X	14	
101	X	79		57		35		13	X
100		78		56	X	34	X	12	
99		77	X	55		33		11	
98		76		54	X	32	X	10	X
97		75		53		31		9	
96	X	74		52	X	30	X	8	
95		73	X	51		29		7	X
94		72		50	X	28	X	6	
93		71		49		27		5	
92		70		48	X	26	X	4	X
91	X	69	X	47		25		3	
90		68		46	X	24	X	2	
89		67		45		23		1	X 6450'
88		66		44	X	22	X		

Note: (1) X = Slotted liner section

(2) Joints have been numbered starting from the bottom of the hole

(3) Average length of liner section = 39.51'





NOTES:

Normal dimensions of slots - 2" x 3/4" (50×

Minimum area of slots - 1.5 sq.in. (9630 m

Number of slots per foot - 16

Area of slot per foot - 24 sq. in (154840m

Metric equivalents of dimensions given in brackets.

FIGURE 3
HGP-A HYDRIL CASING - SLOTTING DETAIL

TABLE 1

WELL TEST CHRONOLOGY OF HGP-A
1976

APRIL 27	DRILLING COMPLETED TO 6450 FEET
APRIL 29 - MAY 24	WELL BORE TEMPERATURE PROFILES MEASURED
MAY 27 - JUNE 1	SLOTTED LINER INSTALLED
JUNE 6	WATER INJECTION TESTS
JUNE 7 - 20	WELL BORE TEMPERATURE AND PRESSURE PROFILES MEASURED
JUNE 22 - 24	UNSUCCESSFUL ATTEMPT TO FLASH HGP-A
JUNE 26 AND 30	TEMPERATURE AND PRESSURE PROFILES MEASURED
JULY 2	HGP-A FLASHED FOR 4 MINUTES
JULY 3 - 19	WELL FLOWED TWICE DAILY TO MAINTAIN CASING TEMPERATURE
JULY 19	WELL FLASHED FOR 50 MINUTES
JULY 20 - 21	WELL FLOWED TWICE DAILY TO MAINTAIN CASING TEMPERATURE
JULY 21	WELL FLASHED FOR 30 SECONDS
JULY 22	WELL FLASHED FOR 4 HOURS
JULY 22 - AUGUST 13	TEMPERATURE AND PRESSURE PROFILES MEASURED
AUGUST 19	WATER SAMPLES OBTAINED AT DIFFERENT DEPTHS IN WELL BORE
AUGUST 26 -	TEMPERATURE AND PRESSURE PROFILES MEASURED

and pressure profiles in the wellbore have been obtained at various times, and beginning August 19 water at different depths in the wellbore has been sampled in order to obtain chemical analyses of the water.

The four-hour well flashing on July 22 was accomplished using the wellhead instrumentation shown in Figure 4. The sonic flow, lip pressure method of James[1] was used to obtain total mass flow with lip pressure being measured at the end of a vertical 6" discharge tube. In addition, an 8" discharge tube mounted horizontally was also flowed for a brief time. Wellhead pressure and temperature were obtained from a bleedline controlled by a 2" valve.

Results of the four-hour flashing are shown in Figures 5 and 6 which give wellhead and lip pressure, and wellhead and lip temperature, respectively. The lip pressure at the end of four hours was 23 psig, which corresponds to a mass flow of about 220,000 lbs. per hour, assuming a specific enthalpy of 600 BTU per lb. Using this figure for specific enthalpy and assuming a conversion efficiency of 15% leads to a usable electric power equivalent of a little over 5 megawatts.

Figure 7 shows a plot of temperature versus pressure for HGP-A a few hours after the four-hour flashing on July 22. The number adjacent to each data point represents the depth of that data point with respect to the surface at the wellsite. Also on the figure is the boiling point curve for pure water. As can be seen, the flash point in the wellbore appeared to have reached a depth slightly greater than 4,600 feet below the surface at the wellsite.

Figures 8 and 9 are plots of temperature versus depth and pressure versus depth for HGP-A for the indicated times after the flashing on July 22, 1976.

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[1] James, Russell, "Measurement of Steam-Water Mixtures Discharging at the Speed of Sound to the Atmosphere," New Zealand Engineering, pp. 437-41, October 1966.

