THE HAWAII GEOTHERMAL PROJECT

SUMMARY REPORT FOR PHASE I

May 1975

SUPPORT FOR PROJECT PROVIDED BY:

National Science Foundation
Energy Research and Development Administration
State of Hawaii
County of Hawaii

****

Management - Coordination	John W. Shupe
Geophysical Program	Augustine S. Furumoto
Engineering Program	Paul C. Yuen
Environmental-Socioeconomic Program	Robert M. Kamins
Drilling Program	Agatin T. Abbott

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DISCLAIMER

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SUMMARY REPORT FOR PHASE I

FOREWORD

The Hawaii Geothermal Project (HGP) was established to focus the resources of the State and the University of Hawaii on a coordinated research effort leading to the development of geothermal power on the Big Island of Hawaii.

Phase I of the Project was initiated in the summer of 1973 with a $252,000 grant from NSF-RANN (National Science Foundation-Research Applied to National Needs), supplemented by $100,000 each from the State and the County of Hawaii. This $452,000 budget was organized into a multidisciplinary research effort in the following program areas: (1) Geophysical - exploratory surveys to define the most favorable areas for geothermal investigations; (2) Engineering - analytical models to assist in interpretation of geophysical results, and studies on energy recovery from hot brine; and (3) Socioeconomic - legal and regulatory aspects of ownership and administration of geothermal resources, and economic planning studies on the impact of geothermal power.

Two additional grants totaling $336,000 were received from NSF-RANN, which have provided operational support for the Project through April 1975. These funds were used: a) to continue the exploratory surveys and support programs in Phase I; b) to begin the establishment of environmental baselines; and c) to initiate planning for Phase II -- the research drilling program. During Phase I a total of $39,000 also was received from a variety of public and private sources, and has provided the necessary flexibility to meet emergencies and opportunities that arose.

On April 10, 1975, notice was received from ERDA (Energy Research and Development Administration) that an HGP proposal for $1,064,000 had been approved, of which $580,000 was earmarked for a research geothermal well. In addition, the State Legislature allocated $500,000 for exploratory geothermal drilling, and the Hawaiian Electric Company has contributed $20,000 to assist with the drilling program. Plans have been initiated for effective utilization of these funds, and drilling of a research hole in the Puna Area of the Island of Hawaii will commence in October 1975, with the objective to obtain intermittent cores and scientific data to a depth of 6000 feet.

May 1, 1975, has been established rather arbitrarily as the beginning of Phase II, the research drilling program. Although the majority of the research projects of Phase I will continue into Phase II, and much of the geophysical data taken during this period remains to be fully analyzed and interpreted, May 1 represents both a two-year anniversary date and the transition from NSF to ERDA funding. Therefore, it seems an appropriate time to prepare this progress report on Phase I of the Hawaii Geothermal Project.

The bulk of this report has been prepared by the program directors and their research staffs and, except for minor editing, their statements appear as submitted by:

Geophysical Program -- Augustine S. Furumoto

Engineering Program -- Paul C. Yuen

Environmental-Socioeconomic Program -- Robert M. Kamins

Drilling Program -- Agatin T. Abbott

These program reports present summaries of results obtained to date in each of the research areas, and include lists of reference publications where these results are reviewed in greater detail. The statements by the program directors are quite candid, reflecting some difference of opinion both in overall program strategy and in the interpretation of data. Although no effort is made in this report to minimize or to resolve these differences, the Management Section does include the rationale for proceeding with a research drilling program and for choosing the selected drilling site.

From the beginning, the Hawaii Geothermal Project has received both encouragement and financial support from Federal, State, and County governments -- as well as from the business community, the utilities, and public interest groups. Although it is still premature to state whether a conventional geothermal field with commercial potential will be identified, the Project has and will continue to make definite contributions to the state-of-the-art for locating, developing, and utilizing geothermal resources. As the Project moves into the research and exploratory drilling program, a better understanding will result of the possible role of geothermal power in helping to develop an appropriate level of energy self-sufficiency for Hawaii.

John Shupe

John W. Shupe, Director
Hawaii Geothermal Project
May 22, 1975

HAWAII GEOTHERMAL PROJECT

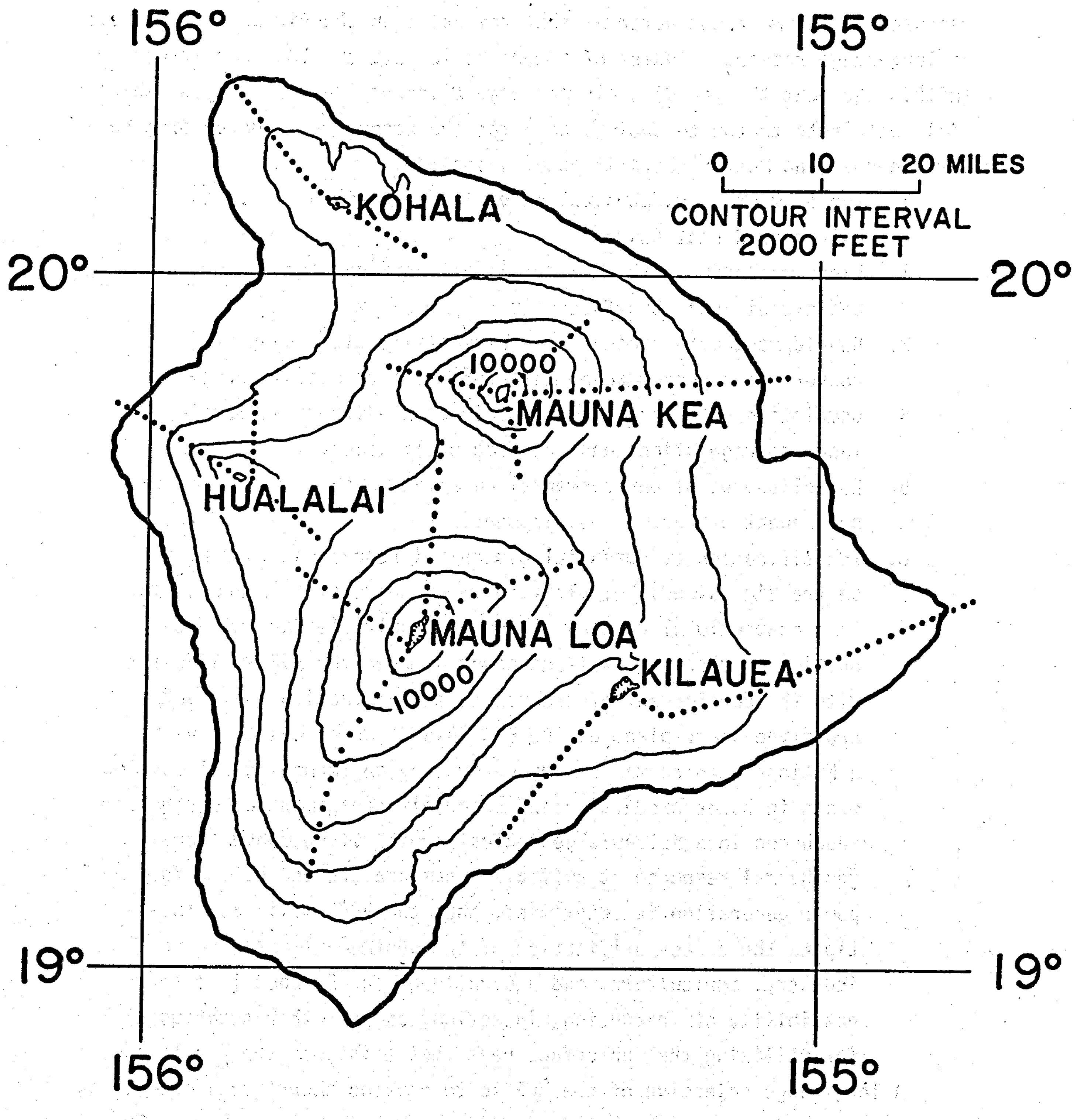
OVERVIEW OF PHASE I

The State of Hawaii, which geographically consists of an island chain stretching across 350 miles of the Central Pacific and separated from the mainland United States by over 2,000 miles of that same ocean, is totally dependent for energy on seaborne petroleum. Hawaii has no known fossil fuel reserves; there is no coal coming into the State by rail; no natural gas pipeline; and no regional electric grid to interconnect its electrical systems with those of other states or even with its separate islands. This complete lack of flexibility makes Hawaii particularly vulnerable to dislocations in the global energy market resulting from real or imagined shortages of petroleum. This is a travesty, since the State is generously endowed with a variety and abundance of natural energy resources: geothermal, solar radiation, ocean temperature differential, wind, waves, and ocean currents -- all potential non-polluting power sources.

The candidate from among these natural energy sources which shows the highest promise for early power generation at commercial levels is geothermal energy. In Hawaii there is an interesting variety of subsurface heat anomalies wihch may exist as: (1) molten magma, (2) hot dense rock, (3) hot porous rock, (4) geothermal steam, and (5) hot water. Any or all of these sources may occur in the proximity of 40°F deep-ocean water, adding to the flexibility in developing effective energy systems.

The Hawaii Geothermal Project (HGP) was organized to focus the resources of the University, the State, and the County of Hawaii on the identification, generation, and utilization of geothermal energy on the Big Island of Hawaii. Figure 1 shows the five volcanoes which form this largest island in the Hawaiian chain. Hawaii is also the youngest of the islands and is still experiencing growth from recent activity of the Mauna Loa and Kilauea volcanoes, so represents the island with the greatest amount of heat at or near the earth's surface. Consequently, the Big Island was selected as the site for initial geothermal exploration.

The research program as developed by the HGP involves an interdisciplinary team of researchers from throughout the University system which conduct scientific investigations on short-range exploratory and applied technology tasks to assist in the early development of any conventional geothermal



VOLCANOES & RIFT ZONES ON THE ISLAND OF HAWAII

Figure 1

resource -- steam or hot water -- that may exist on the Big Island, as well as long-range research studies of a more basic nature. The short-range (within the next ten years) goals and objectives of the HGP, many of which will contribute to the technology base for the recovery of energy from subsurface heat, no matter where it occurs, include:

1. Improvement of geophysical survey techniques for locating underground heat sources.
2. Experimentation with deep-drilling techniques for verifying and exploiting subsurface heat.
3. Development of efficient, environmentally clean systems for conversion of underground heat resources to useful energy.
4. Completion of socioeconomic and legal studies to assist in land use regulations and resource utilization.
5. Establishment of environmental baselines with which to monitor subsequent geothermal development.
6. Identification of potential geothermal resources, initially on the Big Island, but ultimately for the entire island chain. If a conventional geothermal resource suitable for the production of electricity is discovered, then the HGP will assist with the development of the geothermal production field and a prototype power plant on the Big Island, which could serve as a National Geothermal Energy Laboratory on technological developments in power production and reservoir management of earth heat resources in a volcanic geological area. If no conventional geothermal resource at sufficient temperature and volume for power generation is identified, then the HGP will: a) Investigate the direct utilization of the geothermal resource in industry, agriculture, and aquaculture; and b) Look into the possibility of fracturing, injection, and/or other techniques for utilizing the subsurface heat that exists on the Big Island.

A long-range objective of the HGP is to develop techniques, materials, and components for the recovery of useful energy from molten magma. The nature of the basaltic lava flows on the Big Island make this an ideal location for the study of power generation from magma.

The HGP came into being when the 1972 Hawaii State Legislature allocated $200,000 for geothermal research -- $100,000 to be administered through the

County of Hawaii budget. This action was taken prior to the energy crisis and was a progressive step for a state governing body to take. Total support for the HGP through April 1975 has been as follows:

TOTAL PHASE I SUPPORT

State of Hawaii	FY(72)	$100,000
County of Hawaii	FY(72)	100,000
National Science Foundation	FY(73)	252,000
	FY(74)	217,000
	FY(75)	119,000
Other Public & Private Funds	(72-75)	39,000
Total		$827,000

Phase I was organized into four separate programs, encompassing the following research tasks:

Geophysical Program -- Augustine S. Furumoto
- Photogeologic (Infrared Scanning) Survey
- Electromagnetic Survey
- Electrical Resistivity Survey
- Microearthquake and Microseismic Surveys
- Geochemical Survey
- Thermal Survey of Wells

Engineering Program -- Paul C. Yuen
- Reservoir Modeling
- Well Test Analysis
- Ghyben-Herzberg Lens Analysis
- Energy Extraction From High Temperature Brine

Environmental-Socioeconomic Program -- Robert M. Kamins
- Regulatory and Legal Aspects
- Land Use and Planning
- Economic Analysis
- Environmental Baseline Studies

Research Drilling Program -- Agatin T. Abbott

The major emphasis of Phase I was on the Geophysical Program, since the issue of if and where geothermal resources exist is crucial to the project. However, parallel studies were initiated in all supporting programs, so that progress was made in identifying and clarifying the technological, environmental, legal, regulatory, social and economic problems that could impede the development of geothermal power in Hawaii.

Although the analysis and interpretation of field data are still incomplete, the consensus developed early -- both on the basis of preliminary geophysical results and from complementary studies conducted on the Big Island over the past several decades -- that an exploratory drilling program would be essential to check out the subsurface conditions predicted by the surveys. Phase II, the research drilling program, was established to verify interpretation of scientific data and to assist in the determination of whether conventional geothermal resources are present in Hawaii. Dr. Abbott established the Site Selection Advisory Committee in April 1974, and this group has played a significant role in program planning for Phase II.

As of May 1, 1975, the following funds have been identified to continue with Phase I research activity and to initiate Phase II -- the research drilling program:

INITIAL PHASE II SUPPORT

State of Hawaii (appropriated by the Legislature; request has been submitted to the Governor for the release of these funds)	$ 500,000
Energy Research & Development Administration	1,064,000
Hawaiian Electric Company	20,000
	$ 1,584,000

Current plans call for drilling to begin at a site in the Puna Area of the Big Island of Hawaii in October 1975. Cores, fluid samples, and other scientific data will be taken throughout the proposed 6000-foot drilling depth. Subsequent drilling by the HGP is contingent upon results from the initial hole, as well as both long-range strategy and support for developing geothermal resources in Hawaii.

THE HAWAII GEOTHERMAL PROJECT
MANAGEMENT - COORDINATION

A. OVERVIEW OF PROJECT MANAGEMENT

The Hawaii Geothermal Project involves more than forty researchers and support staff from throughout the University of Hawaii system. The two major campuses on Oahu and the Big Island are represented, along with over a dozen research institutes and academic units. Many of the State and County agencies and their staffs are directly involved in the HGP, along with numerous mainland consultants, research organizations, engineering and drilling subcontractors. Because of its potential importance, both for the University and the State, effective coordination among the wide variety of technological, socioeconomic, and political interests at all educational, private, and governmental levels is essential. The Management Program was developed with these diverse interests in mind.

During Phase I of the HGP the Management Program has provided the following: (1) coordination of activities among the research programs; (2) administrative services to assist with implementation of the research; and (3) promotional efforts at the University, State, and Federal levels to help assure adequate visibility and support for the HGP.

Figure 2 is the current organizational chart for the HGP. Principal Investigator and Project Director is John W. Shupe, Dean of Engineering at the University of Hawaii. Dr. Shupe also serves on the Governor's Environmental Council, is chairman of the State Committee on Alternate Energy Sources for Hawaii, and is Interim Director of the Hawaii Natural Energy Institute. He allocates a quarter of his time to coordination of the HGP and is aided in this effort by a full-time Administrative Assistant, Diane Sakai.

Initially there were three co-principal investigators for Phase I, each responsible for the planning and for the direct technical supervision of his research program. As planning for the drilling program got underway, a fourth co-P.I. was added.

Geophysical Program -- Augustine S. Furumoto, Professor of Geophysics

Engineering Program -- Paul C. Yuen, Associate Dean and Professor of Electrical Engineering

Environmental-Socioeconomic Program -- Dr. Robert M. Kamins, Professor of Economics

HAWAII GEOTHERMAL PROJECT

ORGANIZATIONAL CHART

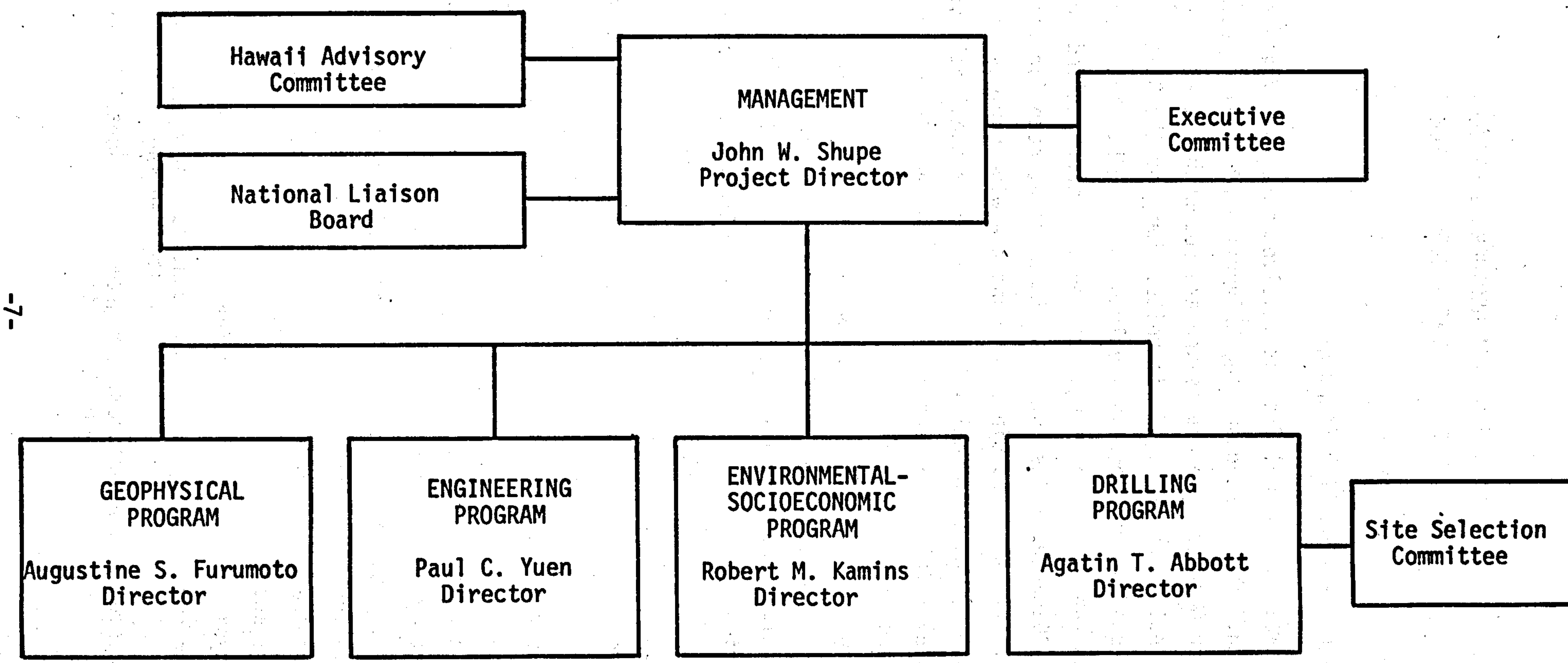


Figure 2

Drilling Program -- Agatin T. Abbott, Professor and Chairman of Geology and Geophysics

Each of these program directors devotes half-time to administration, coordination, and implementation of his respective research program. A separate budget was assigned to each program, in order to assist in establishing technical and fiscal authority and accountability.

The HGP Executive Committee consists of the five principal investigators, plus two additional members who assist the Project Director in assuring the necessary visibility and support throughout the academic community, as well as by the governmental and private sectors: a) Dr. John P. Craven, Dean of Marine Programs at the University and Director of Marine Affairs for the State of Hawaii; and b) Dr. George P. Woollard, Director of the Hawaii Institute of Geophysics and a member of the Governor's Science and Technology Advisory Committee. The Executive Committee: (1) provides technical input in establishing overall goals and objectives; (2) reviews and approves the research program developed under the leadership of the principal investigators; (3) maintains liaison essential to project support, both on and off campus; and (4) monitors progress of the project.

To assure that the HGP has both local and national relevance, systematic evaluation and advice are provided to the Executive Committee and the P.I.'s from numerous sources: a) the NSF and ERDA Program Managers; b) the National Liaison Board; and c) the Hawaii Advisory Committee. The National Liaison Board (membership list attached) consists of the project leaders of other federal-supported geothermal programs, along with a few of the national leaders in geothermal research and development. The purpose of the Liaison Board is to review program progress, to exchange current information on geothermal science and technology, and to advise on future planning and implementation for the HGP. One informative evaluation session of the Board was held in February 1974, and a second meeting is tentatively scheduled after the drilling gets underway.

The Hawaii Advisory Committee (membership list attached) was established to provide interaction with key individuals from industry, government, and the scientific community, whose support is essential to the introduction of geothermal power in Hawaii. Serving on this committee are the Directors of the State Office of Environmental Quality Control, the Department of Planning and Economic Development, and the Department of Land and Natural Resources; the president of the major electric utility company; Director of the County

HGP NATIONAL LIAISON BOARD

Mr. David N. Anderson, Geothermal Officer
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Mayor
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Dr. Paul M. Miwa, Chancellor
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Mr. Herbert M. Richards, Jr.
Board of Regents
University of Hawaii
Box 837
Kamuela, Hawaii 96743

Dr. Robert I. Tilling
Scientist-in-Charge
Hawaiian Volcano Observatory
U.S. Geological Survey
Hawaii National Park, Hawaii 96718

Mr. Carl H. Williams, President
Hawaiian Electric Company
Post Office Box 2750
Honolulu, Hawaii 96803

Dr. George P. Woollard, Director
Hawaii Institute of Geophysics
University of Hawaii, HIG 131
Honolulu, Hawaii 96822

of Hawaii Office of Research and Development; a cross-section of business and industrial leaders of the community; and representatives of citizen groups. This committee meets semi-annually and supplements the Executive Committee in providing the necessary visibility for the HGP, both on and off campus, to assure public and private support for geothermal power in Hawaii.