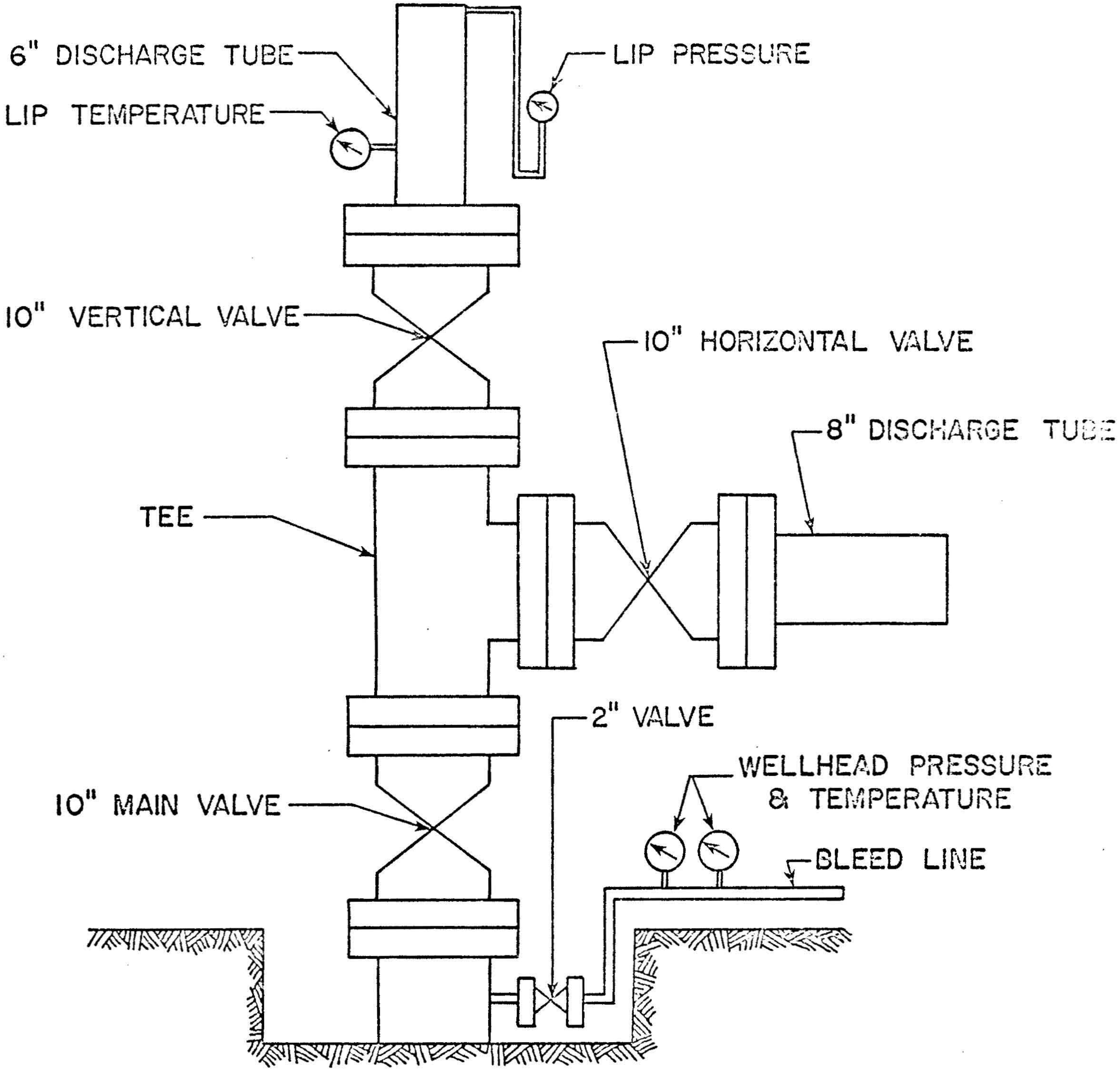


FIGURE 4

SCHEMATIC OF HGP-A WELLHEAD INSTRUMENTATION

FIGURE 5

HGP-A FLOW TEST, JULY 22, 1976