Close liaison has been maintained with all four congressional delegates, who are kept well informed on progress of the HGP. Excellent support, information, and advice is provided by our congressional delegates on any shifts in organizational structure and funding philosophy of federal agencies.

Local interest in the HGP has been high. Encouragement, endorsement, assistance, and/or interaction has taken place with the following organizations, many of whom are represented on the Advisory Committee:

State Departments and Offices

Department of Planning and Economic Development
Department of Land and Natural Resources
Department of the Attorney General
Office of Science Policy
Office of Marine Affairs
Office of Environmental Quality Control
State Task Force on Energy Policy

County of Hawaii

The Mayor's Office
Department of Research and Development
Hawaii County Council

Electric Utilities

Hawaiian Electric Company
Hawaii Electric Light Company

Business and Industrial Concerns

Bishop Estate
Campbell Estate
C. Brewer and Company, Ltd.
Pacific Resources, Inc.
Water Resources International
Honolulu Chamber of Commerce
Hilo Chamber of Commerce
Geothermal Exploration and Development Corporation

B. HGP PERSONNEL SUMMARY

Executive Committee

Agatin T. Abbott, Professor and Chairman of Geology and Geophysics
John P. Craven, Dean of Marine Programs
Augustine S. Furumoto, Professor of Geophysics

Robert M. Kamins, Professor of Economics
John W. Shupe, Dean of Engineering
George P. Woollard, Director of Hawaii Institute of Geophysics
Paul C. Yuen, Associate Dean of Engineering

Geophysical and Drilling Program

Agatin T. Abbott, Professor and Chairman of Geology and Geophysics
Robert W. Buddemeier, Associate Professor of Chemistry
Pow-Foong Fan, Associate Professor of Geology
Augustine S. Furumoto, Professor of Geophysics
Robert Harvey, Research Associate
Douglas P. Klein, Research Associate
Peter M. Kroopnick, Assistant Professor of Oceanography
L. Stephen Lau, Director of Water Resources Research Center
Gordon A. Macdonald, Senior Professor of Geology
Murli H. Manghnani, Professor of Geophysics
Roger A. Norris, Research Associate
Donald W. Peterson, Geologist, Hawaiian Volcano Observatory
Ramanan Ramanantoandro, Assistant Geophysicist
Robert I. Tilling, Chief Scientist, Hawaiian Volcano Observatory
Charles J. Zablocki, Physicist, Hawaiian Volcano Observatory

Engineering Program

Hi Chang Chai, Professor and Chairman of Mechanical Engineering
Bill H. Chen, Assistant Professor of Engineering (Hilo Campus)
Ping Cheng, Professor of Mechanical Engineering
James C. S. Chou, Professor of Mechanical Engineering
Deane H. Kihara, Associate Professor of Mechanical Engineering
Kah Hie Lau, Assistant Professor of Engineering (Hilo Campus)
L. Stephen Lau, Director of Water Resources Research Center
Patrick K. Takahashi, Assistant Professor of Civil Engineering
Paul C. Yuen, Associate Dean of Engineering

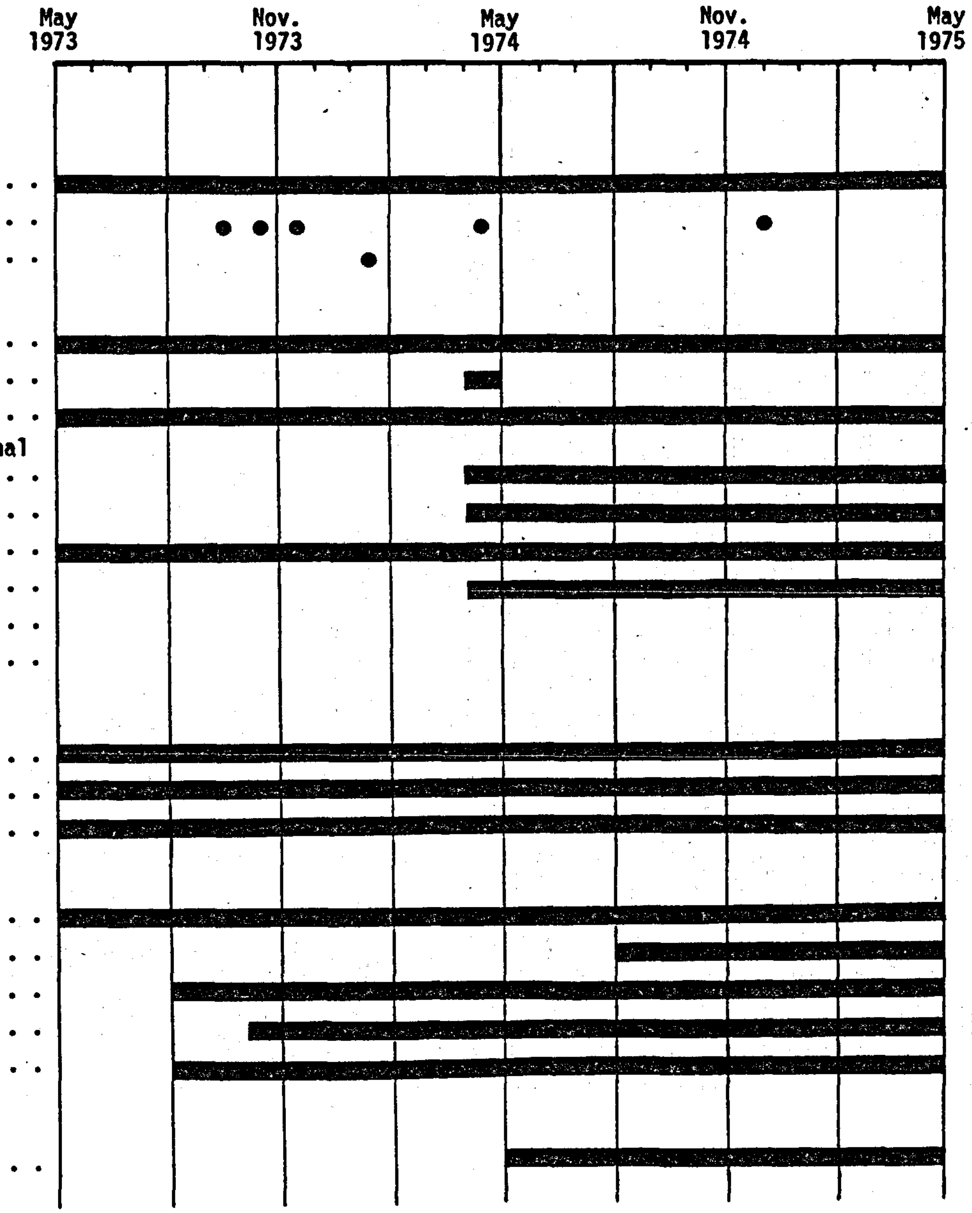
Environmental-Socioeconomic Program

Andrew Berger, Professor of Zoology
Michael J. Chun, Assistant Professor of Public Health
Doak C. Cox, Director, Environmental Center
P. Anders Daniels, Assistant Professor of Meteorology
Nabil A. El-Ramly, Associate Professor of Business Economics
Ruth Gay, Instructor, Botany
Eugene M. Grabbe, Director, State Center for Science Policy & Technology Assessment
Jerry M. Johnson, Assistant Director of Environmental Center
Robert M. Kamins, Professor of Economics
James E. T. Moncur, Assistant Professor of Economics
Richard E. Peterson, Associate Professor of Business Economics
Kap-Kyung Seo, Professor of Business Economics
Sanford M. Siegel, Professor of Botany

C. PROGRAM PLANNING AND EXPENDITURE SCHEDULE

Table I lists the program and expenditure schedule for each research task.

TABLE I
HAWAII GEOTHERMAL PROJECT
PROGRAM PLANNING AND EXPENDITURE SCHEDULE



		TOTAL PHASE I ALLOCATIONS
1.0	Management	$ 63,785
	Hawaii Advisory Committee	
	National Liaison Board	
2.0	Geophysical Coordination & Support	93,038
2.1	Photogeologic Surveys	23,900
2.2	Geoelectric Surveys	123,424
2.3	Theoretical and Numerical Modelling, Computational Geophysics, Magnetic and Gravity Surveys	44,871
2.4	Temperature Survey	27,638
2.5	Seismic Studies	109,822
2.6	Geochemical Surveys	24,109
2.7	Hydrology	
2.8	Physical Properties of Rocks	
3.0	Engineering Coordination and Support	27,349
3.1	Geothermal Reservoir Engineering	83,737
3.6	Optimal Geothermal Plant Design	66,298
4.0	Environmental-Socioeconomic Program Support	50,790
4.1	Environmental Aspects	11,426
4.2	Legal and Regulatory Aspects	9,300
4.3	Land-Use and Planning Aspects	
4.4	Economics	17,561
5.0	Exploratory Research Drilling Program	10,552
		$787,600*

*Includes $100,000 from State of Hawaii and $100,000 from County of Hawaii.

This table summarizes the level of activity during the funding period for all of the research tasks, so provides a general overview of funding and program activity throughout Phase I.

D. SELECTION OF A DRILLING SITE

One of the major management decisions was whether and when to proceed with a drilling program. From the early stages of the HGP, there has been a lack of unanimity on this issue. The proponents for geophysical testing have advocated that funds could be used most effectively in conducting geophysical surveys for analysis and interpretation. Drilling proponents have countered that the volcano area of the Big Island is one of the most extensively studied geological areas in the world, and that drilling is essential to prove out theories and models based upon geophysical-geological-geochemical data.

It was the general consensus at the meeting of the National Liaison Board -- which was held in Hilo, Hawaii, in February 1974 -- that the HGP should move rapidly on planning for a research drilling program. The Board also endorsed the concept that a Site Selection Committee be established to advise on all aspects of the drilling program. Dr. Abbott aggressively proceeded to establish this committee and presents a resume of its activities in the last section of this report.

The decision to proceed with a drilling program was strongly supported by the Hawaii Advisory Committee, and assistance was provided by this group in obtaining an appropriation from the 1974 State Legislature of $500,000 for exploratory geothermal drilling, contingent upon additional federal matching funds.

Seven of the eight-man Executive Committee supported an early drilling program, with the dissenting opinion coming from Dr. Furumoto, Director of the Geophysical Program. This viewpoint is reflected in that portion of this report prepared by Dr. Furumoto.

Initially the drilling program was planned as a series of intermediate and deep holes covering multiple sites. Subsequent negotiations with program managers from NSF, and later with ERDA, limited initial support to one research hole. Therefore, the task for the Site Selection Committee took on even greater importance. As Dr. Abbott discusses in his report, the preferred location chosen by the Site Selection Committee had the unanimous support of the membership, except for Dr. Furumoto. His interpretation of the data, which leads to the favoring of an alternate site, is also presented in his write-up on the Geophysical Program.

The location recommended by Dr. Abbott and his advisory committee has been established as the site for the initial research drill hole, and invitations to bid have been sent to prospective drillers. If negotiations with the selected driller and ERDA approval of the subcontract move smoothly -- as well as the environmental impact statement and the drilling permit from the State -- the tentative schedule calls for drilling to commence in October 1975.

E. PUBLICATIONS

Publications generated by the Management Program include:

1. The Hawaii Geothermal Project: Quarterly Progress Report, numbers 1 through 4, June 1, 1973 through June 30, 1974.
2. Shupe, John W., Geothermal Power for Hawaii: Phase I, presented at the U.S.-Italy Cooperative Seminar on Geothermal Energy, University of Pisa, November 1973.
3. Shupe, John W., "The Hawaii Geothermal Project: Year One Overview", Geothermal Energy, July 1974.

Publications prepared by the research programs are listed as follows:

Program	Page
Geophysical	19, 25, 47, 59, 80
Engineering	81-82
Environmental-Socioeconomic	156

HAWAII GEOTHERMAL PROJECT
GEOPHYSICAL PROGRAM

Augustine S. Furumoto

The report of the Geophysical Program first presents a narrative of the sequence of events involved in the exploration program. The second part includes summaries of the various tasks carried out as part of the geophysical program. The third part attempts to put together the pieces of the puzzle provided by the tasks to evaluate the geothermal potential on the island of Hawaii.

Although by proclamation Phase I of the geothermal project has ended, in reality we are far from coming to conclusions. The field work is not completed nor are the data satisfactorily interpreted. It is stated categorically here that the conclusions arrived at are tentative and the conclusions may be altered as new evidence arrives. It should be noted that the conclusions in the third part of this report are at variance with suggestions for drilling sites presented in the proposal submitted to the National Science Foundation in November 1974.

A NARRATIVE OF THE EXPLORATION PROGRAM

Introduction

Since May 1973, about a dozen staff members of the Hawaii Institute of Geophysics, University of Hawaii at Manoa, have been carrying on a coordinated exploration program for geothermal sources on the island of Hawaii. At the present writing (April 1975), sufficient results have been obtained from field work and interpretation that a revised drilling program can be proposed to test the concepts and models derived from the exploration program.

In this article, a narrative chronicling the various stages of the exploration program is given. It is interesting to note the exploration program as it was planned and as it was actually carried out. The major reason for the discrepancy between planning and actual work is the funding level. As only a fraction of what was requested was obtained through grants, only a fraction of what was planned could be carried out.

A narrative of this type may have value for future workers who plan to carry out similar exploration programs. Perhaps after reading this, some may see gaps and shortcomings in the program and take steps to fill in those gaps.

Proposal and Plans

As originally proposed, the exploration program was to have consisted of 14 tasks grouped in the following general categories.

Aerial methods	
Photogeology	Task 2.1
Magnetic	2.2
Electrical	
Resistivity	2.3
Electromagnetic	2.4
Seismic	
Microearthquake & microseismic	2.5
Offshore ocean bottom seismographs	2.6
Seismic refraction & reflection	2.8
Thermal	
Shallow well drilling	2.7
Deep drill	2.13
Geochemistry	
Solids	2.9
Fluids	2.10
Physical properties	2.11
Hydrology	2.12
Model study	2.14

The package requested was $870,000 for the first year and $1,500,000 for the second year. The large budget items were the seismic refraction and the drilling projects.

Of the $788,000 appropriated for the total project from the National Science Foundation, the State and the County of Hawaii for funding of the project from May 1973 through the 1974 calendar year, $458,000 was assigned to the Geophysics Program. With this level of funding, the decision was made by the program director to allocate funds fully to a few tasks and let other tasks wait. Therefore, the initial exploration program was limited to the following tasks:

- Aerial photogeologic survey
- Electrical resistivity survey by dipole-bipole methods
- Electromagnetic surveys
- Microearthquake monitoring & ground noise surveys

The basis of selection of tasks was the time sequence; those tasks were funded which could start immediately, while those tasks that needed data from other tasks before starting were delayed. Among those delayed were seismic refraction, offshore ocean bottom seismographs, shallow drilling programs and model studies.

Organization of the Exploration Program

Once the tasks were selected, the geophysical exploration program was organized in the following way with task assignments.

Coordination -- A. S. Furumoto
Aerial Photogeology -- A. T. Abbott
Electrical & Electromagnetic -- D. P. Klein, R. Harvey
Microseismic -- A. S. Furumoto

For the task of coordinating the program, Mrs. Carol Yasui was recruited as stenographer and administrative assistant. In addition to typing reports, memos, and purchase orders, her responsibility included keeping a detailed account of the finances of the geophysics program.

Mr. Carrol Dodd was hired as an electronic technician after considering many candidates. His responsibility included designing of some new instruments, as well as assembling component parts to build proven instruments. Especially as the electrical resistivity survey was planning to probe deeper depths than had been done in other parts of the world, a good electronic technician was needed, one versed in field work as well as work in an air conditioned laboratory.

Although the Hawaii Institute of Geophysics since its inception has been engaged in crustal surveys with emphasis in marine geophysics, and although the staff members have been using a variety of techniques in surveying, there were a few survey methods for which equipment and experience were lacking at the Institute. Two of them were infrared scanning surveys and deep probing electrical surveys. It was decided to subcontract a commercial firm to do the infrared scanning survey. As for the deep probing electrical survey, George V. Keller of the Colorado School of Mines was contracted to carry out the initial phase of the surveys while equipment for similar surveys were being built and tested at the Institute.

The organization of the geophysical program was enlarged in May 1974 with new tasks added. The added tasks and persons responsible for them were:

Geochemical Surveys -- P. F. Fan
Temperature Measurement of Wells -- J. Halunen, D. Epp
Microearthquake Monitoring -- W. Suyenaga
Magnetic Surveys -- R. Norris

Of these men, W. Suyenaga had already been in the program doing field work in ground noise surveys. As the seismic task expanded into microearthquake monitoring, he was given charge of the task.

The magnetic survey task was allotted to R. Norris. In addition to this, the ground noise survey also became his responsibility. The analysis and interpretation of the data taken in the ground noise surveys required a man experienced in outdoor surveys and sensitive to various diurnal changes, as well as one capable of writing computer programs. He was able to fill the many faceted requirements.

At the arrival of the data analysis stage in 1975, services of more computer programmers were needed. To fill this need, Mrs. Candance Fenander was recruited into the program.

Overview of Field Work

Field work was carried out through the years of 1973 to 1975 with varying degrees of intensity. As several staff members have academic responsibilities with the Department of Geology and Geophysics of the College of Arts and Sciences, plans were made to dovetail field work with the academic year. Although Hawaii has a stable climate without the extremes of seasons, nevertheless we do have periods of heavy rainfall which preclude outdoor field work. The electrical surveys in particular cannot be done in the heavy tropical storms.

The chart in Figure 1 shows the periods during which field work was done by the respective tasks. The chart also shows academic meetings attended and consulting done by the staff members. There is heavy concentration of field work during the summer months because of release from academic duties and also because the weather is favorable for field work.

Among the traveling done, the geophysics coordinator, A. Furumoto, has visited the geothermal fields of Geysers, California, of Otake and Matsukawa in Japan, and Wairakei of New Zealand. From the geophysical and geological point of view, the most profitable visit was to Wairakei, as the New Zealanders had a deep insight into the geology of their fields. They hypothesized that there was a thermal source of a "hot plate" about 10 to 15 km deep under a graben and hot water rose upwards to be trapped under impervious layers. At Wairakei, the impervious layer was made up of mudstones known as the Huka Formation. In the visits to the Japanese fields, the geophysicists there also pointed out that the geothermal sources were associated with faults and grabens.

The results of the exploration program have been presented at two academic conferences. The infrared scanning survey was discussed by A. Abbott at the U.S.-Japan Seminar on Volcano Energy held in Hilo, Hawaii, February 4-8, 1974. At the Fall Meeting of the American Geophysical Union in December 1974 at San Francisco, A. Furumoto presented the overall results of the exploration program up to that date.

Returning again to the discussion of field work, the schematic diagram of Figure 2 shows how the exploration program was carried out. The blocks do not

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

X = field work
T = travel out of state
M = general meetings

Figure 1   Tabulation of Field Work and Travel Done by the Geophysics Program

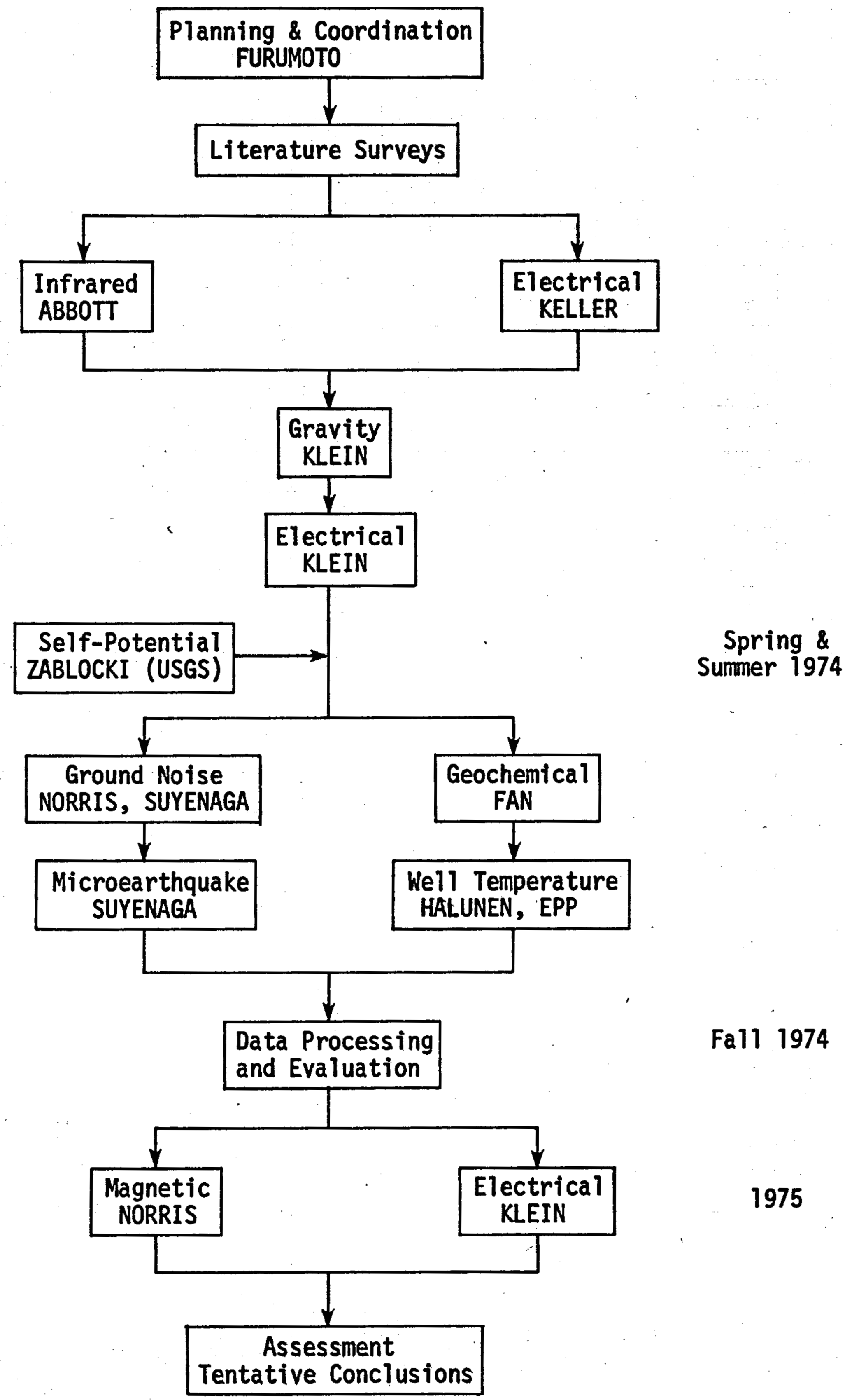


Figure 2   Exploration Scheme

mean that the various tasks were limited in time, but they show how information from one task initiated a subsequent task. For example, from literature surveys, it was decided to start off the field program with infrared scanning surveys over the whole island and an electrical survey over the east rift of Kilauea Volcano. Literature survey continued even as the field work began and influenced all other tasks. The electrical surveys got started in the summer months of 1973 and are still continuing to gather data. The results of the electrical surveys narrowed down the area which seismic surveys were to investigate.

Quite independently of the efforts of the Hawaii Institute of Geophysics, C. Zablocki of the U.S. Geological Survey had been carrying out an electrical self-potential survey over Kilauea Volcano. In return for assisting him with field work, his data over the east rift of Kilauea were made available to the exploration program.

As some gaps in data were noticed in April 1975 while assessing the data and interpretation, a few more weeks of field work are being contemplated for the electrical and gravity surveys.

The above discussion gave an overall view of the field work. The next section will narrate in chronological order the progress of the exploration program.

Chronological Progress of the Exploration Program

Work during 1973

As soon as funds became available in May 1973 to start the exploration program, equipment and instruments were assembled and mobilized at the Hawaii Institute of Geophysics to get in some field work during the summer months. That period of time was characterized unfortunately by a national shortage of materials. For example, bids sent out to manufacturers for seismic amplifiers returned with quotes asking for three months delivery. When the best offer in delivery time was taken, the instruments were actually delivered five months after ordering. The electrical survey was also stymied by slow delivery of components. The Achilles' heel in the electrical survey system turned out to be the switching mechanism.

For the field work, a trailer was purchased in June to serve as a field office. As trailers are rare things to find on Oahu, a small island, it was a very fortunate chance that an automobile dealer happened to have a trailer he wanted to sell badly. Otherwise, 50% of the purchase price of a trailer is the shipping cost from California. The trailer was modified and outfitted during June and July.

Before we narrate the sequence of the exploration program, a few geological names should be pointed out with the aid of the map in Figure 3. The island of Hawaii is made up of five volcanoes: Kohala, Hualalai, Mauna Kea, Mauna Loa and Kilauea. With each volcano are associated rift zones; each rift zone is named according to the direction it radiates. For example, Mauna Loa has four rift zones, southwest, west, north and northeast; Kilauea has two rift zones, southwest and east rifts. In particular, the area through which the east rift of Kilauea cuts through has been called the Puna District, which includes the villages of Kapoho and Kalapana.

The first task to be in the field was the electrical survey by G. Keller of the Colorado School of Mines. Keller was already in Hawaii to supervise a drilling project in the summit area of Kilauea, a project funded by the National Science Foundation, and it was only a matter of days for him to mobilize for field work.

Since surface manifestations of fumaroles, steam vents and lava flows of 1955 and 1961 made it all too evident that the east rift of Kilauea was still very hot, it was decided to obtain rapid results about the east rift by contracting Keller to do electrical surveys. Keller carried out his surveys in June-July 1973. From his data, he concluded that in the east rift area, there are patches of low resistivity rock layers, as low as 5 ohm-m. These anomalous layers existed at somewhat deep levels, from a depth of 600 m to 2100 m.

As mentioned previously, the infrared scanning survey was subcontracted to a commercial firm, the Daedalus Corporation of Ann Arbor. The flying, done by Towill Corporation of Honolulu, was carried out from July 27 to August 4, 1973 and surveyed the rift zones of Kilauea, Mauna Loa and Hualalai. When the results were in, what looked like thermal anomalies were seen along the east rift and southwest rift of Kilauea and the southwest rift of Mauna Loa. From this survey then we decided to limit further surveys to the three rifts.

In August 1973, the HIG staff members were able to go out in the field to do electrical surveys and microearthquake monitoring. For the electrical surveys, a loop-to-loop induction method of survey was carried out over the Puna area. As the loop-to-loop method was designed for shallow probing, the surveys were done over areas where Keller's survey had shown low resistivity anomalies. The loop-to-loop method showed that there was a thin layer of low resistivity at about sea level in addition to what Keller found. It was concluded after consulting well temperature data that this thin, low resistivity layer was hydrothermal

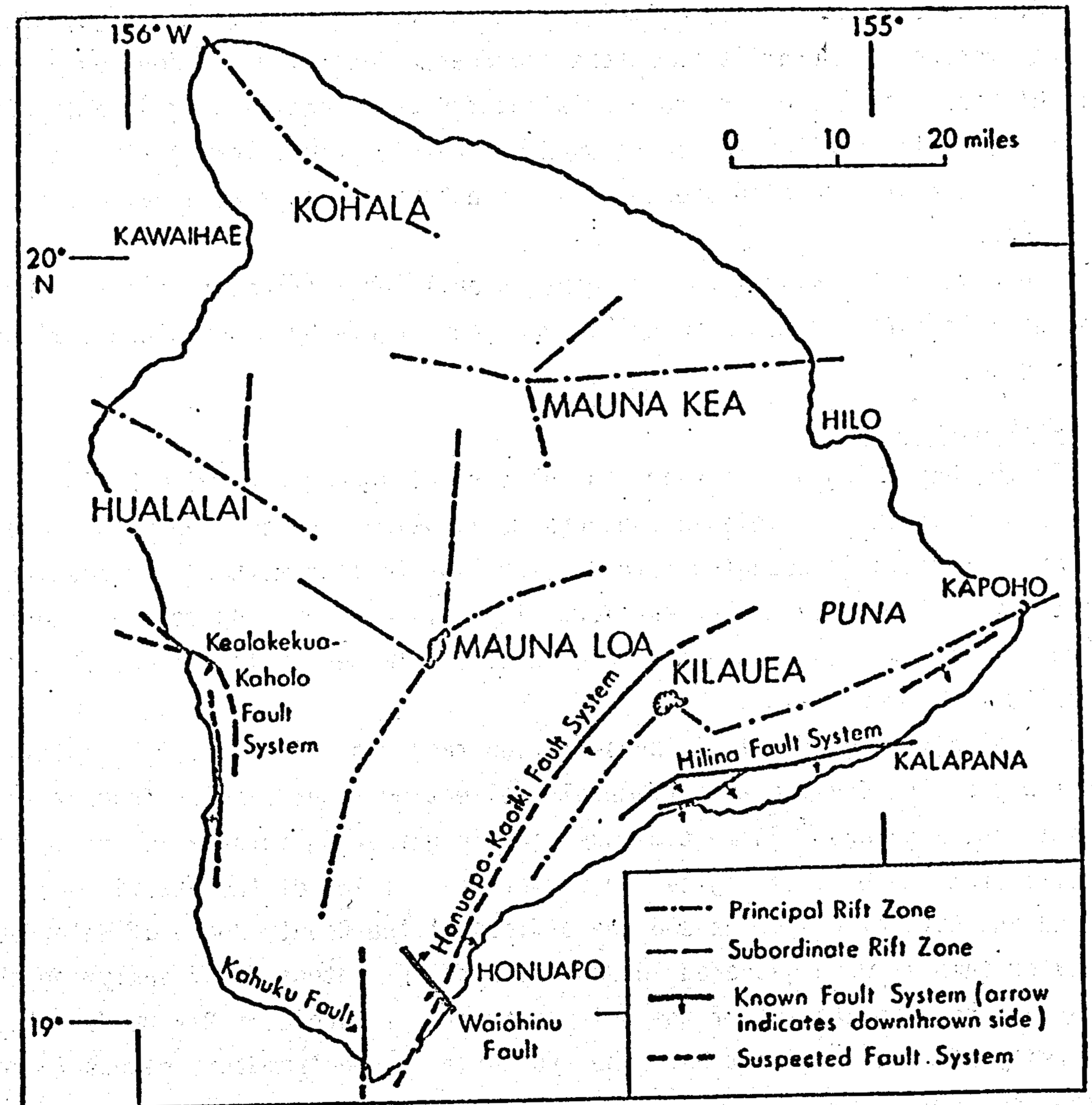


Figure 3 Map of the Island of Hawaii with Volcanoes and Associated Rift Zones

water coming off the rift zones. The temperature of this layer ranged from 50°C to 92°C, not hot enough for geothermal consideration.

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

The rest of the year 1973 was spent in building instruments for the anticipated work in 1974. Again slow delivery of components by manufacturers plagued the program.

Work during 1974

At the beginning of the year, the electrical survey team with Klein as party chief was again in the field in the Puna area, using line to loop method and Schlumberger galvanic sounding method. The line to loop method confirmed the low resistivity detected by Keller earlier. The galvanic sounding method determined the resistivity values of the dry rocks above the water table. The values varied from 6000 to 30,000 ohm-m.

In January, a geochemical investigation task was initiated. The initial effort was of low level activity, merely collecting water samples from existing wells in the Puna area. Some time was used in gathering information on location of wells from the U.S. Geological Survey offices, files of the Hawaii Department of Land and Natural Resources and the offices of the County Board of Water Supply. The water samples were gathered in January with the intention of analyzing them in May at the laboratories of the University of California at Riverside. As the University of Hawaii did not have the type of mass spectrometers necessary for isotope determinations suited to our purpose, it was decided to rely on the kindness of the people at Riverside. The actual analyses were to be performed by graduate students from the University of Hawaii using Riverside equipment.

During the week of February 4-8, the U.S.-Japan Science Seminar on Volcano Energy was held in Hilo. The seminar, sponsored by the National Science Foundation and Japan Society for the Promotion of Science, was attended by 60 persons. A. Abbott presented the results of his infrared scanning survey in the first day of the seminar. Many papers relating to the thermal processes of Kilauea were given. The seminar was of particular advantage to the geophysics exploration program as A. Furumoto was a co-chairman of the seminar and in that position had early access to the manuscripts and taped recordings of the proceedings.

During the last week of February, Suyenaga and Furumoto carried out a ground noise survey over the Puna District. The Puna District had an overall high level of ground noise on account of the surf pounding on the precipitous rocky shore. However, a pocket of noise high in the 4 to 8 hz range above the background level was found. This pocket could not be correlated to any geophysical anomaly found up to that time, but it was better defined later and was correlated to resistivity anomalies.

During April, the electrical survey team attempted further loop to loop and galvanic soundings in the Puna area. The work was often frustrated by torrential rains. When electrical work was unfeasible, a gravity survey was done over a stretch of highway. Data from this gravity profile were valuable later in determining the dimensions of the dike complex under the east rift.

In May the isotope analyses of water samples from Puna were done by G. McMurtry, who had traveled to the University of California at Riverside for that purpose.

The summer months saw a variety of field work. The geochemical survey got underway in June to gather more samples. The electrical team carried out surveys over the southwest rift of Kilauea and the southwest rift of Mauna Loa. The results of these surveys showed that the possibility of geothermal sources in these rifts were much, much smaller than the east rift of Kilauea. Also, a ground noise survey of these rifts showed that microseisms in these areas are all attributable to surf beats on the precipitous shoreline. These findings led to the decision to concentrate on the east rift of Kilauea.

At the request of the Research and Development Department of the County of Hilo, the Hualalai rifts were surveyed electrically, although infrared scanning surveys were unpromising. The electrical surveys turned in negative results, as far as low resistivity layers were concerned.

In August, a seven station array of seismographs was set up in the Puna area to monitor microearthquakes. The stations were in operation for three weeks, night and day. One difficulty was that due to absence of public utility electricity, a gas-line driven generator had to be installed at the base station. The noise from the generator, although operated only to recharge batteries, interfered with the monitoring.

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

In November the geophysics group met in seclusion at a rented room in a hotel in Waikiki to evaluate the results of the geophysical surveys. Each task presented its up-to-date results, but the tasks had not progressed to the stage of definitive conclusions. Only the self potential data from Zablocki could show a contour map with recognizable bull's eye. Self potential data require only simple processing to show recognizable contours, while other types of data, such as seismic, require weeks and months of processing. But self potential data can easily be interpreted erroneously as there are many possible mechanisms, chemical, thermal, mechanical, that can generate electromotive force underground. After much debate, the geophysics group concluded that geophysical evidence available does not justify a drilling program to search for a geothermal source. More time will be needed to sort out the data and to put pieces of the puzzle together. Plans for more field work were laid.

Although the consensus of the geophysics program was made known to the other programs in the Hawaii Geothermal Project, the desire to start drilling in 1975 overrode the misgivings of the geophysics program. So the geophysics coordinator agreed to go along with an exploratory drill hole to test geophysical data. This fine distinction, exploratory hole to test data vs exploratory hole for geothermal source, was lost in the writing of the renewal proposal which was submitted to the National Science Foundation in December.

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

A lengthy renewal proposal for 1975 to include drilling funds was submitted by the participants in the geothermal project in the early part of December.

In December, more water samples for geochemical study were gathered to have them analyzed at Riverside in January 1975.

Work during 1975

The site chosen by the drilling committee was based on self potential data and on the surface manifestation of an offset in vents along the east rift. Keller's survey seem to indicate that this area was characterized by higher resistivity than background but Keller's data were sparse. To check this out a dipole-bipole survey was done over the proposed drill site in January. Fortunately a small area, less than 2 km^2, of low resistivity was found near the proposed drill site. Aeromagnetic surveys were done over the entire island of Hawaii in 1965, but the coverage over Puna was not dense. The difficulty is that the absence of navigational markers made close spaced flights rather meaningless. To augment data coverage a magnetic survey on the ground surface was done with a rented magnetometer in January. The results showed that there were many magnetic materials near ground surface which tend to obscure deeper sources. However, proper spatial filtering and averaging brought out the deeper anomalies, especially sections of non-magnetic material.

In March, a critique of the proposal submitted by the entire geothermal project in December was received. The critics singled out the lack of geophysical evidence to justify a drilling program. The geophysics coordinator was not surprised at the criticism as such an answer was really expected. The proposal was submitted prematurely, before geophysical data could be properly analyzed and interpreted. By March, however, the data collected in 1974 was processed to a stage where early attempts at interpretation could be made.

From analyses of gravity, magnetic and microearthquake data, the intrusive zone or dike complex under the east rift of Kilauea was outlined and determined as to width and depth. The magnetic data also showed that only the northern half of the dike complex was hot enough to be above the Curie temperature. As the Curie temperature for tholeiitic basalt ranges from 100°C to 300°C, water circulating near the dike complex will be hot. Electrical data have located patches where bulk resistivity of rocks is as low as 5 ohm-m, perhaps indicating places where hot water could be circulating. For geothermal purposes, hot water should be ponded or confined in reservoirs. There are hints that, contrary to what geologists have thought all along, there may exist impermeable cap rocks to form hot water reservoirs.

Concluding thoughts

At the present time, April 1975, the major part of the field work for Puna has been done. The other parts of the island of Hawaii have also been examined.

The unpromising results from the other parts of the island encourage us to concentrate on Puna.

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

Task 2.1
Photogeologic Survey: Imagery from Infrared Scanning of the Rift Zones of Kilauea and Mauna Loa

A. T. Abbott

Introduction

From July 31 through August 4, 1973 night time flights for obtaining infrared imagery along the east and southwest rift zones of Kilauea and the southwest rift zone of Mauna Loa were undertaken on the island of Hawaii. Flights were also made on Hualalai and Kohala volcanoes, but because of inconclusive results are not included in this report. Ground control stations had been established during daylight hours several days prior to starting the flight program. Students stationed at the ground central points guided the aircraft on predetermined flight paths by the use of directional lights which were visible to the plane's navigator. Results of the infrared scanning program are considered to be very successful. Events leading up to the final imagery on 8 x 10 color prints will be discussed below.

A firm specializing in infrared surveys, Daedalus Enterprises of Ann Arbor, Michigan was selected as best equipped and experienced in Hawaiian conditions to accomplish the infrared imagery survey. Towill Corporation of Honolulu provided the aircraft, pilot and navigator and submitted a report with maps and black and white aerial photographic mosaics. These firms earlier the same year had flown paths for Dr. George Keller of the Colorado School of Mines, who was engaged in locating a deep drill hole near the summit of Kilauea.

Flight Paths and Descriptions

(1) East Rift Zone of Kilauea

Two long parallel flight paths were flown along the East Rift Zone from points outside the boundary of Hawaii Volcanoes National Park to Cape Kumakahi. Shorter paths crossing the two long parallel lines were flown at the intersection of the rift zone with the main highway between Pahoa and Kalapana. Approximately 35 line miles of usable record was obtained. From this the following strips were selected for reproduction in infrared false color imagery:

Three miles of flight paths high on the rift zone at an average ground elevation of 2100 feet provide excellent examples of rift lineation and temperature aureoles. The DIGICOLOR prints showed a temperature range of 14°C to 20°C. Numerous sites along the rift showed spots of white color indicating the temperature exceeded the highest range on that temperature set. This is not surprising in view of the fact that wisps of steam are issuing from some of the vents probably as a result of meteoric water coming in contact with residual heat of lavas from the 1966 eruption in this area. Downslope from the steam vents, a fairly extensive area shows a slightly higher surface temperature than its surroundings, by an average of 1°C.

The area for the second set of DIGICOLOR prints in the Kilauea east rift zone was selected from a flight path of approximately two miles in length across the area of intersection of the rift zone and the Pahoa-Kalapana highway at a ground elevation of approximately 1000 feet. The temperature range of this path is 16°C to 25°C or 1.5°C per color. Again numerous sites showing white along the rift zone indicate local hot spots and an aureole of decreasing temperatures are distributed outward from the rift. Fine examples of surface temperature zones are demonstrated in this imagery.

(2) Southwest Rift Zone of Kilauea

A flight path 12 miles long was followed from the point of intersection of the western boundary of Hawaii Volcanoes National Park and the main highway between Kilauea summit to Pahala to a point on the sea coast approximately 4 miles east of Punaluu.

The altitude maintained was about 3000 feet above ground level. Throughout most of the strip a thermal anomaly was evident along the Great Crack. The temperature range on the flight path was 18°C to 22°C. Of unusual interest on this path is a thermal anomaly in a target-like pattern near the southern end of the Great Crack approximately 1-1/4 miles from the coast line at an elevation of 300 feet above sea level. The target-like pattern is 1200 feet wide, 1600 feet long. The roughly circular pattern of thermal anomaly lies 600 feet northwest of a splinter extension of the Great Crack. The highest temperature within the target area reaches the red color or 22°C in two small spots, and within the Great Crack extension, small local spots reach white, or off scale.

The anomaly appears to be associated with the lower slopes along the south side of Puu Kolekole, a prehistoric cinder cone, and with the extension of the Great Crack.

This surface thermal anomaly as registered by infrared scanning imagery should receive careful attention as a potential area for further geophysical investigation and possibly research drilling.

(3) The Southwest Rift Zone of Mauna Loa

A flight path with the total length of approximately 22 miles followed the southwest rift of Mauna Loa from an elevation of approximately 7000 feet above sea level to the tip of South Point. Only the lowest five mile section of this path to the tip of South Point showed any significant thermal anomalies. This portion has been reproduced in DIGICOLOR and prints developed.

The temperature range on one subset is 16°C to 22°C. Thermal anomalies appear along the cliff face of the Kahuku fault as clusters along the base of the cliff and as linear features possibly indicating bedding planes in the lava flows. Numerous spots along the cliff register red and a few local areas show white, or off scale.

The cause of these anomalies is not known at the present time. The Kahuku fault scarp, which reaches 400 feet in height in this area, faces west. Consideration must be given to the possibility. that the anomalies result from residual late afternoon solar heat. The imagery was taken at 0030 hours in order to reduce the effect of residual heat. The physical distribution of the warmer areas does not appear to show a pattern that might be caused by residual heating, nonetheless, this factor must be kept in mind.

Another, more intriguing possibility lies in the concept that heat may be rising from depth along the plane of the Kahuku fault and issuing at the base of the cliff and along bedding planes of the lava flows. The Kahuku fault is a major structural feature of Mauna Loa shield volcano. It extends ten miles inland from the coast and has been followed out to sea for a distance of over 15 miles. Depth recordings made on board the R/V Valdivia in 1973 while steaming past the extension of the fault 4 miles off shore registered a vertical displacement along the fault plane of 1900 meters.

Further geophysical and geological work should be concentrated in the section of the lower portions of the Kahuku fault. This may have promise as an area in which to locate an array of research drill holes.

Also of interest along the South Point shoreline as registered by the infrared imagery is the temperature distribution in the sea water. Directly offshore a large patch of water shows as a white area indicating that its temperature is greater than 22°C. It is not recognized at this time whether this is a bay of warm surface water brought in by ocean currents or wind or whether the warming is caused by some other process.

Task 2.2
Geoelectric Surveys on Hawaii: 1973 - 1975
D. P. Klein

Geoelectric surveys have been performed in the areas indicated in Figure 4, chosen largely on the basis of recently active volcanism or known existence of anomalous thermal conditions (Macdonald, 1973).

The geoelectric methods applied were:

1. Dipole-bipole mapping: G. V. Keller (1973).
2. Dipole-bipole mapping: Hawaii Institute of Geophysics (H.I.G.)
3. Line-loop (time domain) inductive sounding: H.I.G.
4. Line-loop (time domain) inductive sounding: C. K. Skokan (1974) of the Colorado School of Mines
5. Self-potential mapping: C. Zablocki of the U.S.G.S.
6. Galvanic (Schlumberger) sounding: H.I.G. and C. Zablocki
7. Loop-loop (frequency domain) sounding: H.I.G.