VARIATION IN WELLHEAD & LIP PRESSURE WITH TIME

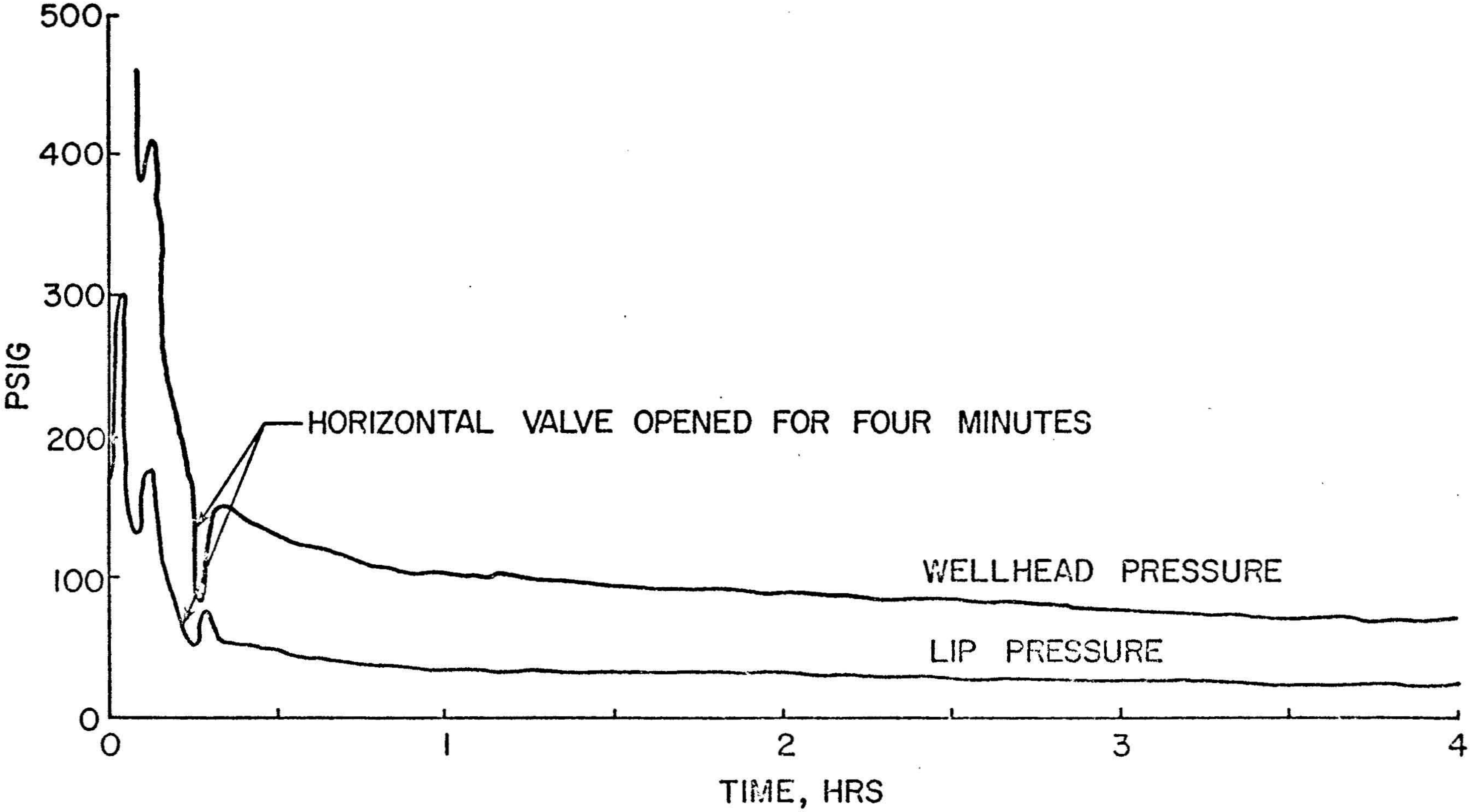
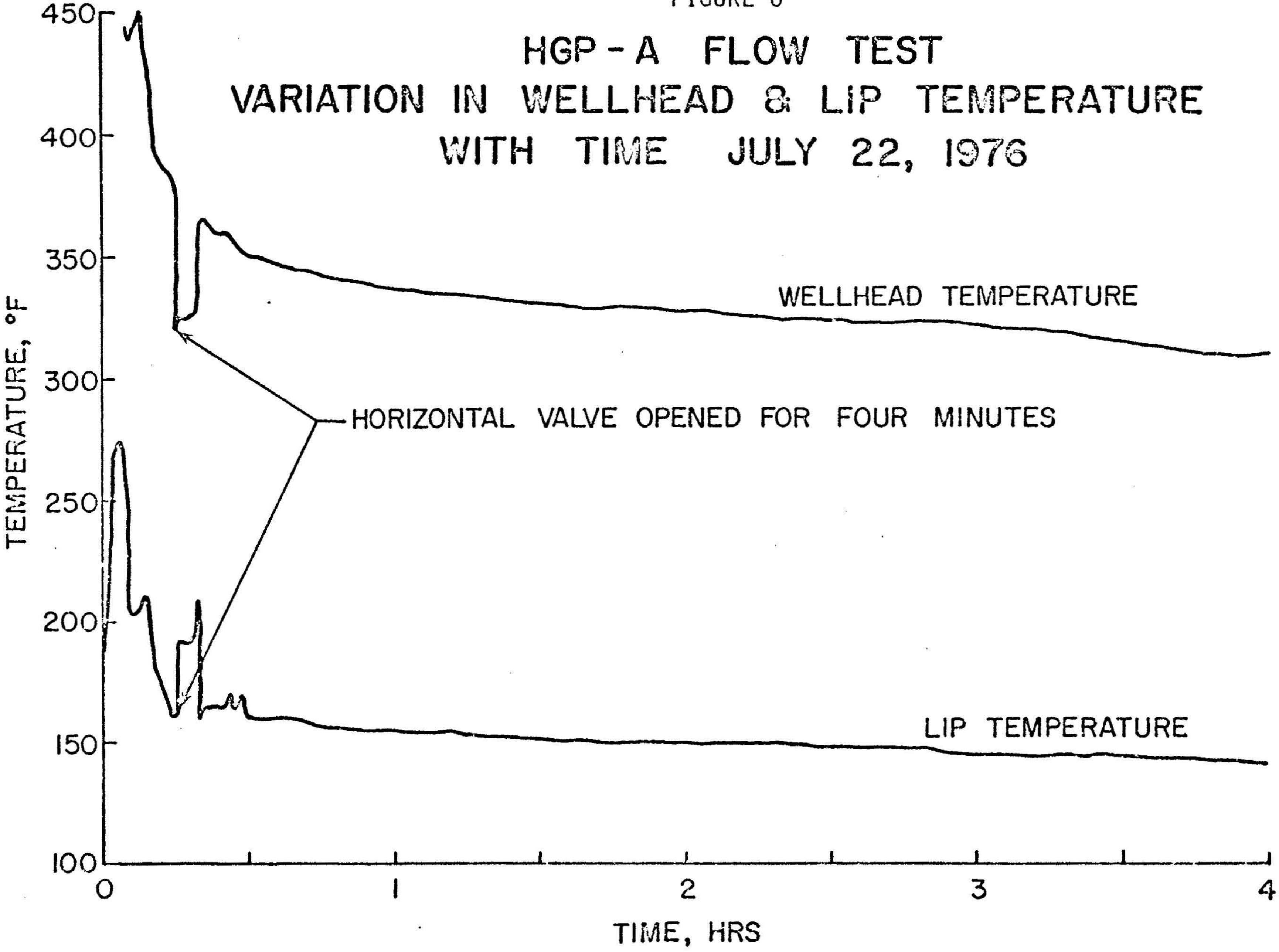