The conclusion reached as a result of these surveys is stated below. It is the crux of our progress to date. The sections following: (II) summarize the reconnaissance data over the island of Hawaii, and (III) summarize the main points regarding detailed surveys in the primary geothermal candidate area.

I. Conclusion

The results of geoelectric surveys on the island of Hawaii provide promising evidence of hydrothermal conditions beneath parts of the Kilauea East Rift Zone on the extreme northeastern side of the island (referred to as Puna or the Puna Anomaly, see Figure 4). Preliminary interpretation of several complimentary data sets converge to two targets in this area (described in part III), one of which was chosen (note entirely on geoelectric evidence) for a drill site. The geoelectric evidence contributing to this selection is summarized in part III of this report.

The present state of our interpretation contains many ambiguities, most of which we believe result from the unique situation of Puna. The geothermal target is probably an unconfined hydrothermal system heated by deep (greater than 500 m depth) rift zone intrusives. This target is situated in porous, saline-water saturated lava. This is not a favorable situation for a precise definition of the target by geoelectric methods. Furthermore, if the geothermal target is as postulated above, there is a good chance it will not be economically viable. However, these ambiguities cannot be cleared up without drilling. In the light of this and the crying need for definite data on geothermal resources we do not hesitate to recommend an exploratory hole.

II. Reconnaissance Results

Reconnaissance induction soundings were made in the lower regions of the southeast rifts of both Kilauea and Mauna Loa volcanoes (areas 3 and 4 respectively, Figure 4). Soundings were also made in the saddle area between the Hualalai and Mauna Loa domes (area 5, Figure 4).

Nineteen soundings were made in the regions of the southwest rift of Kilauea, 22 in the southwest rift of Mauna Loa, and eight on the Hualalai-Mauna Loa saddle. Maps of the areas are given in Klein and Kauahikaua (1975). The data are still being being processed as reduction priorities have been biased toward the Kilauea east rift data discussed below. Nevertheless, based on field reduction that gives a minimum apparent resistivity (see Klein and Kauahikaua, 1975) it is fairly certain that none of the above areas contain significant geothermal prospects. As Table 1 shows, the apparent resistivities in these regions are higher than expected for a hot-water-saturated rock which is expected to have a resistivity of less than about 10 ohm-m.

Keller's group (1973) made reconnaissance dipole-bipole galvanic measurements in the region on the northwest coast of Hawaii (area 2, Figure 4) where water wells show slightly anomalous temperatures of a few degrees (°C) above normal. These latter measurements also did not provide evidence of low resistivities that could be geothermally generated.

Keller's (1973) main reconnaissance effort was in Area 1 (Figure 4). Here the dipole-bipole survey isolated an anomalous region on the lower part of the rift zone of Kilauea Volcano (the "Puna Anomaly"). Apparent resistivities in this anomaly range from 5 to 20 ohm-meters (ohm-m) compared to values of greater than 200 ohm-m measured elsewhere outside the immediate volcanic edifice of Kilauea.

Plots of the generalized apparent resistivity trends against source-receiver separation for the Puna survey of Keller (1973), are reproduced in Figure 5. These data illustrate the anomalous low apparent resistivities (solid lines) of the lower regions of the East Rift Zone in comparison to data in the other parts of Area 1.

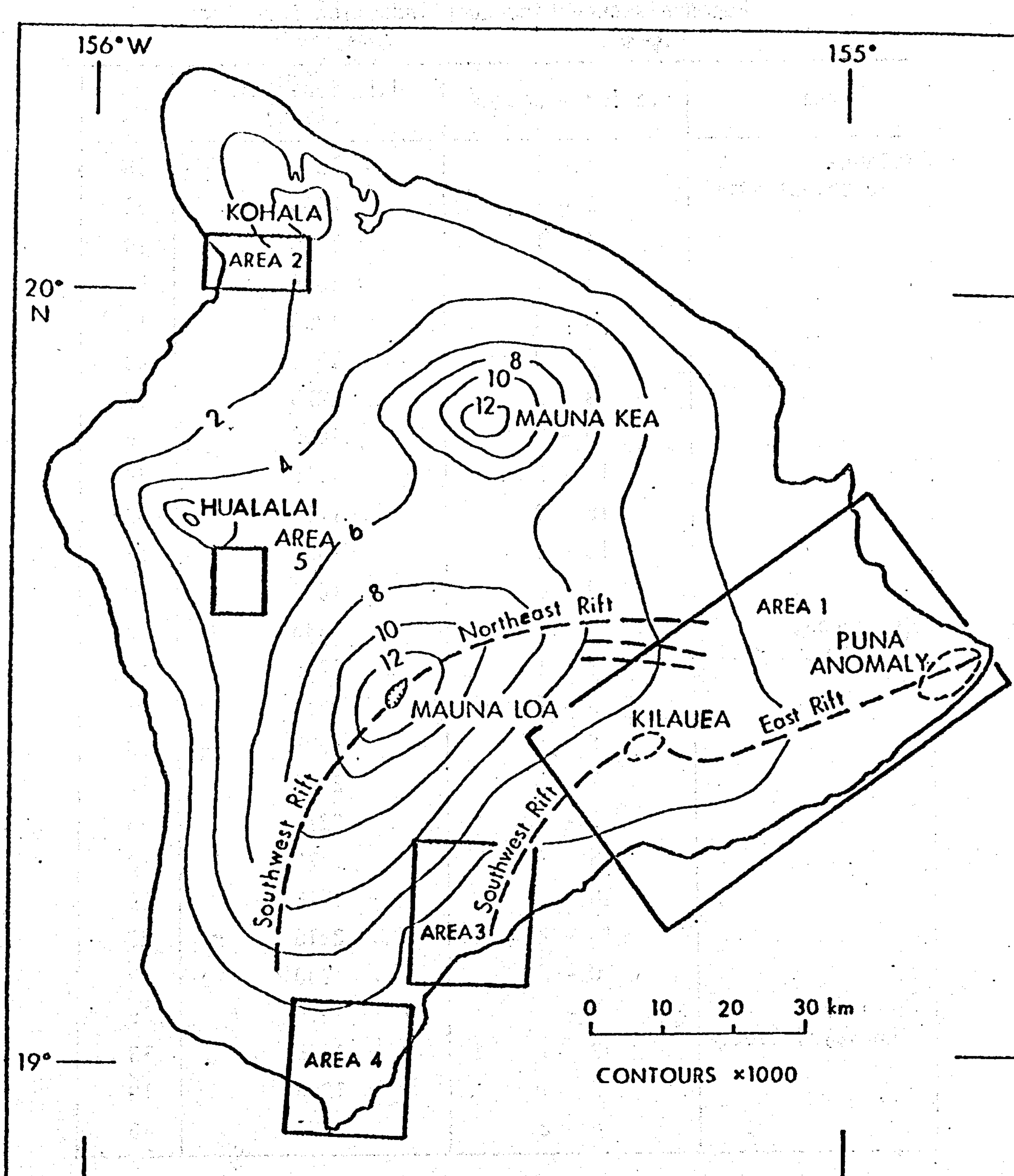


Figure 4 Areas of Geoelectric Surveys on the Island of Hawaii
Elevation contours are feet x 1000

Table 1 Minimum Apparent Resistivities (ρ_a, in ohm-m), from Reconnaissance Line-Loop Induction Soundings

Area	Station - Source	Half-Separation (meters)	ρ_a
Kilauea, Southwest Rift	1 - 1	1690	18
	2 - 1	2205	53
	4 - 1	1190	19
	5 - 1	2525	50
	6 - 2	1260	14
	7 - 2	1990	48
	8 - 2	2275	56
	9 - 2	1090	13
	12 - 3	1565	28
	15 - 3	1120	13
	18 - 3	2355	14
	19 - 3	1600	20
Mauna Loa, Southwest Rift	1 - 1	1385	13
	3 - 1	1745	12
	4 - 1	2215	17
	5 - 1	2625	19
	7 - 1	2425	17
	8 - 1	2210	33
	15 - 2	1475	13
	18 - 2	1775	29
	19 - 2	2215	23
	20 - 2	1280	19
Mauna Loa-Hualalai Saddle	1 - 1	1925	38
	2 - 1	1325	13
	5 - 1	1295	19
	6 - 2	2355	40

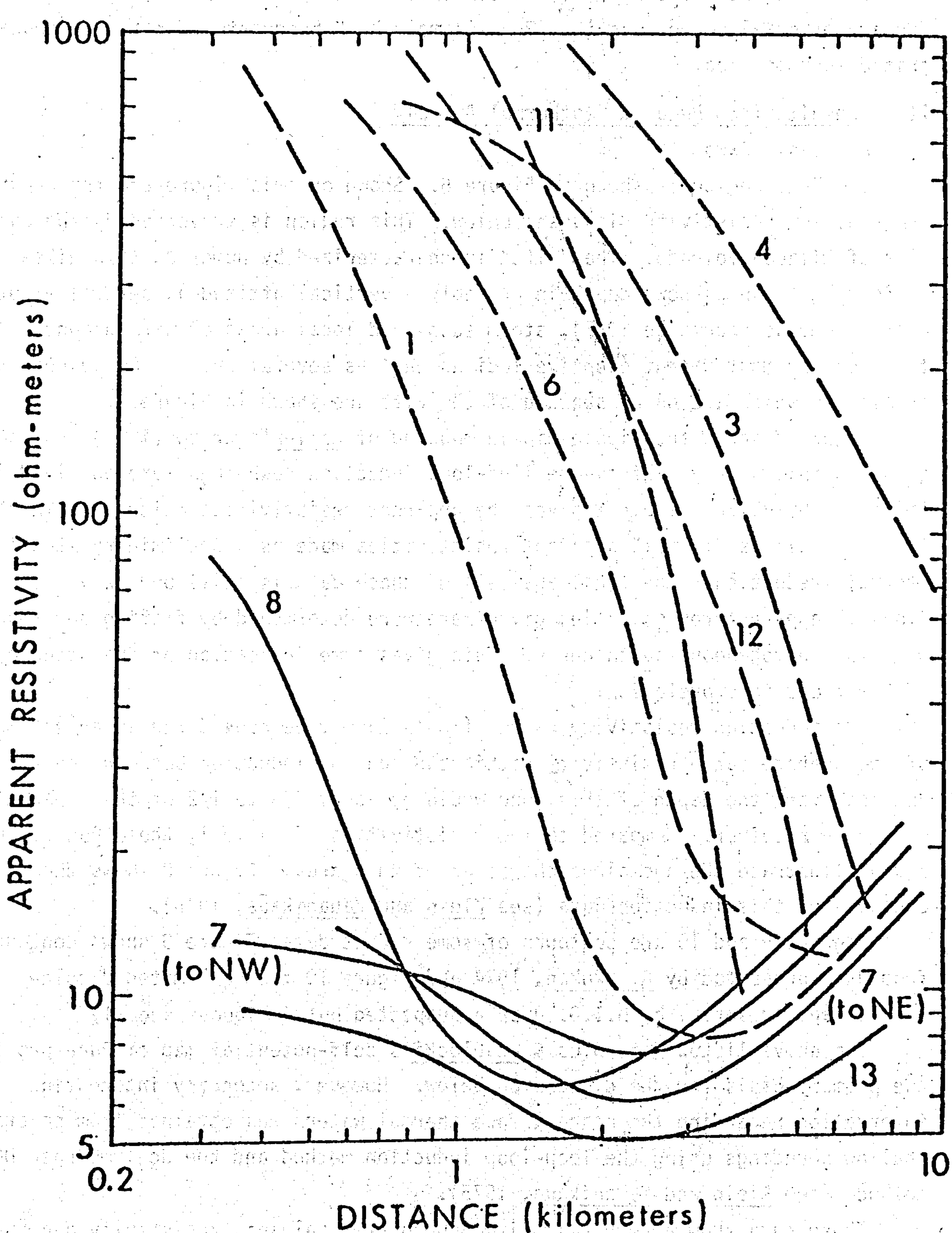


Figure 5 Generalized Trends of Apparent Resistivity versus Source-Receiver Separation of the Dipole-bipole Resistivity Survey. The solid lines are the trends from stations in the Puna Anomaly. The dotted lines are the trends of selected data from stations outside the Puna Anomaly (from G.V. Keller, 1973).

Based on the above results, we concluded that the most promising candidate for a geothermal source was the "Puna Anomaly." Subsequent efforts were concentrated in this area.

III. Results from Puna, A Geothermal Anomaly

A. Basic Data

The Puna region is shown in Figure 6. Shown on this figure are the general areas of low resistivity discussed below. This region is traversed by the east rift of Kilauea Volcano. The "rift" is characterized by numerous thin dikes (extending to an unknown depth in probably a vertical attitude), several eruptive vents (some as recent as 1962), steam seeps and local areas of warm ground. The trend of the most recent eruptive loci as well as several known warm to hot water localities which are on or seaward of the rift are shown in Figure 6.

Figure 7 shows the dipole-bipole mapping of Keller's group (1973). Subsequent to this survey, thirty-one line-loop induction soundings were obtained in this area by H.I.G. Table 2 gives the apparent resistivities calculated in the field as well as "formal" apparent resistivities made as a preliminary step in "formal" reduction. The final analysis of these data is still underway. Our "formal" apparent resistivities given here were determined by fitting our reduced data to a homogeneous-earth curve. This gives some indication of the accuracy of our field interpretation.

The induction resistivity values (Table 2) may be considered as an estimate of the average earth resistivity within the zone of induction between the source and receiver; the depth of this zone would be about 1/3 to 1/2 of the separation of source-receiver. Compared to the resistivities of Table 1, these Puna values again illustrate the anomalous character of this area. Figure 8 shows the contours of this induction data (see Klein and Kauahikaua, 1975).

Figures 9 and 10 are contours of some recent data; Figure 9 shows contours from data presented by C. Skokan, 1974 and Figure 10 from a limited dipole-bipole mapping survey by H.I.G. over a suspected but ambiguous anomaly.

The above listed data plus C. Zablocki's self-potential map of Puna provides the primary basis for the discussion below. However, secondary interesting information regarding the near-surface thermal waters was obtained from several shallow soundings using the loop-loop induction method and the Schlumberger DC method (see Klein and Kauahikaua, 1975).

These data show a very resistive 6000 ohm-m, galvanic resistivity overburden overlying a conductive substratum. The top of the conducting material is

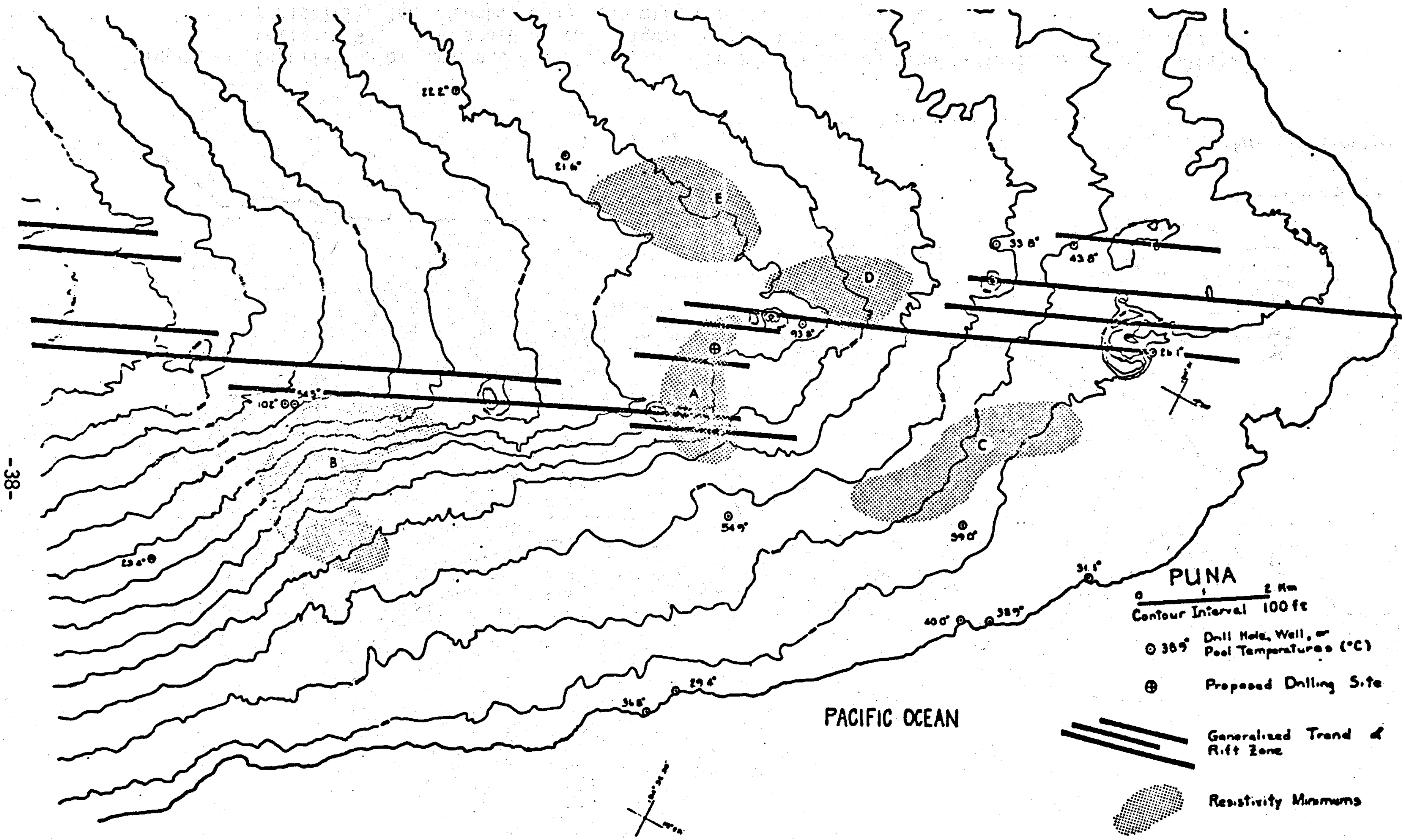


Figure 6 Contour Map of the Puna Area Showing the Generalized Trend of the Rift Zone and Temperature Samplings from Drill Holes, Wells, and Pools. The resistivity minimums (stippled areas lettered from A to E) are compiled from Figures 7 through 10. Areas A and B are the most promising geothermal prospects for reasons summarized in the text.

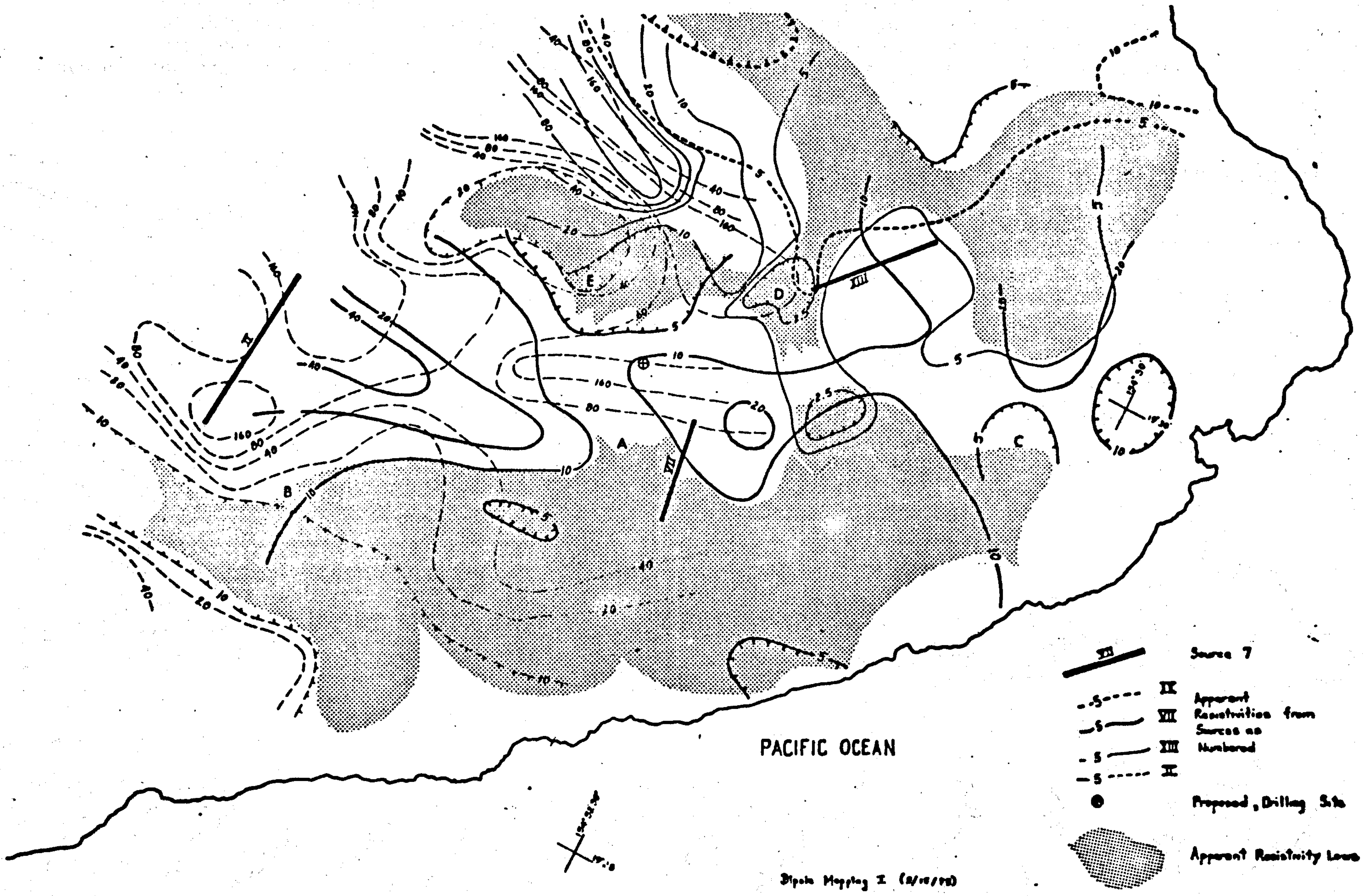


Figure 7 Compilation of Apparent Resistivity Data in Puna based on Bipole-dipole Galvanic Mapping, Keller, 1973. The scale of this figure is the same as Figure 6 and their letters show resistivity lows roughly congruent with the areas of Figure 6.

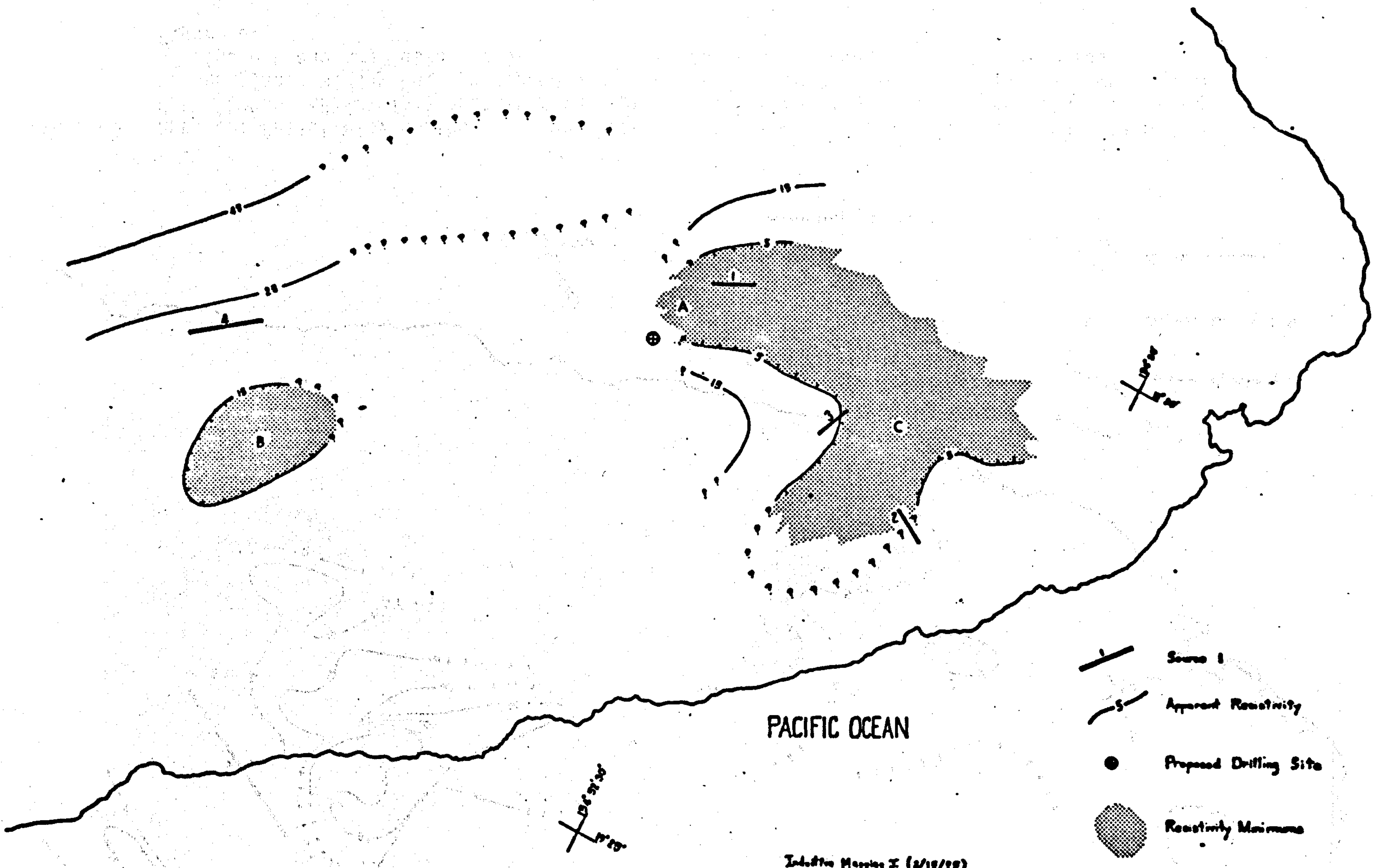


Figure 8 Apparent Resistivity Contours in Puna based on Line-loop (time domain) Inductive Sounding, Klein and Kauahikaua, 1975. Contours are controlled by placing resistivity values midway between source and receiver (see text). The scale is the same as that of Figure 6 and the letters show resistivity lows roughly congruent with the areas of Figure 6.

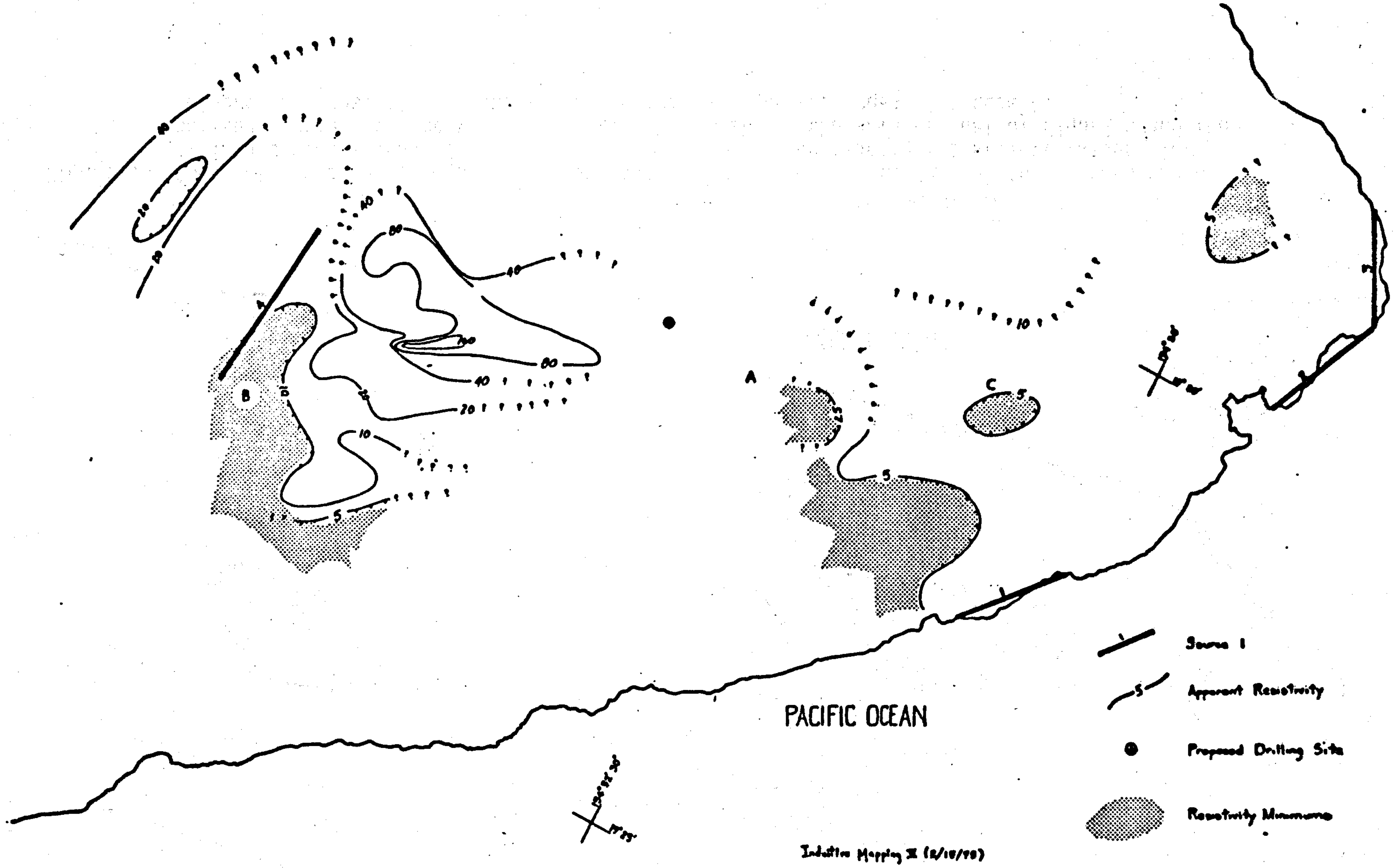


Figure 9 Apparent Resistivity Contours in Puna based on (time-domain) Inductive Sounding obtained by C.K. Skokan, 1974. This data is reinterpreted by controlling the contours with resistivity values placed midway between source and receiver (see text). The scale is the same as that of Figure 6 and the letters show resistivity lows roughly congruent with the areas of Figure 6.

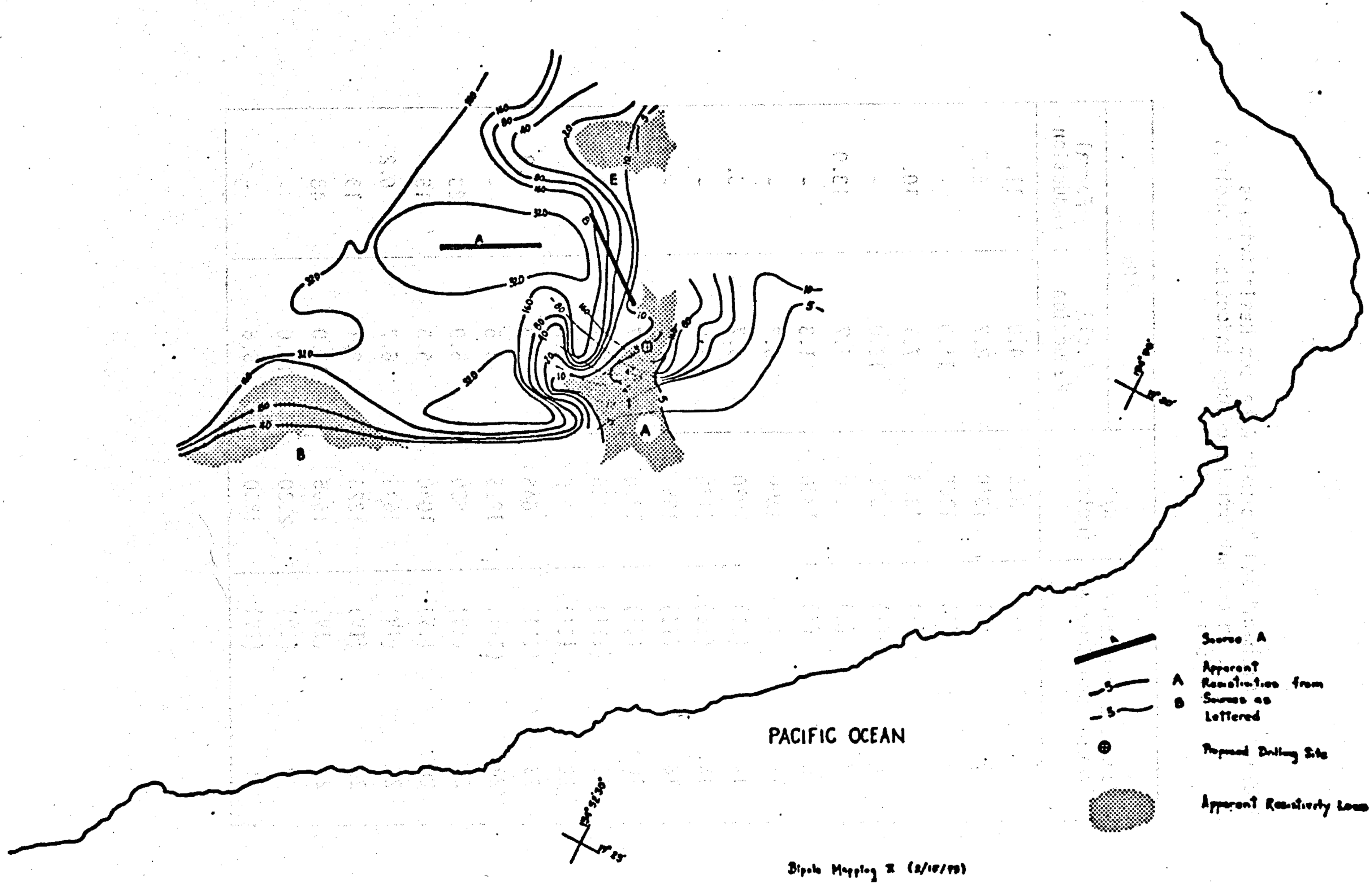


Figure 10 Compilation of Apparent Resistivity Data in Puna from Bipole-dipole Galvanic Mapping. The data is from a survey of the Hawaii Institute of Geophysics (HIG). The scale of this figure is the same as Figure 6 and the letters show resistivity lows roughly congruent with the areas of Figure 6.

Table 2 "Minimum" and "Formal" Apparent Resistivities (ρ_a, in ohm-m) from Line-Loop Induction Soundings in Puna

Magnetic Induction Station and Source		R/2 (meters)	ρ_a	
			Field Reduction	Formal Reduction
1	(I)	839	4.0	11.
3	(I)	1310	8.7	6.7
4	(I)	1765	11.0	-
5	(I)	1375	7.1	10.
6	(I)	1570	12.0	-
7	(I)	1250	7.7	13.0
10	(I)	1330	1.3	-
12	(I)	1850	6.7	-
14	(II)	1020	3.7	5.
15	(II)	1750	5.0	-
16	(II)	1550	4.8	-
18	(II)	1330	3.7	-
21	(III)	1495	7.7	7.7
22	(III)	975	3.6	-
23	(III)	645	2.8	3.8
24	(III)	1225	3.5	-
25	(IV)	890	5.9	23
26	(IV)	1040	6.3	15
27	(IV)	1645	6.7	6.2
28	(IV)	1325	9.1	13
29	(IV)	1595	17.0	48
30	(IV)	2230	10.0	-
31	(IV)	1850	5.6	-

generally close to sea level and is considered to be a marker between conductive water-saturated basalts below and dry basalts above.

The inductive resistivity of the second layer ranges from 2 to 10 ohm-m, which is lower than expected for cool-water-saturated rocks and would be more typical of rocks in brackish to saline water having temperatures of 50 to 100°C. Well-hole temperature profiles (D. Epp and J. Halunen, personal communication) indicate that, below the rift (i.e., seaward), temperatures are indeed encountered in this range. Commonly however this temperature regime is only a few meters thick and then cools again.

The combined shallow-resistivity and well-hole data show that seaward of the rift the area is underlain by a thin zone of hydrothermal fluids (probably heated by rift intrusives during seaward flow through a highly permeable rock).

B. Discussion

The data will be discussed here primarily in terms of locating a favorable site for exploratory drilling, in other words in terms of horizontal geoelectric mapping. The possible resistivity structure and temperature pattern with depth is considered by Klein and Kauahikaua, 1975.

The dipole-bipole mapping results are summarized in Figure 7 and Figure 10. The shaded areas are resistivity minimums where the letters in the zones relate generally to the areas indicated in Figure 6 by corresponding letters.

The interpretation of dipole-bipole mapping was based essentially on multiple correlations of data from several source bipoles. Apparent resistivities calculated from dipole-bipole data are strongly affected by the source-receiver configuration, as well as the true resistivity structure. It is possible to have artificial resistivity lows and highs in dipole-bipole mapping that are spatially incongruent with the true resistivity high and lows (Lee, 1973; Furgerson and Keller, 1974). These ambiguities can be resolved only by comparing data from two or more sources with different orientations.

An example of such an ambiguity in the present survey (in Area A), is well-illustrated in Figure 7 where two apparent resistivity trends cross each other, one a relative high, the other a relative low.

On the other hand, the apparent resistivity of some areas is generally consistent between data from different sources which indicates that the apparent resistivity is showing some real structure in the earth. For example, the high resistivity region between areas A, B and E, the high resistivity region just northeast of area E and the low resistivity areas seaward of the rift zone.

The apparent low resistivity of area B is not certain, based only on the data summarized in Figure 7; however, further substantive geoelectric evidence is available in the original survey report (Keller, 1973).

The consistency of the apparent low resistivity in area E or the high resistivity to the north is probably misleading as this area is saturated with cultural features such as pipes and closely spaced groundings of power lines that may have an unknown effect on the source current distribution in this area.

The data set in Figure 10 was obtained to clear up some of the ambiguities of the data of Figure 7. In particular, the initial interpretation of the data (Figure 7) placed more weight on the apparent high resistivity trend crossing area A than the conflicting cross trend of low apparent resistivity (Keller, 1973). If this area is highly resistive there is inconsistency between the correlation of SP data and resistivity data. There is an unambiguous positive SP anomaly over area A and previous experience with SP in Hawaii indicates that highs are associated with hydrothermal activity and should correlate with resistivity lows (C. Zablocki, personal communication). Such a correlation, for instance, exists over area B and is fairly well established by surveys on the summit of Kilauea Volcano.

The results summarized in Figure 6 show that area A is characterized by an apparent resistivity low. This resistivity low is strong from source A and weaker but indicated from source B. The inconsistency in apparent resistivity that might be inferred between sources A and B is not serious. The receiver dipoles of source B are much closer to the near end of the source bipole in the anomalous area than are the receiver sites of source A. This results in a configuration effect where the electric fields of source B are reflecting the highly resistive overburden above sea-level.

An interesting relationship in the contours of source A is the two relative lows symmetric about the east end of the bipole. This pattern is in qualitative agreement with the pattern expected from a "fault" contact where the discontinuity is normal to the source bipole orientation and the far side of the "fault" is less resistant than the side of the bipole, (Lee, 1973). The asymmetry in the observed lows indicates that the "fault", if so interpretated, is askew from an orthogonal orientation to the source. The hypothetical discontinuity could be oriented more toward the orientation of the rift zone and rather than a "fault" the data could be reflecting a "dike" of low resistivity. The rift here can be considered as a dike swarm containing considerable remnant heat from recent magma injections and characterized by a zone of hydrothermal waters in contact with the dikes at depth.

The induction data summarized in Figures 8 and 9 comes from large (2-4 km) separation line-loop time-domain soundings. The data is described in detail by Skokan, 1974, and Klein and Kauahikaua, 1975.

The apparent resistivity contours in Figures 7 and 10 were controlled by placing the calculated resistivities at a point half-way between the source and receiver. Such a presentation incorporates the assumption that the region of "average" influence (the sampling region) lies between the source and receiver.

The question arises of which region affects the inductive response amplitudes or decay time of a fixed source time-domain system, e.g. the near-source region or the near-receiver region. A quantitative answer to this question requires a-priori assumptions about the resistivity structure, in which case, analog or numerical models of the response can be compared against the data. If the structure can be assumed to be "reasonably" uniform, it is justified to proceed to analytical interpretations using one-dimensional models. This is clearly not the case in Puna, though one-dimensional analysis may be qualitatively useful. Strictly speaking by using the concept of apparent resistivity one automatically assumes the earth to uniformly conducting and in this context it is intuitively correct to take the "apparent" resistivity as an average resistivity in the region between the source and receiver. This is done here but only as a preliminary step in analysis and the apparent resistivity data is presented in this way with some reservation.

The depth extent of the inductive sampling is also questionable. Analytical models of induction data for the one-dimensional case indicate that the limiting depth of inductive influence for controlled source system seems to be 1/3 to 1/2 the source-receiver separation. When there is a highly conductive substrata the depth of penetration is considerably less. In general, however, the present inductive soundings are probably influenced by deeper zones than the previously discussed galvanic data. This follows from: 1) high-resistivity overburden which negligibly affects the inductive system, 2) the generally larger spreads obtained when using the inductive systems.

The inductive data in Figures 8 and 9 in general correlates with the galvanic data of Figures 7 and 10 in those regions of overlapping coverage.

The high resistivity area between A and B agrees with the suggested concept of geoelectric structure in the following way. If the rift zone is a dike swarm, hot in localized areas due to recent magma injections, and relatively impermeable to lateral water movement, it could partially trap fresh water on its inland side causing a well developed Ghyben-Herzberg lens inland of the rift. If the freshwater head was 10 feet above sea level this would cause a low resistivity lens about 400 feet thick. Well data above the rift supports this contention, for instance, the well head at the most inland wells (see the temperature indications in Figure 7) is 10 to 16 feet. Such a thick relatively low resistivity lens would have a profound effect on the sounding data.

C. Conclusions

Based on two or more sets of complimentary geoelectric data that collaborate each other and additional supportive evidence listed below, the low resistivity areas A, B are interpreted to reflect hydrothermal conditions at depth. An exploratory drilling venture in either or both of these areas is appropriate.

Areas A and B are characterized by high SP anomalies which in the Hawaii region are a strong indication of hydrothermal conditions.

Area A was known to be astride a significant earthquake swarm in 1961 (Don Koyanaga, personal communication through C. Zablocki).

The rift trend is displaced near area A. Considering the voluminous eruptive activity (1955) just east of the break, it is conceivable that some sort of blockage to magma movement downrift is present. This would point toward the possibility of an unusual concentration of magma at depth. The microearthquake activity may be related to a strain release associated with such magma buildup.

The known warm water seeps seaward of area A indicate that this area is possibly an escape vent for deeper hot waters.

Warm waters are also known seaward of area B. Area B is also known for the most active steaming vents in Puna. Two drill holes near these steam vents in 1961 encountered near boiling temperatures before they reached depths equal to sea level. They were abandoned but the steam issuing from this area has not abated in 14 years.

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Task 2.2A

Electrical Resistivity Survey Conducted by G.V. Keller

A. S. Furumoto

The electrical resistivity surveys by George V. Keller were done in June and July 1973 and a report entitled "An Electrical Resistivity Survey of the Puna and Kau Districts, Hawaii County, Hawaii" was submitted by him. The method he used is known as the dipole-bipole mapping method. In short, he caused a large amount of current to flow into the ground through metallic electrodes driven to depths of 20 feet or deeper, and then with a pair of receiver probes he measured the current and voltage coming from the source in the area surrounding the source. With proper allowance made for depth of penetration with respect to distance from the source, the average resistivity of the ground between the dipole source and the receiver probes is determined. The survey in effect gives an integrated picture of resistivity with respect to depth. From data of many soundings, proper analyses can give a rough profile of resistivity variation with depth. As the method is adapted to cover a larger area for a single source that can be done by galvanic sounding method, it is a good reconnaissance tool.