Figure 6

HGP - A FLOW TEST VARIATION IN WELLHEAD & LIP TEMPERATURE WITH TIME JULY 22, 1976



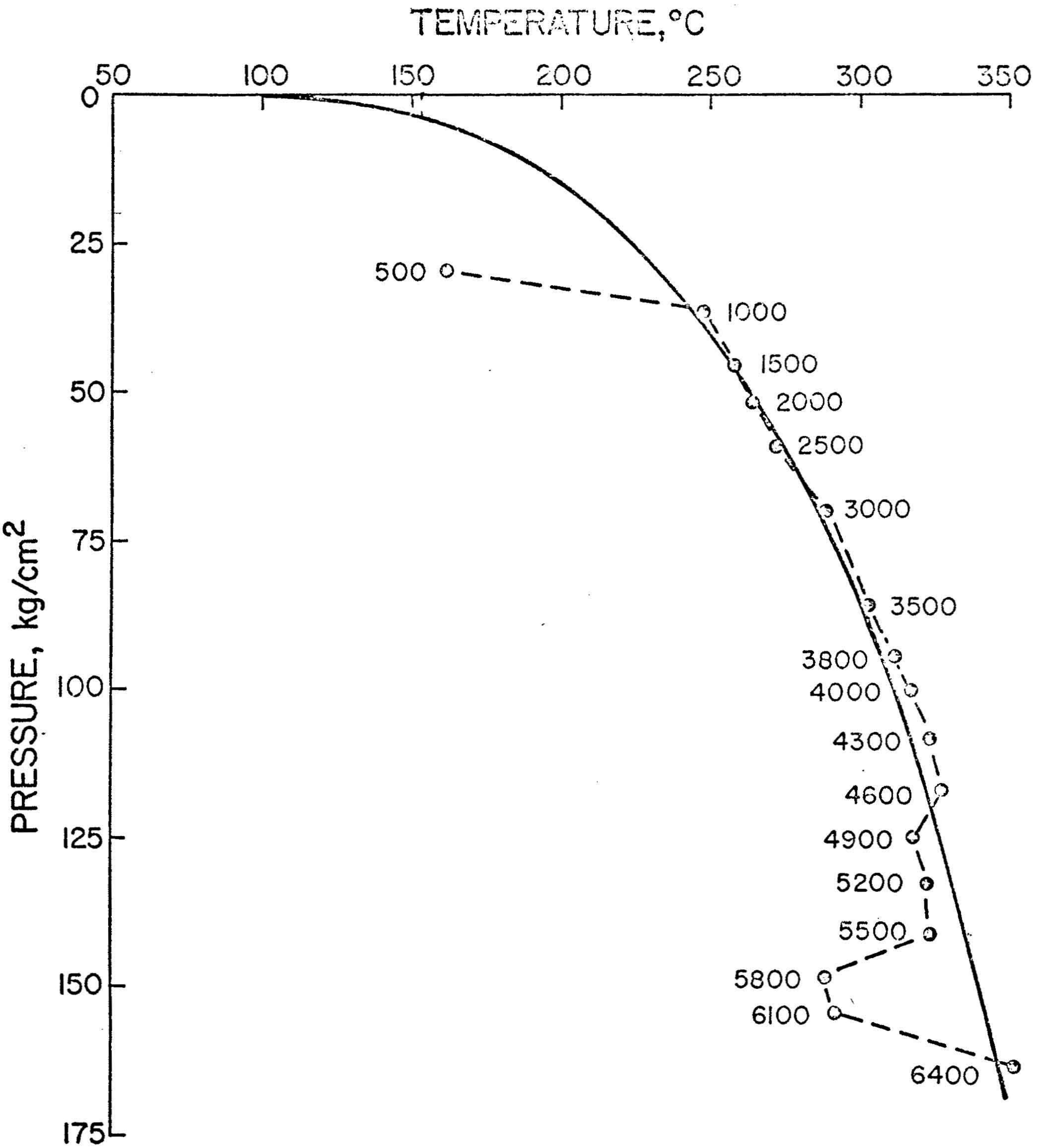


FIGURE 7

TEMPERATURE VS PRESSURE
FOR HGP-A
July 22, 1976
After Four-Hour Discharge

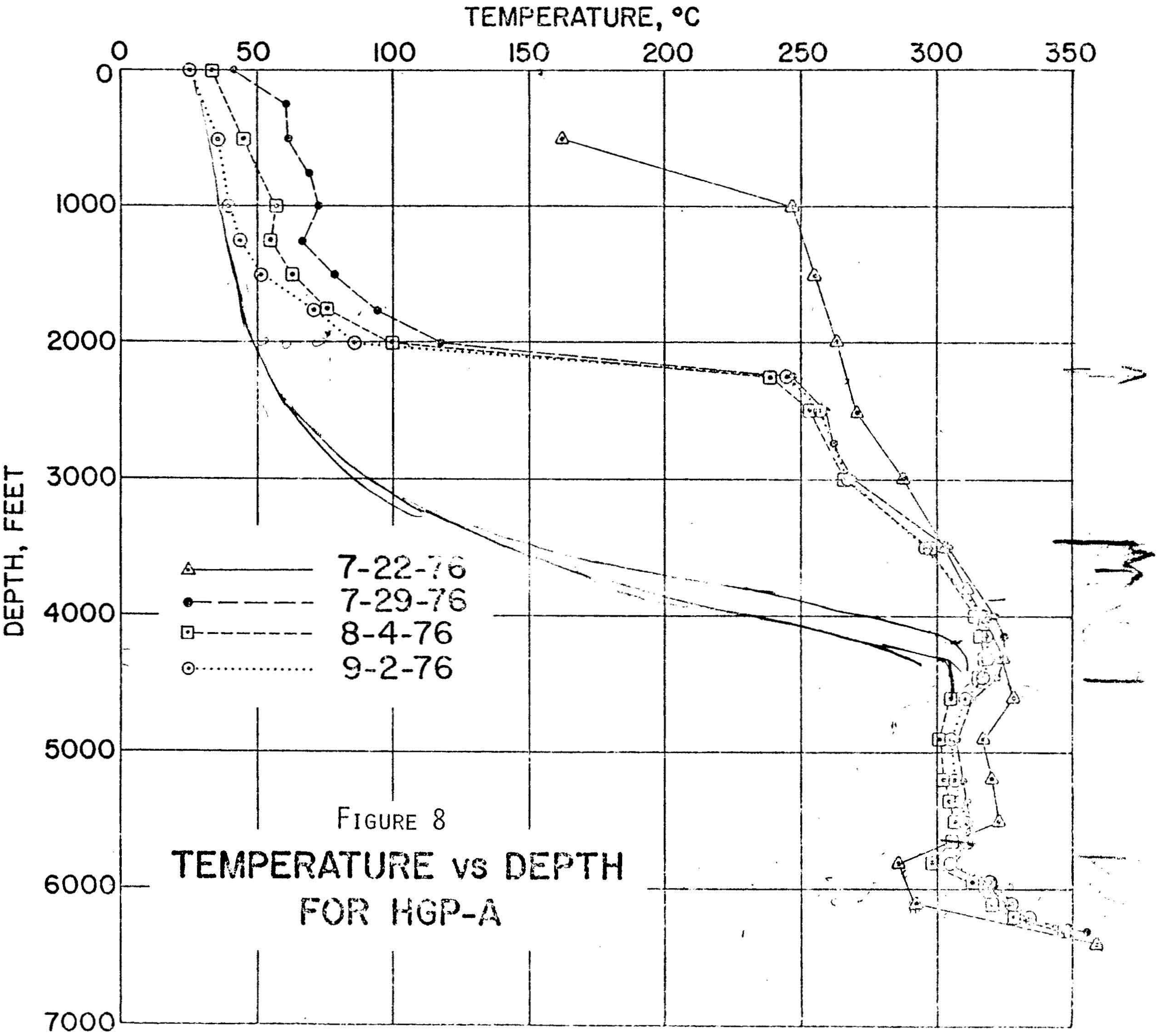


FIGURE 8

TEMPERATURE vs DEPTH FOR HGP-A

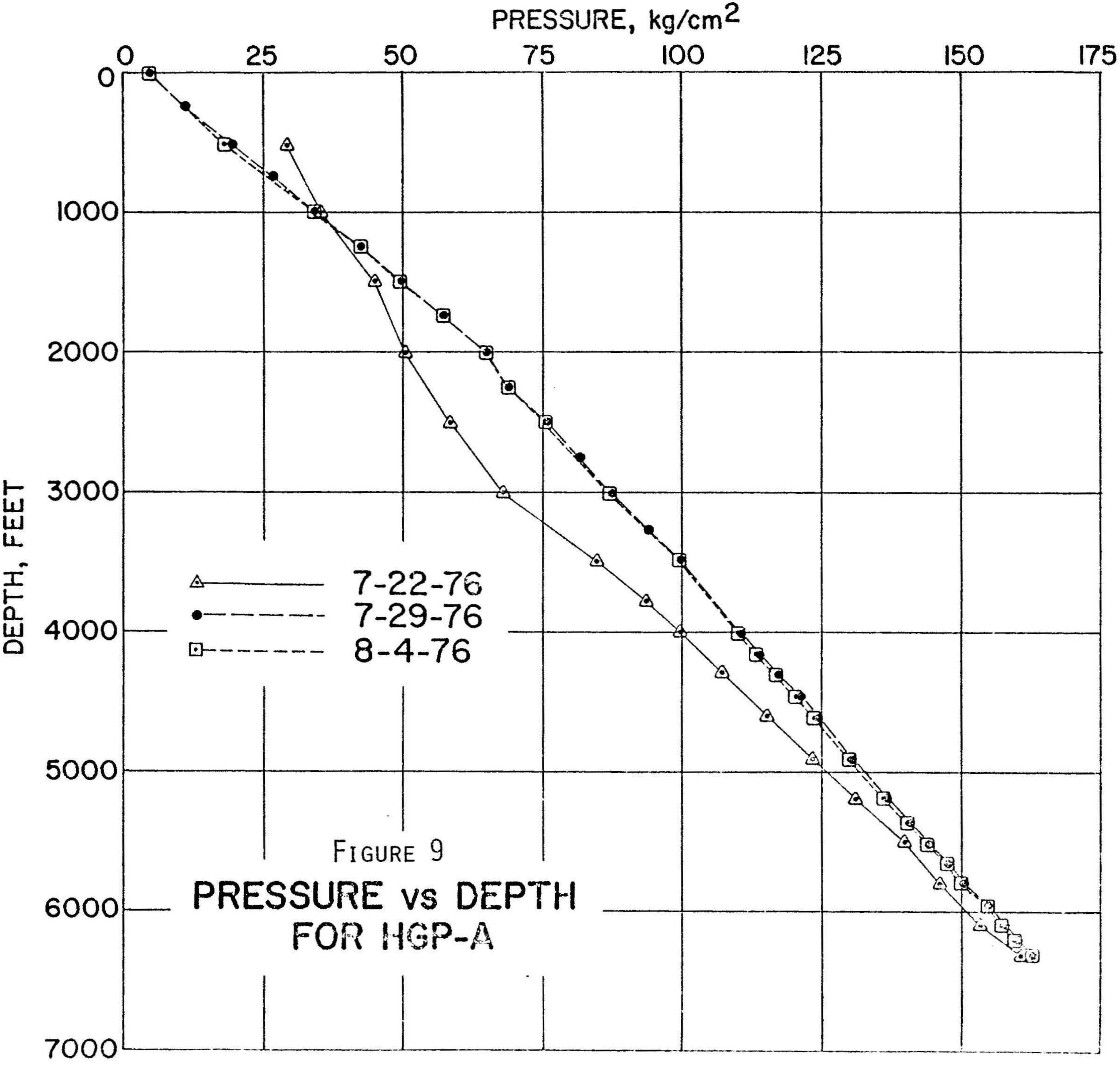


FIGURE 9

PRESSURE vs DEPTH FOR HGP-A

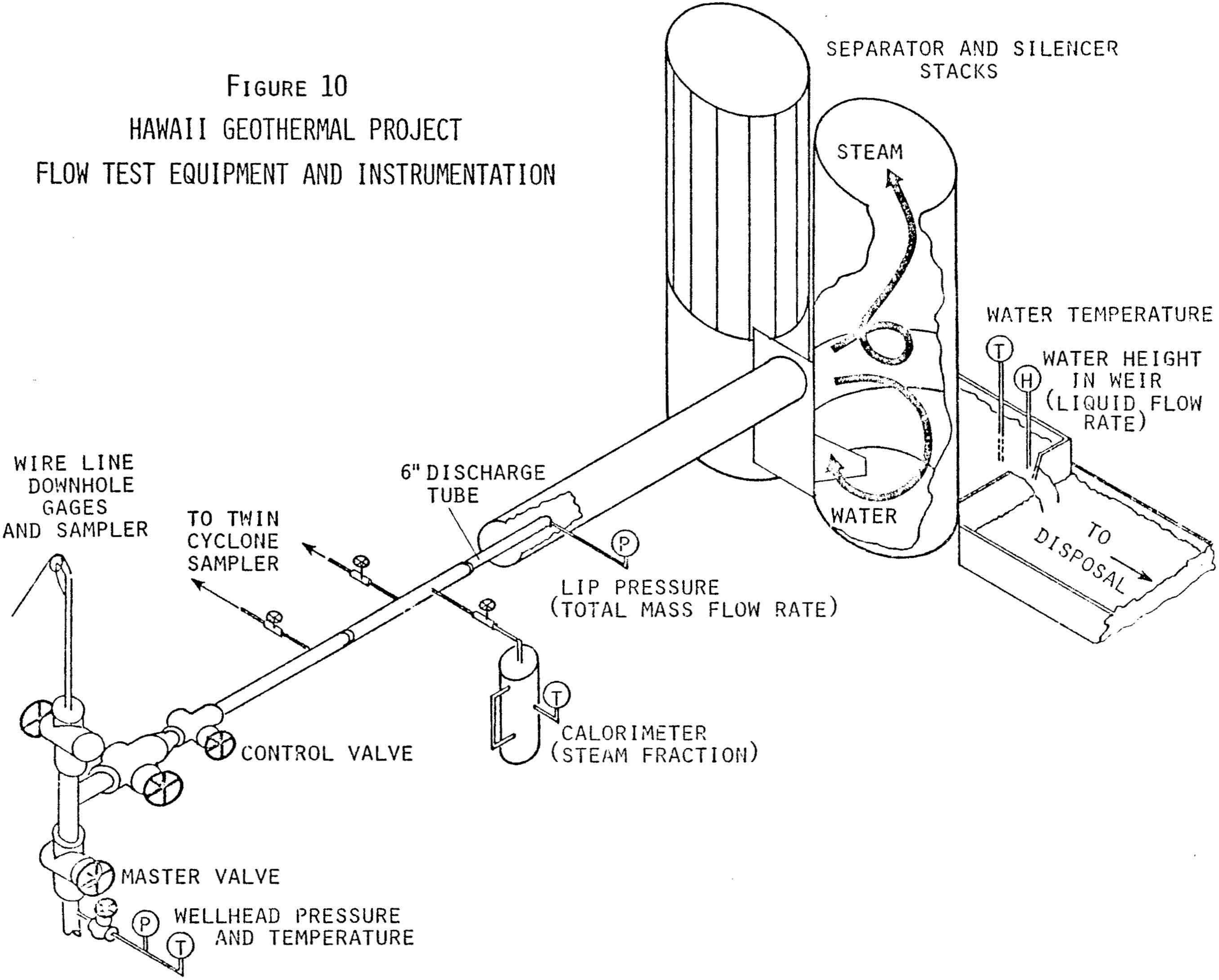
As shown in Figure 8, the temperature profile obtained one week after the flashing was fairly close to equilibrium, except that the portion of the well that is cased is continuing to decrease slowly in temperature. The temperature profiles also appear to indicate that the major production region is probably between 3,500 and 4,500 feet and that a lesser producing zone of probably lower temperature may exist around 6,000 feet.