The map of Figure 11 shows three areas of low resistivity which were obtained by interpreting the data maps provided by Keller. We shall designate the western area as the Opihikao anomaly, the central area as the Pahoa anomaly and the eastern one as the Kapoho anomaly. The three areas had resistivity profiles as given in the following table with depths in meters.

Resistivity Profiles

	Layers	Resistivity
Opihikao	0 - 600 m	20 ohm-m
	600 - 2100	5
	2100 - ∞	very high
Pahoa	0 - 600 m	20 ohm-m
	600 - 2100	8
	2100 - ∞	very high
Kapoho	0 - 700 m	10 ohm-m
	700 - 2000	3 - 4
	2000 - ∞	very high

The low resistivity of the Kapoho was attributed to high salinity from salt water intrusions. The anomalies of Opihikao and Pahoa were attributed to thermal sources.

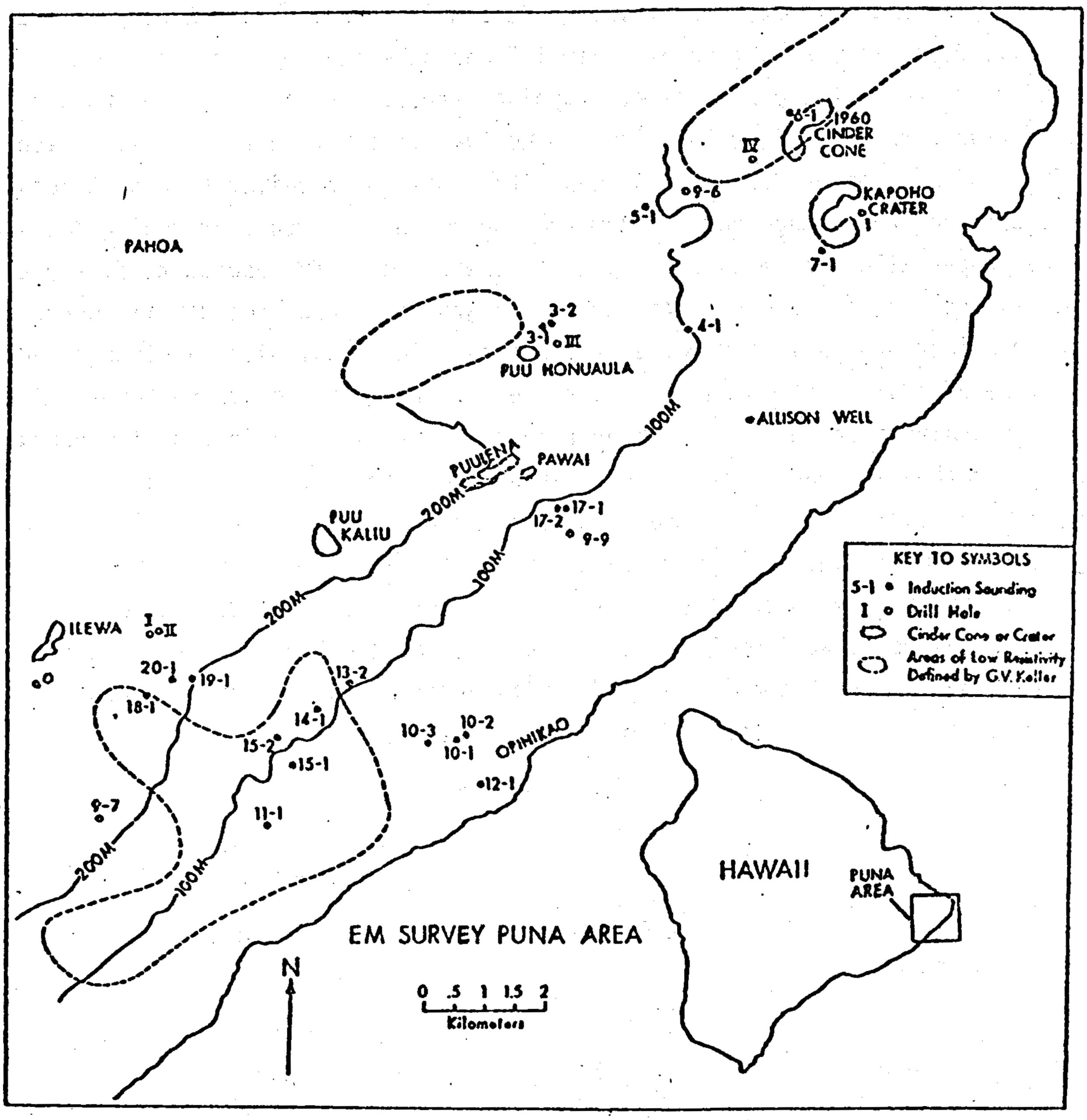

Figure 11 Low Resistivity Areas from Keller's Surveys

Task 2.3A
Gravity Survey to Determine Dike Complex Size

A. S. Furumoto and D. Klein

Ten years ago, a Bouguer gravity map was published by Kinoshita (1965). The map was not particularly useful to the geothermal project because the gravity stations were confined to the highways and were spaced at 2 km intervals. As an estimate of the size of the intrusive zone or dike complex under the east rift was deemed necessary, a gravity survey of close spacing of stations was carried out in April 1974 over a stretch of Highway 13 in the Puna District (Figure 12). The distances between stations and the elevations were carefully measured by surveying technique using transit, chains and rod. Bouguer corrections were applied to the data and the values were projected against the solid line of Figure 12. The rationale for the projection was to obtain a Bouguer profile perpendicular to the orientation of the east rift.

The transverse turned out to be too short for proper analysis. To overcome this deficiency, several values from Kinoshita's (1965) data were incorporated to form the gravity profile of Figure 13. The value of 275.3 milligals in both Figures 12 and 13 shows where the two surveys had occupied the same station and hence could be tied in.

To interpret the data, we first applied the buried horizontal cylinder model given by Nettleton (1940). The results gave the depth to the axis of the buried cylinder as 8200 feet or 2.5 km below sea level. For different density contrasts, the radius of the buried cylinder varied as shown in Table 3.

Table 3

Density Contrast	Radius (kilofeet)	Radius (km)
0.6 g/cm^3	5.3	1.6
0.5	5.8	1.8
0.4	6.4	2.0

The Bouguer gravity profile did not go far enough to show the zero level with respect to the anomaly. But juggling with gradient values and using the buried cylinder model, we obtained the maximum Bouguer anomaly for this profile as 25.9 milligals.

We then applied Skeels' (1963) method to find the dimensions of a buried horizontal rectangular prism. For different density contrasts we obtained the width, top, bottom and center of the prism anomaly, as shown in Table 4.

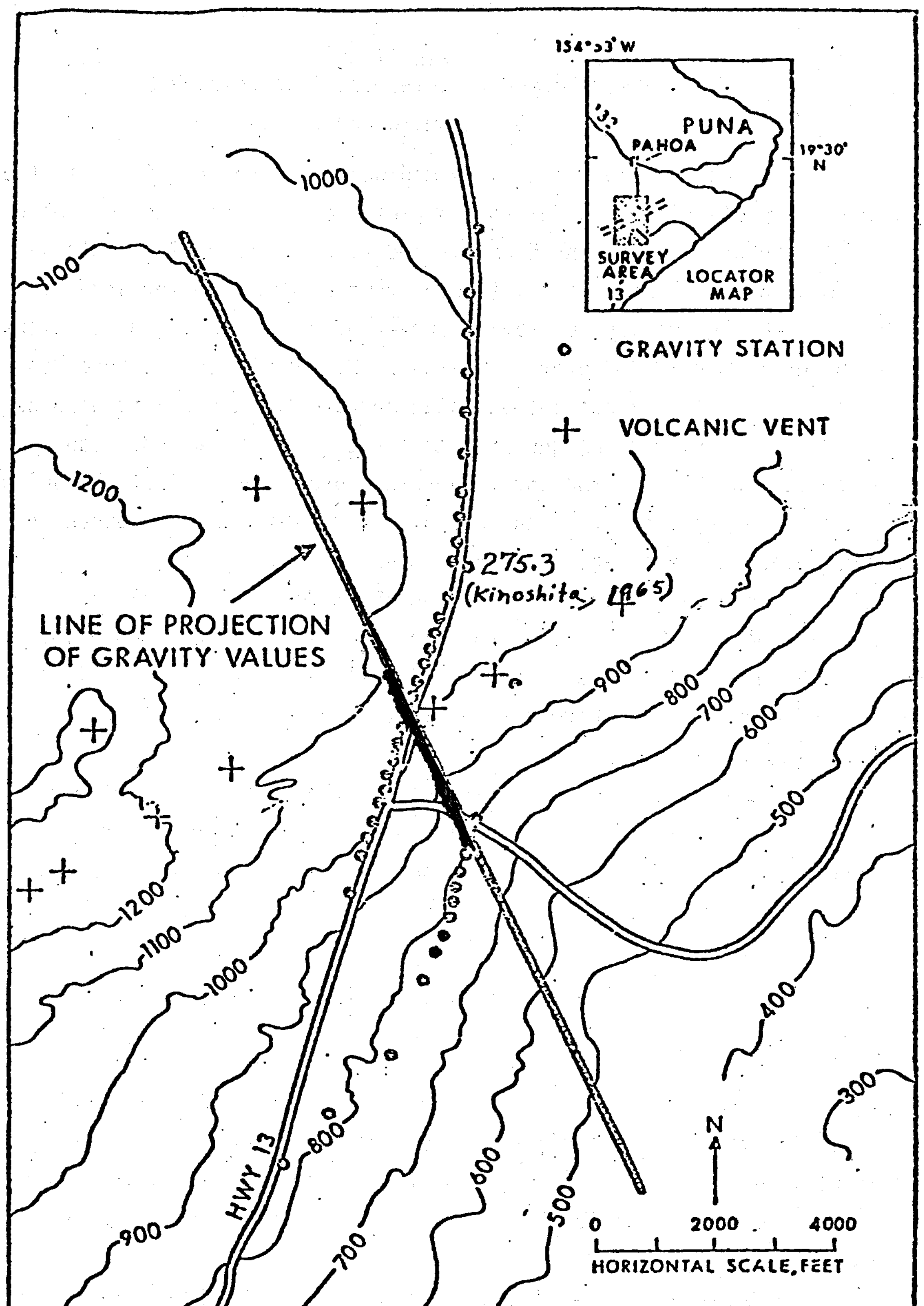

Figure 12 Survey Area and Gravity Stations

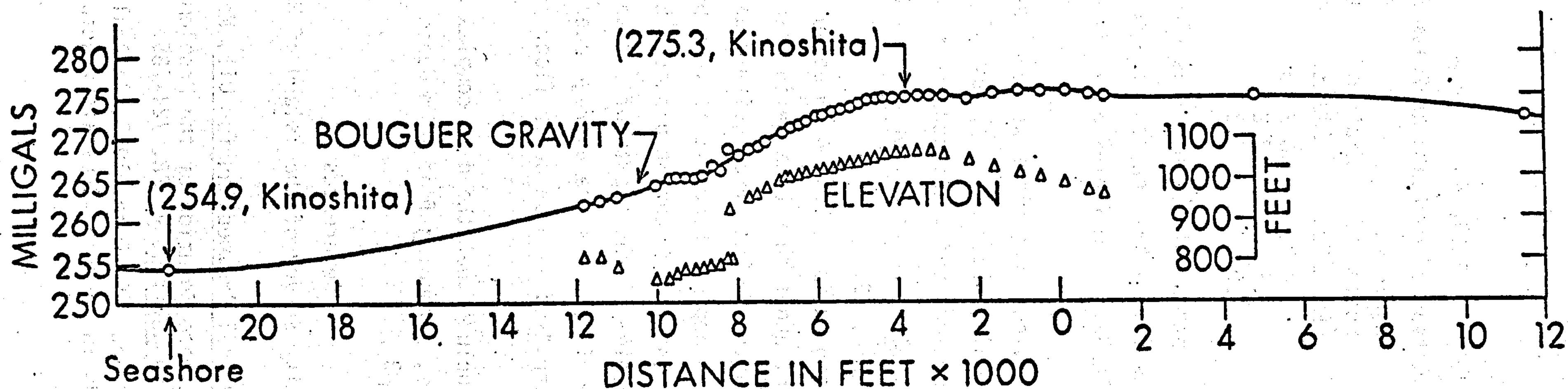

Figure 13 Gravity Profile

Table 4

Results for an Assumed Rectangular Prism Anomaly

Density Contrast	Depth to Top of Anomaly	Depth to Bottom of Anomaly	Width of Anomaly	Depth to Center of Anomaly
0.6 g/cm^3	1.0 km	3.4 km	3.2 km	2.2 km
0.5	0.87	3.6	3.2	2.2
0.4	0.69	4.0	3.2	2.3

We have chosen a density contrast of 0.6 g/cm^3 as the highest because this is what Strange, Woollard and Rose (1965) have chosen for their analysis of volcanic intrusives in the Hawaiian Islands. From Tables 3 and 4, we can conclude the following:

(1) The width of the anomalous body which we have identified as the dike complex is 3.2 km. This agrees with topographic expression.

(2) The depth to the anomalous body, the dense part of the dike complex is 0.7 km to 1.0 km below sea level, or about 1.0 to 1.3 km below the surface near Highway 13.

The bottom of the dike complex is at best 4 km below sea level according to the analysis. There is a doubt about this because in using Skeels' method we assumed uniform density contrast. We know from seismic data that the density of neighboring rocks increase with depth. Hence it is very possible that the bottom of the dike complex is deeper than 4 km, but it probably bottoms out at about 5 km. This agrees with the common notion of the growth of a Hawaiian volcano, that it starts by extruding onto a sea floor. As the average ocean basic depth is 5 km, the dike complex formed by extruding onto an ocean floor is at most 5 km deep at its bottom.

From gravity data, we conclude that the dike complex approximates a horizontal rectangular prism, 3.2 km wide, extending from 1 km depth to 5 km depth, and with a density contrast of 0.6 g/cm^3.

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Task 2.3B
Puna Magnetics

R. Norris and A. S. Furumoto

Hawaiian rock has no magnetism when its temperature is above its Curie point and is quite magnetic at lower temperatures. So if there is substantial amount of hot matter beneath the surface in the rift zone it may be expected to cause a mile-long peak-and-trough feature on the magnetic intensity map. The shape of the feature, and knowledge of the likely range of susceptibility of the surrounding cooler material, makes it possible to estimate the volume and depth of the hot material.

An airborne magnetic survey map by Malahoff and Woollard (1965) shows the east rift zone as an intensity plateau with a shallow (100γ) east-west trough. A ground survey was done to bring out the detail needed for local estimation and drill site location.

The ground measurements were made 8 feet above the surface with a total-field magnetometer. Exploratory short traverses on foot showed hundred-gamma anomaly roughness at wavelengths of a few paces and thousand-gamma roughness commonly found at wavelengths on the order of a tenth of a mile. This short wavelength roughness may be regarded as noise due to surface and shallow variations which are fine-scale but very close to the magnetometer. Deeper features appear as long-wave modulation of the short wavelength background noise.

After gaining familiarity with the nature of the anomaly field the operation was made mobile by attaching the magnetometer head to the end of a stout 12-foot bamboo pole mounted on the front bumper of a small car. The reading errors due to the presence of the vehicle were calibrated around the compass with the absolute position of the magnetometer head held constant. The survey traversed the highways, byways and dirt roads at a speed of 5 miles/hour and a measurement each 8 seconds--amounting to 90 samples/mile (about every 59 feet). Figure 14 shows the pattern of the measured tracks; the rift zone runs east-west through the middle of it. The field data were plotted immediately after reading the digits off the magnetometer. The graphs were later digitized onto cards and the measured tracks were digitized from a map onto cards. The heading error was found to be represented by a 4th-order Fourier series and was incorporated into the corrections applied to the field data.

As a preliminary analysis to be in time for this report, we attempted a hasty interpretation by fitting curves from the results of Malahoff and Woollard (1965) and by using a few computer programs from the paper by Talwani (1959).

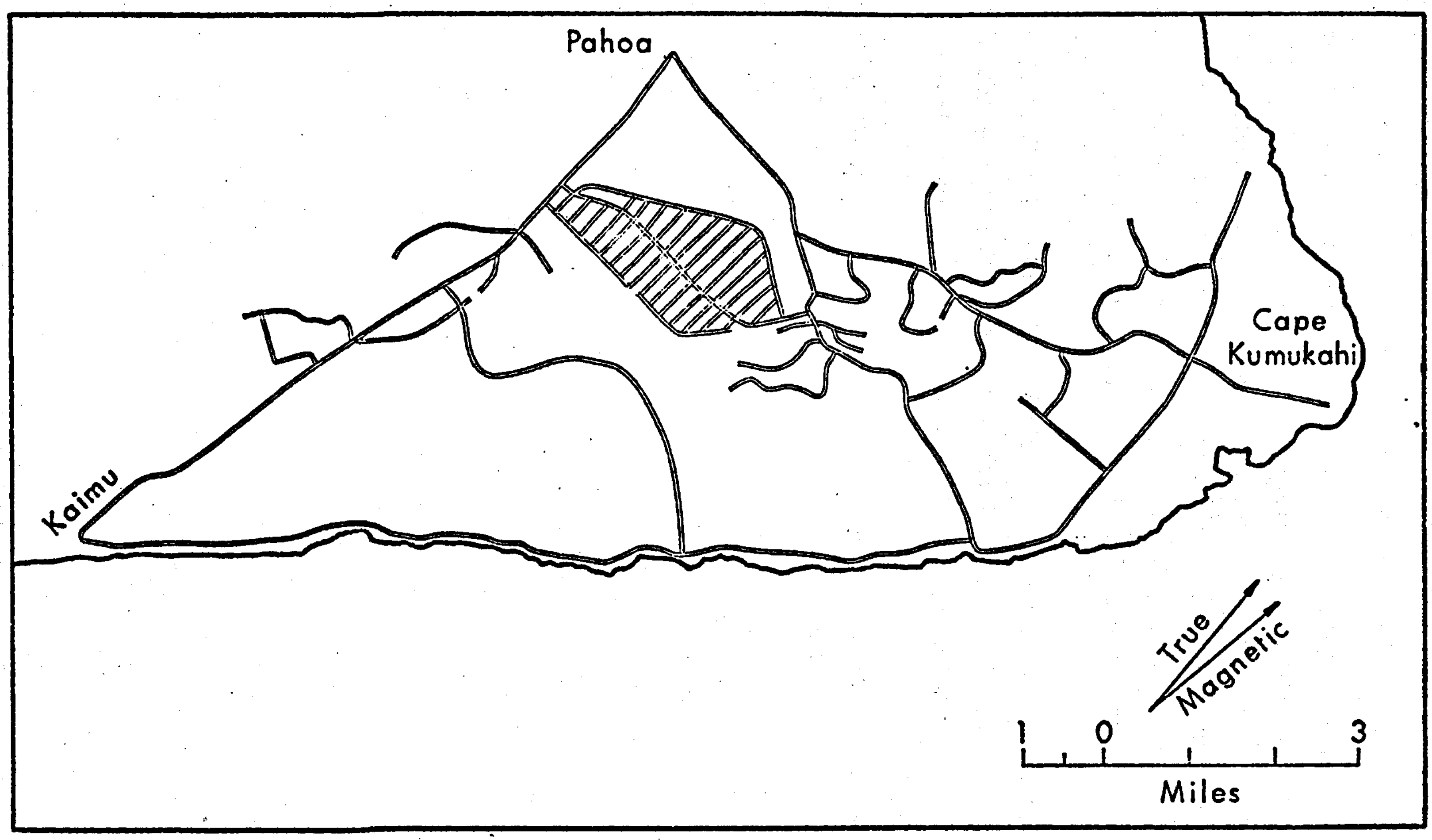

Figure 14 Tracks of Magnetic Measurements in Puna

We used the aeromagnetic data of Malahoff and Woollard (1965) and the magnetic profile along the highway from Kaimu and Pahoa (see Figure 14). Another assumption we used was that the dike complex as defined by gravity data was on the whole hot enough to be above the Curie temperature.

The structure of the east rift as deduced from these early results of magnetic analysis is shown in Figure 16. The general low intensity over the Puna area indicates that there are holes of non-magnetic material in a matrix of magnetic rock. From Malahoff and Woollard's (1965) data, the non-magnetic prism from Mile 3.6 to 5.9 in Figure 16 was outlined. The surface magnetic profile of Figure 15 shows several peaks and troughs. The peak of Mile 5.1 and trough of Mile 6.8 in Figure 15 can be accounted for by a highly magnetic prism from Mile 5.1 to 6.8 in Figure 16. The trough of Mile 1.2 and the peak of Mile 3.6 in Figure 15 can be explained by another non-magnetic hole in Figure 16 from Mile 1.2 to 3.6.

The larger non-magnetic hole from Mile 3.6 to Mile 5.9 is due to the hot material in the dike complex. The hot material is about 1.5 km thick and is at a depth of about 1.2 km below surface.

The smaller non-magnetic material extends from Mile 1.2 to 3.6. It is about 0.8 km thick and its depth of burial is really not certain, although we have made it an extension of the larger hole. The smaller hole could be much shallower.

The non-magnetic property of the smaller hole is not explainable by intrusions from the dike complex. Gravity data does not support dike material extending that far.

One possible explanation is that hot water from the dike complex traveled downslope to heat rocks in that section to temperatures above the Curie point. This hypothesis is not too far fetched when Curie temperatures are considered. Unfortunately laboratory determined Curie temperatures of Hawaiian rocks are not available, and hence Curie temperatures must be calculated from mineralogical composition. Macdonald and Katsura (1964) listed the average composition of tholeiites and olivine tholeiites as 2.5% TiO_2, 3.03% Fe_2O_3 and 8.53% FeO. When these are compared with the titanomagnetite Curie temperature chart (Nagata and Ozima, 1967), the Curie temperature comes to about 200°C. However, Macdonald and Katsura gave the data for a sample (c131) from Puna as 3.65% TiO_2, 2.44% Fe_2O_3 and 10.34% FeO. From the chart this sample would have a Curie temperature of 70°C. Hence it is not inconceivable that hot water coming off the dike complex could reduce the magnetic susceptibility of rocks.

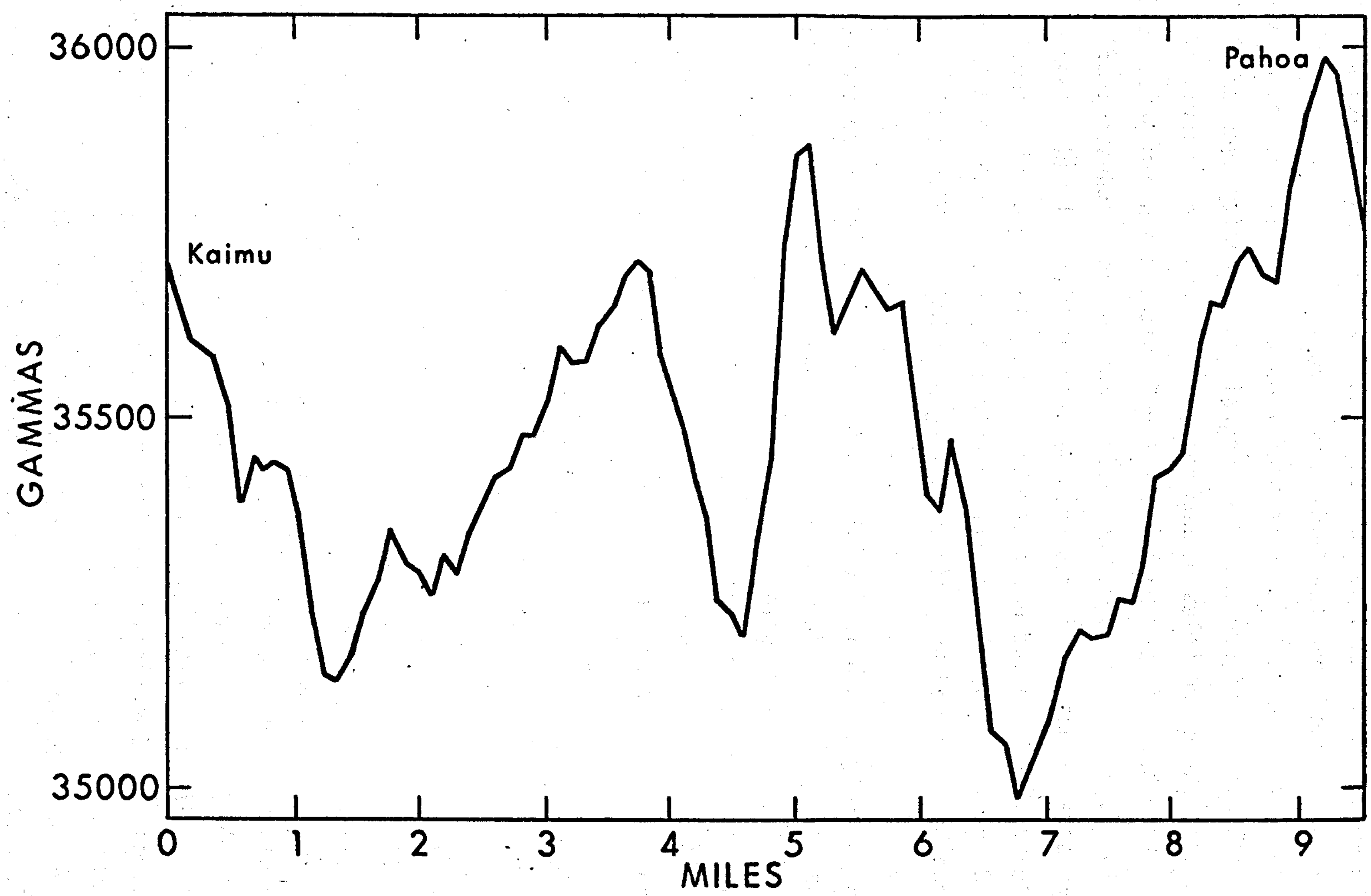

Figure 15 Space Filtered Magnetic Profile from Kaimu to Pahoa

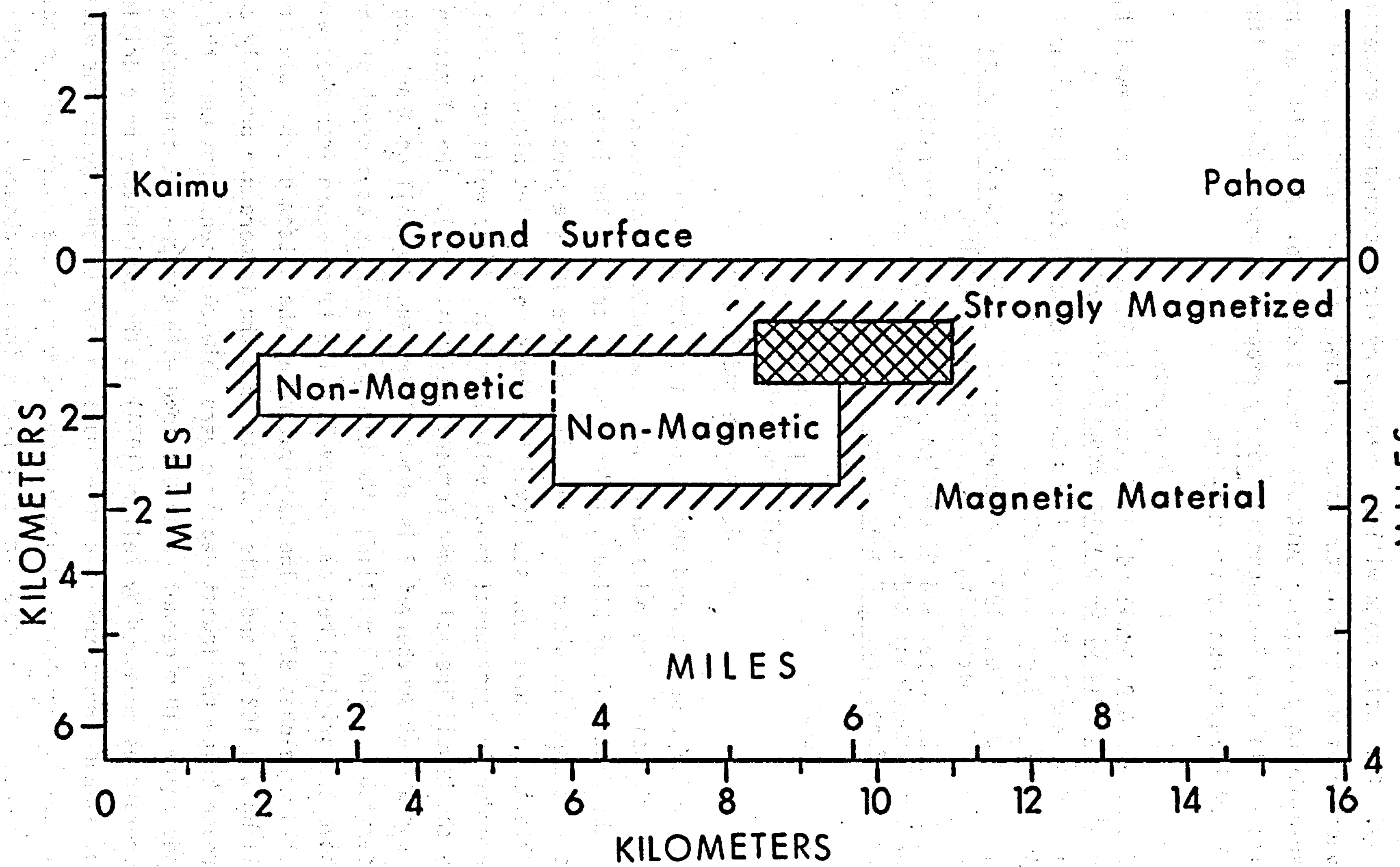

Figure 16 Magnetic Anomalies in the East Rift of Kilauea

Up to the present time, only one traverse of our survey has been examined seriously. The entire data will be examined by representing the magnetic field as a function of map coordinates to be smoothed and contoured by SYMAP (a geography computer-plotting package). Suitable cross-sections of the field can then be used with the Talwani 2-D magnetic anomaly program to model whatever linear features are brought out by the mapping.

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Task 2.4
Well Temperature Survey

J. Halunen and D. Epp

During 1974, we measured the variation of temperature with depth in a number of wells on Hawaii. The wells which have the highest temperatures are located on or near the East Rift of Kilauea in the Puna district. The location of the wells and the rift zones is shown in Figure 17. Figure 18 is a plot of temperature versus elevation above mean sea level for these wells. The highest temperatures were recorded in "geothermal test" wells 2 and 3. Those wells were drilled in 1961 by the Hawaii Thermal Power Company (Stearns, 1966). The elevation of the ground surface at Geothermal 2 is about 315 m, and the well does not penetrate to the water table. Since drilling, the hole was caved in at a depth of about 110 m, 60 m above the original bottom. Below 75 m the temperature increases with depth, and at 110 m reaches 97°C. The temperature at the bottom of the hole at the time of drilling was 102°C, and this suggests that the temperature probably continues to increase below the lowest depth we were able to reach. How much the temperature increases below 110 m cannot be ascertained with the present temperature data. The temperatures measured by Keller (1974) in the exploratory hole drilled just south of Kilauea increases to a local maximum (∿85°C) just below the water table (∿500 m depth), and increases again from ∿1000 m to the bottom of the hole. It cannot be determined whether the temperature increase observed at Geothermal No. 2

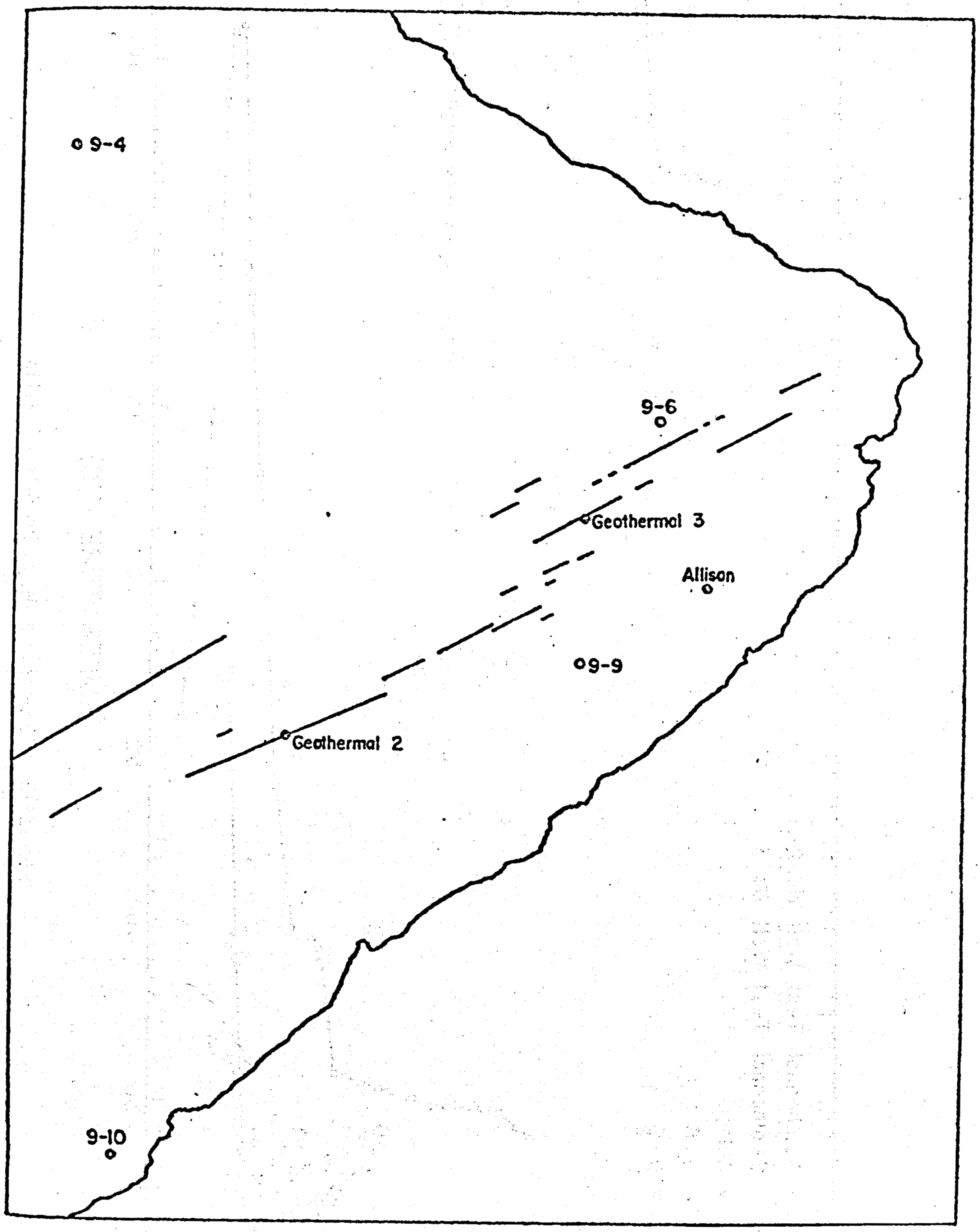

Figure 17 Location of Existing Wells in Puna Area

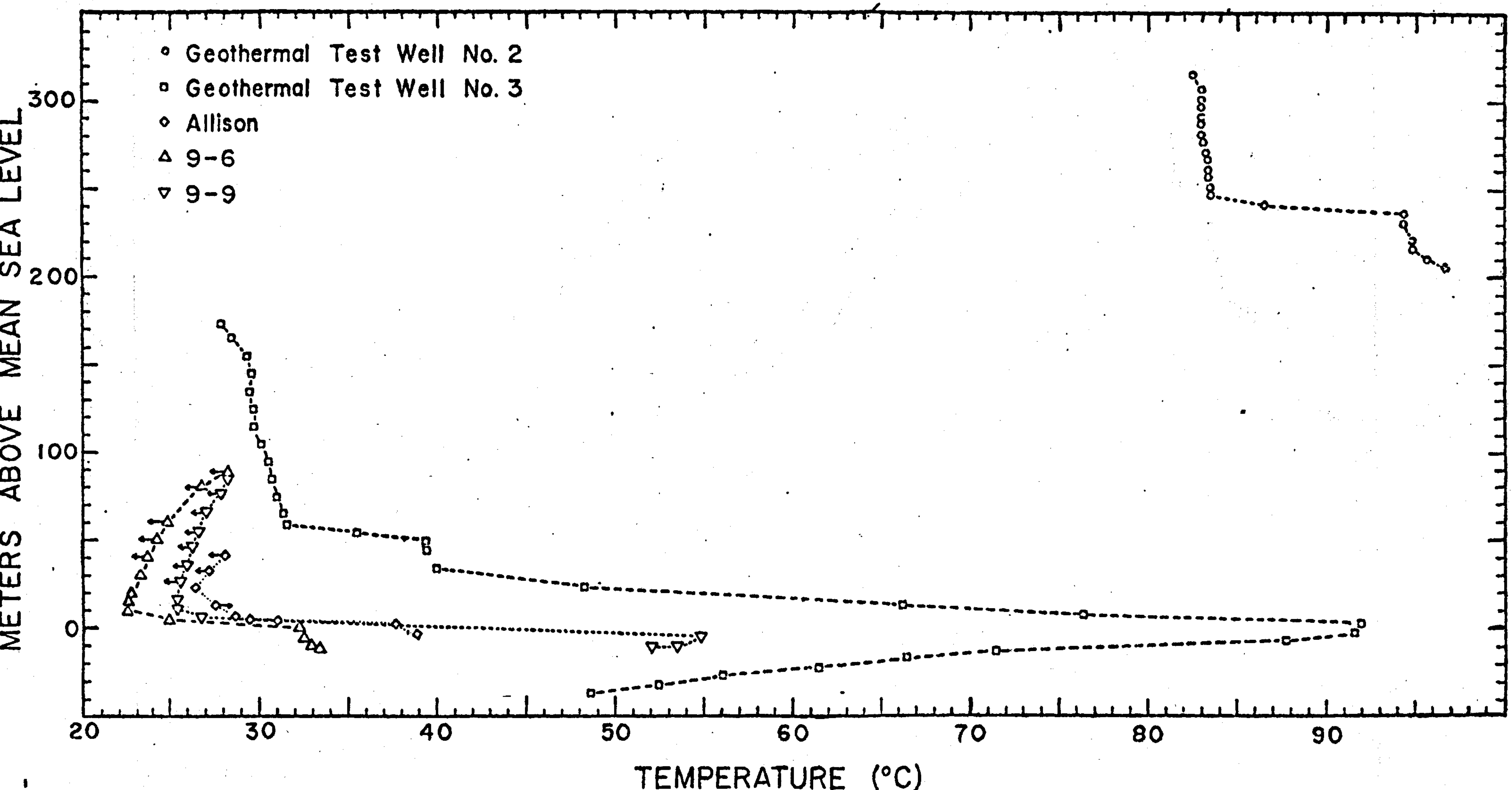

Figure 18 Temperature-Depth Profile of Wells

correlates with the upper or lower temperature increase observed in the hole south of Kilauea.

The other wells shown in the figures penetrate the water table. An increase in temperature at the water table is characteristic of these wells and is most pronounced at Geothermal test well number 3. This well, and to a lesser extent well number 9-9 also decreases in temperature near the bottom of the hole. Because these wells are located close to the coast, the fresh water lens is thin. It appears that the high temperatures observed are confined to this lens, thus lending support to the hypothesis that in this area groundwater has passed through a high temperature region as it flows seaward. The high temperatures observed may, therefore be related to heat source upslope from these wells.

Figure 17 also shows the location of two wells (9-4 and 9-10) that are several miles from the rift zone. The temperatures in these wells are less than 27°C at all depths. Temperatures in other wells in this area which are not near the rift zone are also low.

The temperature data presented here, together with Keller's (1974) data, suggest that exploratory drill holes should be located along the East Rift zone, perhaps somewhere between Kilauea and Geothermal No. 2.

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Task 2.5A

Results of the Microearthquake Survey and Seismic Studies of the Lower East Rift

W. Suyenaga

A seven seismometer seismic array was operated in Puna, Hawaii during August 16 to September 9, 1974. Figure 19 shows the location of the seismometers. About 39 earthquakes in the vicinity of the array were recorded and their hypocenters calculated by HYPO71, a program developed by members of the U.S. Geological Survey (Lee and Lahr, 1971). The crustal model used in the hypocenter calculation was the preferred one (Model A) of Ward and Gregerson (1973). Epicenters based on this model are plotted in Figure 19. Later analysis showed that the rift zone, over which most of the seismometers were placed, most probably consists of higher velocity material. Using a revised crustal model with a 6.8 km/sec layer at 4 kilometers, the earthquakes were relocated slightly deeper with large changes

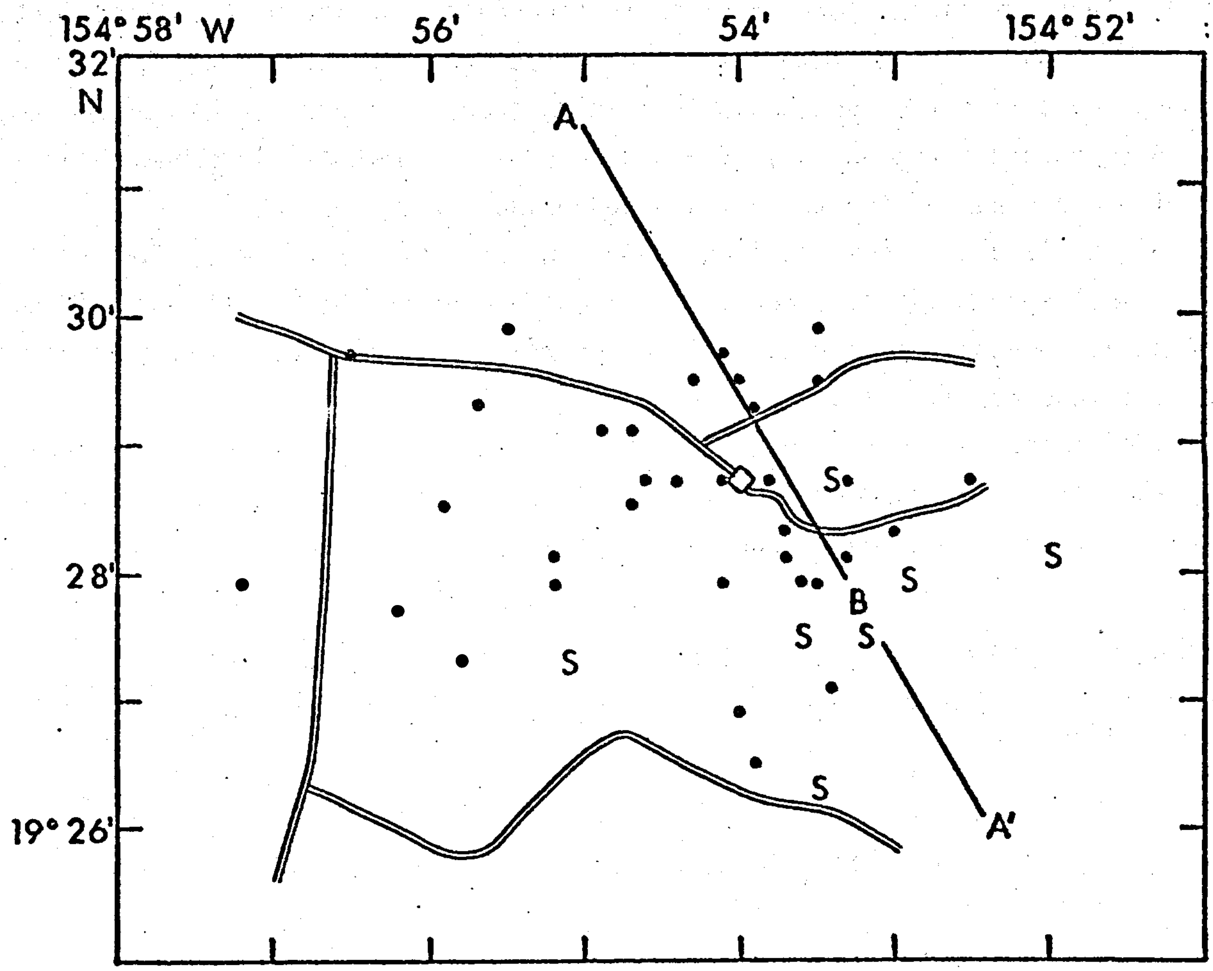

Figure 19 Epicenters of Observed Microearthquakes

in some of the epicenters. Thus the epicenters in Figure 19 should be considered with this in mind.