The following tests and analyses are planned for the next budget period:

1. Temperature and pressure profiles
2. Sustained long-term discharge
3. Variable flow-rate discharge
4. Pressure drawdown and buildup
5. Steam quality
6. Casing integrity
7. Cold fluid influx
8. Downhole flow meter
9. Interference tests using observation waterwells
10. Scaling and corrosion effects of effluent
11. Chemical analyses of downhole water samples

Figure 10 is a sketch of the planned equipment and instrumentation for the discharge test. As shown, the method involves basically the James technique for measuring total mass flow with twin cyclone separators for silencing and separation of steam and water. A 90° notch weir is used to measure the liquid flowrate, permitting steam quality and specific enthalpy to be calculated. In addition, a calorimeter will be used to provide an independent measurement of the specific enthalpy. A 2" twin cyclone sampler will be used to obtain gas and vapor samples for chemical analyses and a recovery tube will be mounted on the wellhead to permit temperature and profiles to be obtained during the flow test.

FIGURE 10
HAWAII GEOTHERMAL PROJECT
FLOW TEST EQUIPMENT AND INSTRUMENTATION



During the period when the well test equipment is being built and installed, preliminary tests will be undertaken prior to actual flashing flow. First will be a casing integrity test to determine whether any collapse of the casing has occurred. A "go-devil" with an outside diameter slightly smaller than the casing diameter of 8.755 inches will be lowered slowly on a wireline to probe for any significant blockage of the well bore.

A second test will involve slow, non-flashing flow through the bleed line until roughly three times the casing volume has been emptied. Fluid temperatures will be monitored at the wellhead and at various depths during this period and water samples will be taken before and after the test. Analysis of the temperature and chemical data should give some indication whether there is cold fluid entering the wellbore over the casing depth or at the junction of casing and liner.

Following this phase, the flow rate through the 2-inch bleed line will be increased gradually until flashing flow is achieved. This gradual increase will permit the wellhead casing to reach operating (flashing) temperature without being subjected to stresses associated with sudden increases in temperature.

Once the temperatures of the system are at operating levels, tests to determine the production capacity of HGP-A will be undertaken. During this phase the well will be allowed to flow at various fractions (e.g., 10%, 25%, 50%, 75%, 100%) of wide open flow. Measurements taken during this series of tests will allow determination of production flow rate and steam fraction as functions of wellhead conditions. This information, along with chemical analyses of samples of steam, liquid, and noncondensable gases, will aid in the future selection of an energy conversion system--whether it be a permanent unit or a small portable unit to be used in conjunction with further testing of HGP-A.

A longer term, sustained discharge test will follow for the purpose of estimating reservoir characteristics. For this phase the well will be flowed at a constant rate for periods of two weeks or longer and transient pressure measurements taken at the bottom of the well. The pressure drawdown and buildup (after the well is shut-in) data will allow a rough estimate of the permeability and extent of the reservoir to be made. Also to be measured are the characteristics of the effluent (temperature, specific enthalpy, chemical composition, etc.) in order to detect any changes in the producing zones or alleviation of possible skin damage.

In an attempt to pinpoint the producing zones, downhole flow meter tests are being contemplated. Should these tests prove feasible, downhole flow meters will be placed so as to straddle a suspected producing zone, providing information leading to a determination of the fluid produced in that stratum.

In conjunction with these sustained long-term discharges, the water levels of several water wells in the immediate vicinity will be monitored. Any measurable changes will be incorporated in the evaluation of the reservoir.

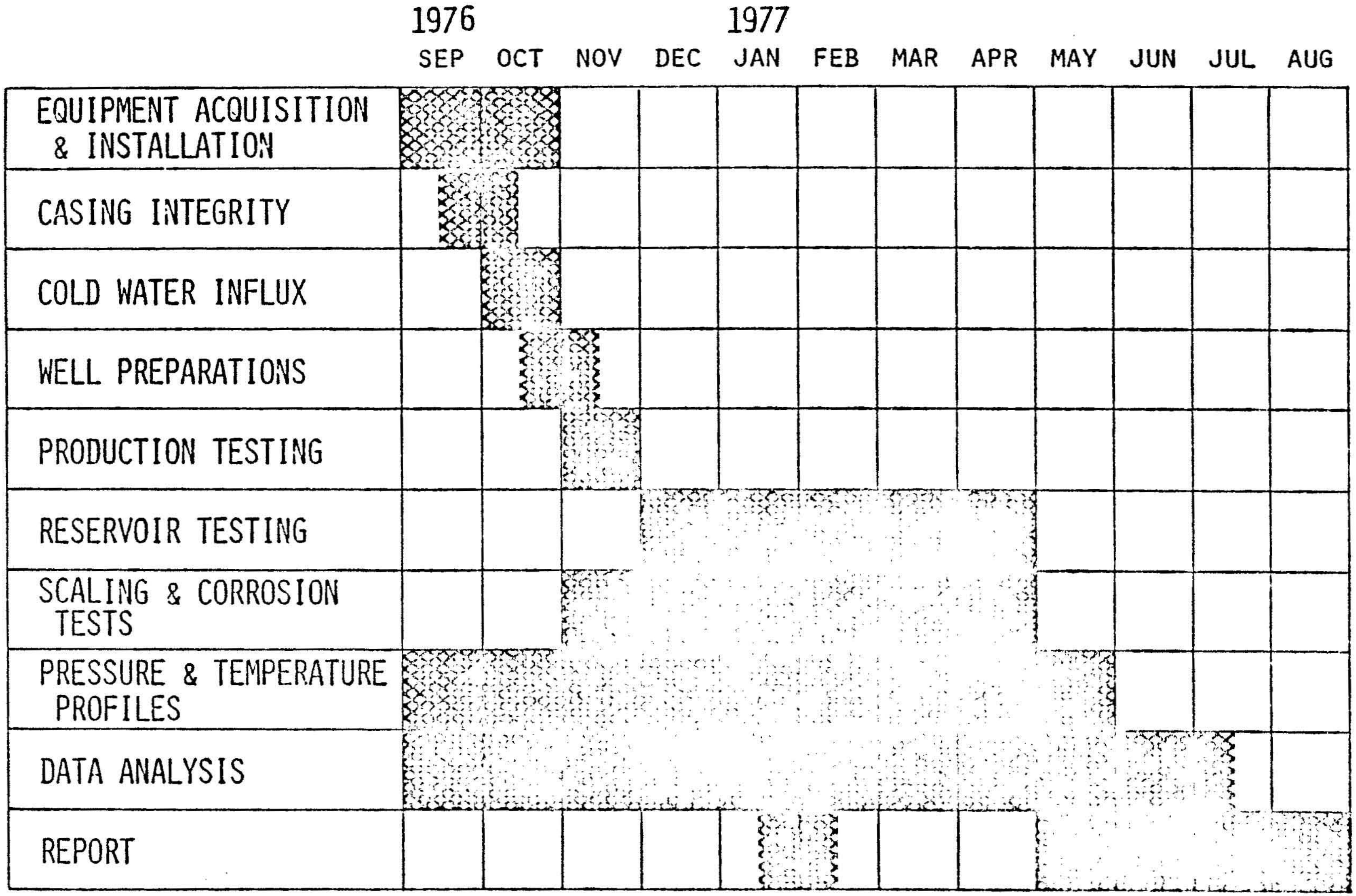
Concurrent with the well production testing and reservoir evaluation phases, tests will be conducted to evaluate the scaling and corrosion effects of the effluent. Specimens of various materials will be located in the following areas: (a) on the separator wall, (b) in the liquid behind the weir, and (c) in the air surrounding the discharge, and examined periodically.

Throughout the course of the well testing program, downhole water samples and temperature and pressure profiles will be taken during those intervals when the well is shut in or is being bled through the 2-inch bleed line.

Figure 11 is a time schedule for the tests described. The FY 1977 budget for these well tests and analyses follows Figure 11. The budget for the chemical analyses of water samples as well as a description of the methods to be used are given elsewhere.

FIGURE 11

WELL TEST AND ANALYSIS PROGRAM SCHEDULE



	1976 SEP	OCT	NOV	DEC	1977 JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG
EQUIPMENT ACQUISITION & INSTALLATION	▨	▨										
CASING INTEGRITY	◨	◧										
COLD WATER INFLUX		▨										
WELL PREPARATIONS		◨	◧									
PRODUCTION TESTING			▨									
RESERVOIR TESTING				▨	▨	▨	▨	▨				
SCALING & CORROSION TESTS			▨	▨	▨	▨	▨	▨				
PRESSURE & TEMPERATURE PROFILES	▨	▨	▨	▨	▨	▨	▨	▨	▨			
DATA ANALYSIS	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	◧	
REPORT					◨	◧			▨	▨	▨	▨

BUDGET

Task 3.2 -- Well Test and Analysis

		ERDA	State
1. Salaries and Wages			$37,755
Scientific Discipline Personnel			
Faculty Associate, B. Chen, Associate Professor-100% of time for 1 1/2 summer months @ $2068 per month			3,104
Faculty Associate, D. Kihara, Associate Professor-100% of time for 2 summer months @ 2472 per month			4,944
Faculty Associate, P. Takahashi, Associate Professor-100% of time for 1/2 summer month @ $1979 per month			990
Faculty Associate, P. Yuen, Professor-100% of time for 1/2 summer month @ $3728 per month			1,864
Research Associate, A. Seki-100% of time for 9 months @ $1026/mo., 3 months @ $1064/mo.			12,426
Support Personnel			
Administrative Assistant-50% of time for 9 months @ $889/mo., 3 months @ $921/mo.			5,382
Pre-Baccalaureate Students (including costs for well and instrumentation security and data taking during flow tests)			9,045
2. Fringe Benefits			3,811
3. Equipment		$37,000	
Separator-silencer, fabrication & installation		23,000	
Security -- fencing, lighting, shed		5,000	
Instrumentation & recording system		5,500	
Pressure transducers & assoc. equip.	1,700		
Temperature transducers & assoc. equip.	1,300		
Chart recorders & supplies	2,500		
Twin cyclone gas sampler		2,150	
Additional Kuster equipment		1,350	
2 clocks @ $450/clock	900		
Pressure element	450		

	ERDA	State
4. Supplies, Materials and Spare Parts	5,273	1,577
Calorimeter	1,200	
Instrumentation supplies & miscellaneous parts	1,000	
Corrosion & scaling test specimens & supplies	2,000	
Spare parts for Kuster equipment	850	
Supplies & materials for silencer		1,577
Miscellaneous supplies & materials	223	
5. Travel (Including field operations)	8,000	
6. Other Direct Costs		23,262
Site preparation		1,500
Rentals		3,500
Publications		800
Machine Shop Services		500
Computer Services		1,500
Consultant Services		9,300
Contingency		3,000
5.00% RCUH Service Fee		3,162
TOTAL PROJECT COSTS	$50,273	$66,405

Task 3.3

RESERVOIR ENGINEERING

F. Yuen and P. Takahashi

The several tasks described elsewhere in this proposal as part of the Hawaii Geothermal Project have produced, and will continue to produce, data and models relevant to the Pahoa geothermal field and to HGP-A. Task 3.3, Reservoir Engineering, will be concerned with analyses of these data and models, and the integration of these diverse data into working hypotheses which will define the parameters of the Pahoa geothermal field and will both explain and predict the operation of HGP-A. Task 3.3 will provide the engineering analysis which, in conjunction with the geosciences input, will provide a better understanding of the extent and characteristics of the geothermal reservoir.

Much pertinent data, both past and future, will be available from the HGP groups responsible for geophysics, geology, geomchemistry, hydrology, and well testing. Task 3.3 will be concerned with analyses of these data and a comparison of the actual conditions encountered with the predictions made earlier about the reservoir and the well. Where discrepancies have occurred, attempts will be made to resolve the differences.

Following these analyses, an effort will be initiated to synthesize a working description of the Pahoa geothermal field, so that information can be extracted concerning the parameters of the field and the operation of HGP-A. Information will be sought on such parameters as the size and boundary locations of the reservoir, the characteristics and locations of the permeable and impermeable regions, the location of the heat source, the source and chemistry of the fluid, the recharge mechanism for the reservoir, the total available energy and the possible production rates, the quality of the steam, including the amount of noncondensable gases, dissolved solids and corrosive materials. This will be done in close cooperation with geosciences personnel.

With these results from the synthesized model, the parameters needed for the design of a portable power plant to be installed at the site and connected to HGP-A can then be specified. Such factors as inlet and outlet pressures and temperatures, mass flows, fluid condition and environmental effects will be obtained for the specifications. Depending upon the results of the comprehensive flow test, it is anticipated that a portable wellhead generator will then be put on line and connected to HGP-A for field tests. In addition to obtaining actual power data under operating conditions, this will also permit the next stage of well testing to be achieved relatively simply without the need for special silencing equipment.

Following the synthesis of a model of the Pahoa geothermal field, the next step will be to prepare a development plan for the field. Information such as the specific locations of wells to be drilled, the depths of these wells, the casing and lining programs, the collection and transmission systems, and the permanent power plant design will be obtained. The experience gained in drilling HGP-A, the data from the synthesized model of the Pahoa geothermal field, and the operational data from the portable power plant will all contribute to a development plan for the Pahoa geothermal field.

The next phase of the reservoir engineering program, again in cooperation with the geosciences, will consist of the extrapolation of these results to a plan for the study of the development of the Opihikao anomaly shown in Figure 1, or possibly to expansion of the program to Oahu or Maui. By this time sufficient data should be available from the operation of HGP-A and its wellhead generator, and the attendant costs for developing the Pahoa geothermal field should be adequately defined, so that an informed plan and estimate can be written for the development of other potential geothermal sites throughout the State.

The budget which follows reflects only those costs which are associated with the analysis and synthesis of data and models from the tasks described elsewhere. Task 3.3 is dependent upon this input and, within its limited budget, has provided support for a graduate student to assist in the analysis and interpretation of water samples by Task 2.6--Hydrology--which otherwise may be overextended. However, with the level of funding as budgeted for Task 3.3, it should be recognized that only a start can be made in developing a comprehensive reservoir engineering program.

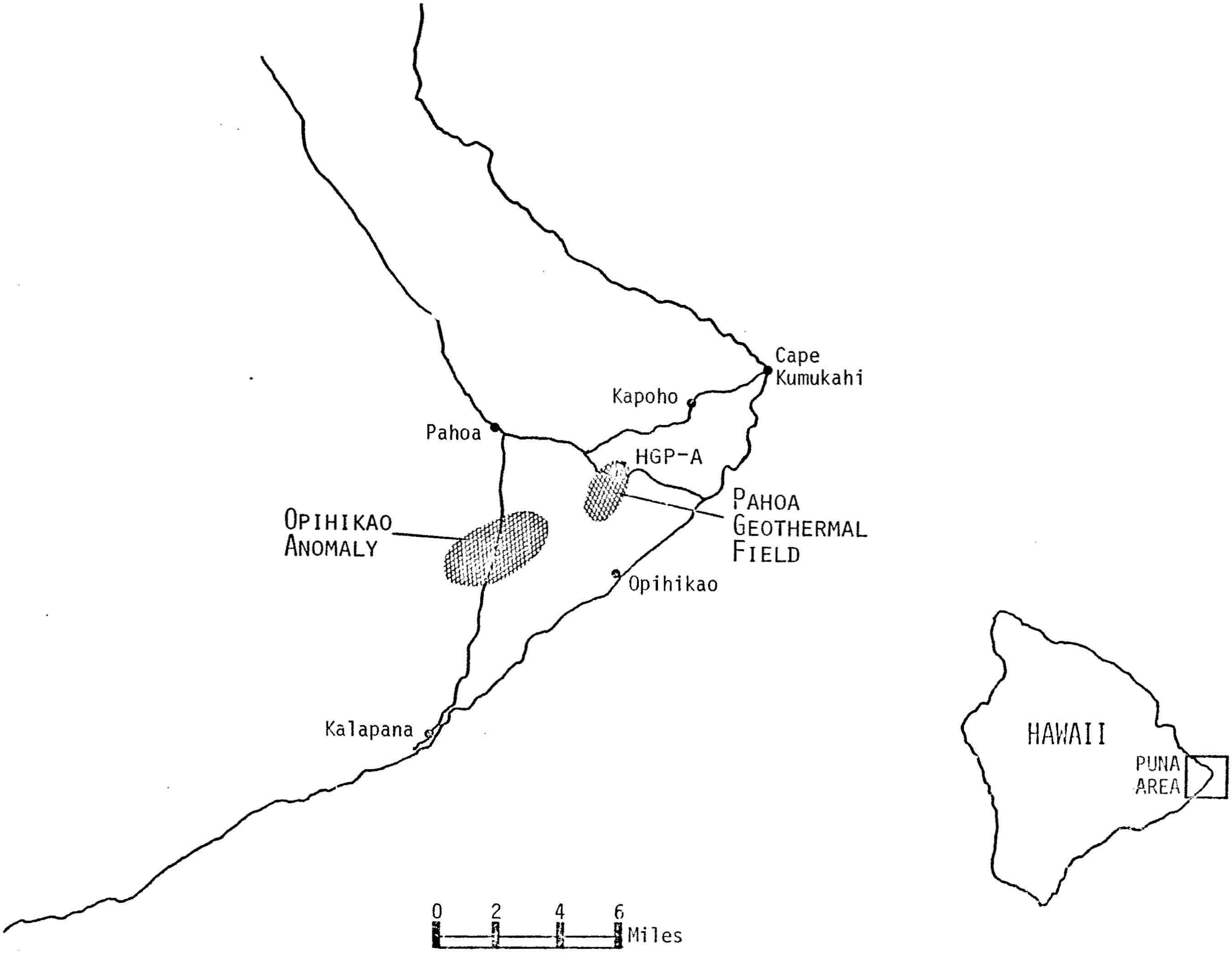


Figure 1 MAP OF PUNA AREA

BUDGET

Task 3.3 -- Reservoir Engineering

1. Salaries and Wages		$16,191
Scientific Discipline Personnel		
Faculty Associate, P. Yuen, Professor-100% of time for 1/2 summer month @ $3728 per month	1,864	
Faculty Associate, P. Takahashi-Associate Professor-100% of time for 1/2 summer month @ $1979 per month	990	
Two Graduate Assistants, 50% of time for 12 months @ $914 a month	10,968	
Support Personnel Pre-Baccalaureate Students	2,369	
2. Fringe Benefits		778
3. Travel		1,750
1 mainland trip	900	
5 interisland trips @ $170	850	
4. Other Direct Costs		3,833
Supplies	1,000	
Computer Services	2,000	
Reproduction & Xeroxing	633	
Communications	200	
5. Indirect Costs		7,448
Total Task 3.3 Costs		$30,000

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 significantly 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	$ 5,243
Scientific Discipline Personnel	
Faculty Associate, B. Siegel, Associate Professor, 100% of time for 1 summer month @ $2472 per month	2,472
Faculty Associate, S. Siegel, Professor, 50% of time for 2/3 summer months @ $3563 per month	1,671
Support Personnel - Pre-Baccalaureate students	1,100
2. Fringe Benefits	$ 96
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)	$ 809
6. Indirect Charges: 46% of Salaries and Wages	$ 2,412
Total Project Costs	$11,050