Results of the study of microearthquakes occurring near the array are: 1) there is no concentration of hypocenters in any one area or on any one plane and 2) earthquake activity decreased below about five to seven kilometers with the deepest event occurring at about 14 kilometers. A projection of hypocenters on a plane perpendicular to the rift zone (Figure 20) shows the hypocenters falling into an approximately three kilometer wide area vertically beneath the surface expression of the rift zone. The epicenter plot (Figure 19) shows slightly more activity near the array with a decrease toward the southwest. This may be due to increased attenuation due to distance. In the opposite direction, there is a distinct lack of activity in the rift zone toward the northeast. With regard to the decrease in earthquake activity with depth, attenuation with increased path-length may be a factor. However, examination of the records of deepest events showed that they were large and well-recorded. Any similar events from deeper depths would also have been recorded.

In addition to the earthquakes near the array, several earthquakes in the upper east rift and Kilauea summit were recorded. Epicenters calculated by our array were compared with those calculated by the Hawaiian Volcano Observatory network (R. Koyanagi, personal communication, 1975). Four earthquakes located by HVO in the upper east rift were located northward by our array. The HVO locations are more accurate since our array is far off to one side. This misplacement was caused by a relative delay of arrival time at our south station. Since this station was the only one significantly off the rift zone, it is proposed that the East Rift Zone is comprised of a relatively higher velocity material. Similar observations have been reported by Ward and Gregerson (1973) and Hill (1969).

The seismic network of the Hawaiian Volcano Observatory has included at least one station near Pahoa. A continual public record of their results have been published in the HVO Summaries. We have augmented our study with their data in two ways: 1) event count of local earthquakes and 2) location of larger earthquakes in the vicinity of our array. Event counts show a low level of seismicity in the lower east rift with occasional one to two month swarms. Koyanagi, Swanson and Endo (1972) report that these swarms are not associated with deflation, with Kilauea summit. Most of the earthquakes located by the HVO from 1964 through 1969 were larger events (approximately greater than m=2) of the swarms. Epicenters of these earthquakes were not evenly distributed along the rift zone. There was a concentration of activity on the southern edge of the rift zone about four kilometers southwest of our base station. Continuing to the

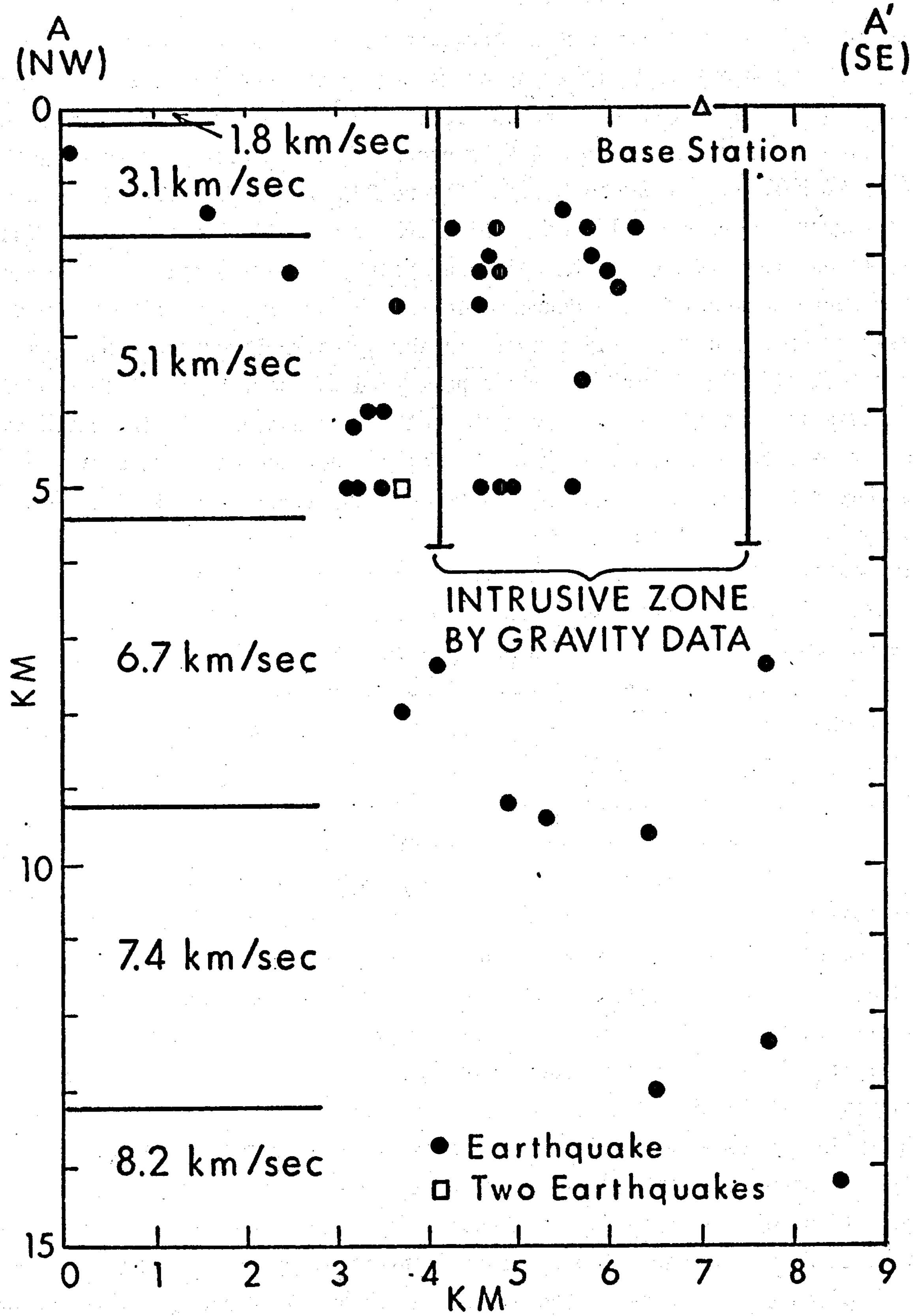

Figure 20 Depth of Foci of Earthquakes

southwest along the rift zone, there is a decrease in activity. As with our survey, there is a lack of activity to the northeast along the rift zone.

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Task 2.5B
Ground-noise Survey

R. Norris and W. Suyenaga

A survey of ground noise was made to complement the other kinds of surveys aimed at locating a possible geothermal power source. The survey covered the triangular area with vertices at the villages of Pahoa, Kapoho, and Kalapana in the Puna District. The measure of ground noise was taken to be the mean-square vertical velocity of the ground surface expressed in decibels relative to a convenient reference. The part of the ground-noise spectrum recorded was the frequency band 1 hz to 30 hz -- some sites of known geothermal activity have been found to have unusually intense ground noise in frequencies below 10 hz. The survey recordings were processed to produce maps of logarithmic intensity at 3 db contour intervals. Maps were drawn of the broadband noise (1-30 hz) and of narrow bands centered on 2, 4, 8 and 16 hz.

The August 1974 survey accomplished 59 measurement stations distributed about the 30 to 40 square mile Pahoa-Kapoho-Kalapana triangle. Each measurement was a 10-minute long magnetic tape recording of a 1 hz low-cut geophone output. The tape-recorded analog voltage was processed in the laboratory to yield the mean-square voltage (which is proportional to sound intensity) in decibels. Two processing methods were used: for the lower frequencies (2 hz and 4 hz) an integration method was used; for the higher frequencies (8 hz and 16 hz) an average power-level method was used. The resulting logarithmic intensities were plotted and contoured on the map of the area. Figure 21 shows the 4 hz intensity distribution with 3 db contour interval (thus each level of shading represents

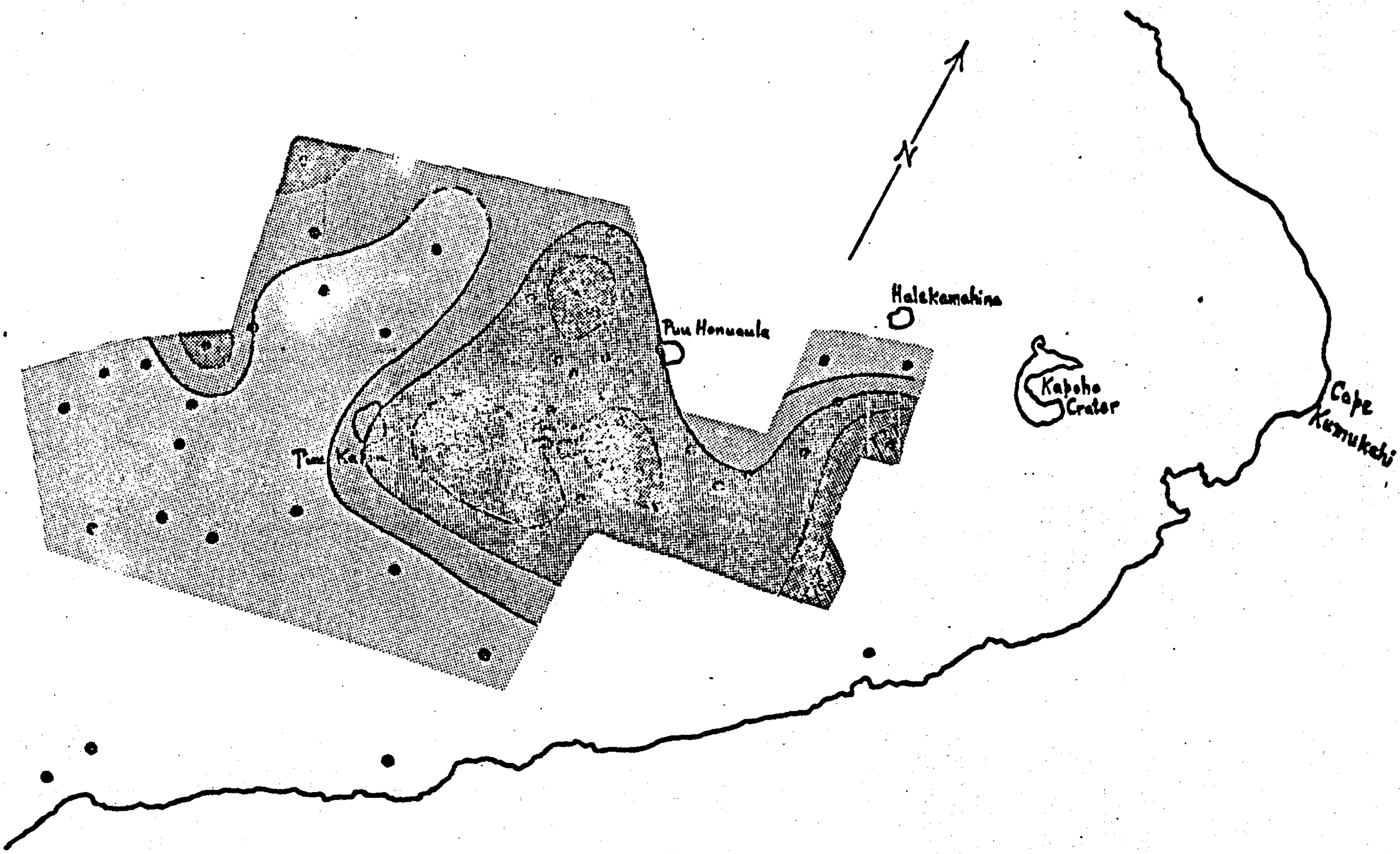

Figure 21 3 db Interval Contours of 4 hz noise. The darker area, the higher the amplitude.

double the sound intensity of the level beneath it). This distribution is in fair agreement with J.J. Skokan's results (given in his Ph.D. Thesis, December 1974). There is a well-defined moderate high of 9 db in the vicinity of Puulena Crater (the high to the east is based on only two measurements) but noise contrasts of this degree are not enough in themselves to be diagnostic of geothermal activity at depth. When viewed together with the results of other surveys the evidence accumulated so far makes the Puulena Crater area the likeliest prospect of the East Rift Zone for geothermal activity at depth. Another representation of the data to look at is the site-to-site sound spectrum comparison, this may be more revealing than power-level maps.

The August 1974 survey was preceded by four less extensive reconnaissance surveys. They were in (a) an area in Puna similar to the August study, (b) around an anomalously high noise level station near Kapoho found during a, (c) an area south of the town of Pahala and (d) on and around the 1868 lava flow on the down thrown side of Kahuku Pali at South Point. The first survey took place in February 1974 and the latter three during June 1974. The recording procedure was similar to that of the August survey. Data analysis proceeding along several different lines in an effort to determine the best one. Results of study (a) showed an expected increase of noise as the shoreline was approached. As mentioned, there was one station of anomalously high noise level. Readings around this site (survey 6) showed no pattern of noise level. Also, no significant noise patterns were found in surveys c and d.

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Task 2.6
Geochemical Studies

P. F. Fan

Stable Isotope Analyses

Thirty-six water samples from the Island of Hawaii have been analyzed for their O^{18}/O^{16} ratios. The samples represent groundwaters collected from twenty wells, two warm-water springs and one steam well. Four samples of local precipitation were also collected at Hilo, Hawaii. The stable isotope ratios are presented as δO^{18} values,* along with in situ temperature and salinity values, in Table 5. The locations of these samples are presented in Figure 22.

* $\delta O^{18} = \left[\frac{O^{18}/O^{16}\ \text{samp}}{O^{18}/O^{16}\ \text{std}} - 1\right]$ 1000 in ‰ rel. SNOW.

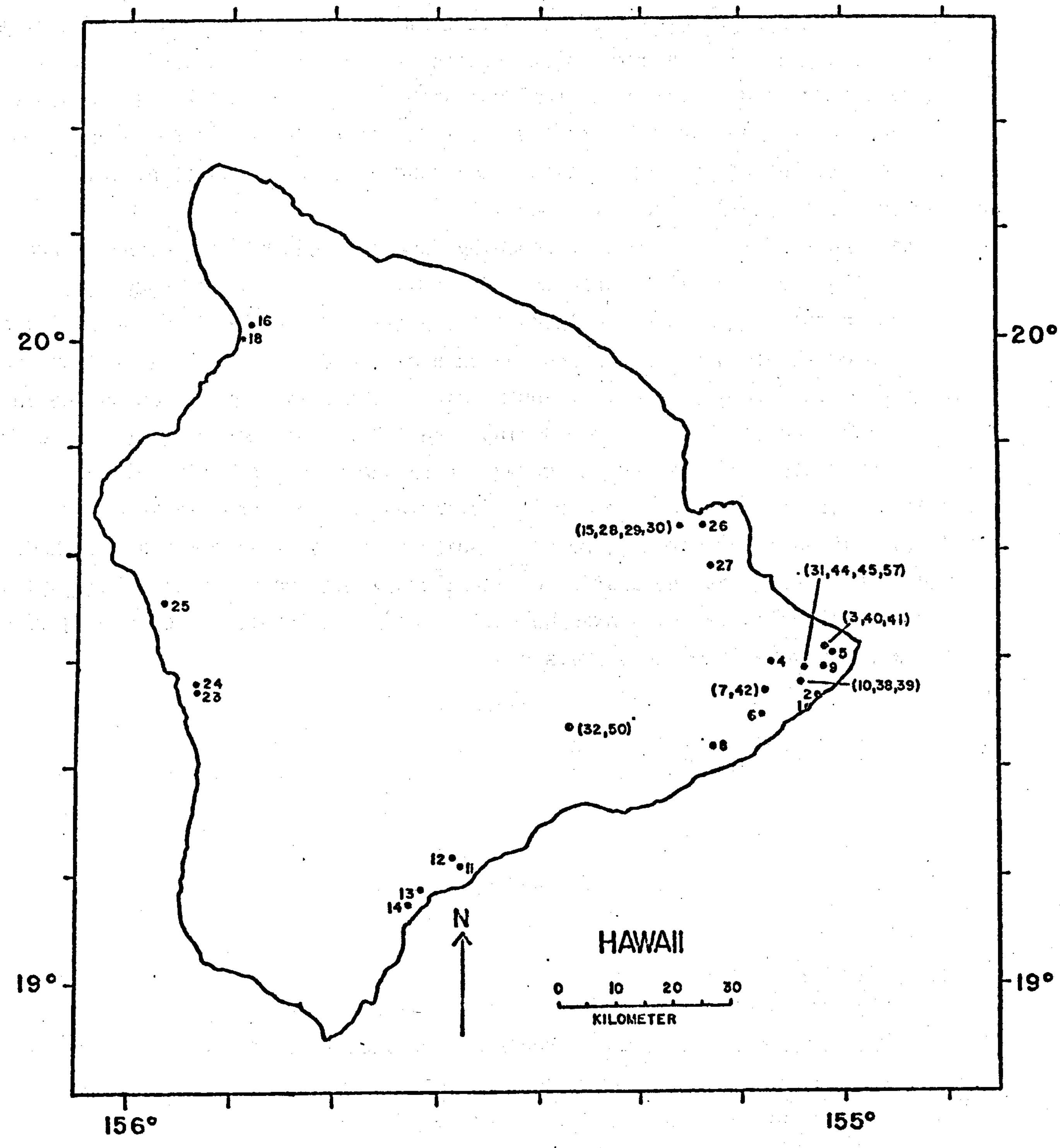

Figure 22 Location of Wells

Table 5

Sample No.	Well Name	Temp. (°C)	Salinity (‰)	δO18 (‰)
1	Pohoiki Hot Spring	35	7.0	-2.70
2	Allison Hot Spring	31	10.5	-2.15
3	Kapoho Landing Strip	38	1.3	-3.14
4	Pahoa	23	0.5	-3.73
5	Kapoho Crater	25	0.8	-3.62
6	Kalapana	24	0.5	-3.41
7	Geothermal Test #2	83	-	-4.47
8	Pulama	28	0.6	-3.94
9	R.E. Allison	38	1.4	-3.24
10	Malama-Ki	56	18.0	-1.72
11	Palima	21	0.3	-6.56
12	Pahala	--	-	-5.37
13	Ninole Springs	21	0.5	-4.54
14	Honuapo Sugar Mill	--	-	-3.84
15	Local Rain 2/12/74	--	-	-1.80
16	Kawaihae Test	31	0.8	-4.17
18	Mauna Kea	27	1.0	-5.07
23	Keei	21	0.3	-4.23
24	Keauhou	22	0.3	-4.97
25	Kailua #12	25	1.2	-4.05
26	Hilo Electric	24	0.2	-3.28
27	Keaau Sugar Mill	22	0.4	-3.84
28	Local Rain 6/17/74	--	-	-2.07
29	Local Rain 7/3/74	--	-	-1.14
30	Local Rain 7/17/74	--	-	-1.33
31	Geothermal Test #3	93	5.0	-2.39
32	Keller's Kilauea Test	75	2.3	-4.68
50	Keller's, Depth 100'	83	2.6	-4.66
38	Malama-Ki, surface	53	11.2	-1.56
39	Malama-Ki, Depth ~ 43'	54	15.0	-1.50
40	Kapoho Landing, surface	34	1.3	-2.95
41	Kapoho Landing, Depth ~ 50'	34	1.0	-3.04
42	Geothermal Test #2	86	0.1	-2.39
44	Geothermal #3, surface	95	5.0	-2.50
57	Geothermal #3, Depth ~ 50'	86	5.1	-2.43
45	Geothermal #3, Depth ~ 50'	88	5.0	-2.51

The δO^{18} values obtained are somewhat ambiguous without δD values (deuterium/hydrogen ratios) since one cannot determine where these waters plot on the meteoric water line of Craig (1961). This line is defined by the relationship:

$$\delta D = \delta O^{18} + 10 .$$

The objective is to see if any of these waters exhibit the "oxygen shift" from this line indicative of isotopic exchange between rock and water at elevated temperatures (generally greater than 150°C). We are currently awaiting the completion of a hydrogen mass spectrometer.

Figures 23 and 24 are plots of δO^{18} versus in situ temperature and salinity, respectively. There appears to be some correlation between δO^{18} and temperature although the relationship does not hold for the highest temperature wells. The salinity versus δO^{18} plot shows that there may also be some correlation between δO^{18} and salinity for the Malama-Ki and Geothermal Test #3 water springs. Seawater advection may be affecting the isotope values here.

Dissolved Silica Analyses

Fifty-four analyses of dissolved silica from the island of Hawaii, plus ten analyses from the island of Maui have been made using colorimetric techniques. Twenty-one groundwater wells, two warm-water springs and one steam well were sampled from the island of Hawaii. Five groundwater wells were sampled from the island of Maui. In addition, four samples of local precipitation have been analyzed from the island of Hawaii. The results show an average dissolved silica content of 49 ppm for the Maui wells and an average content of 49 ppm for most of the Hawaii wells. The four samples of local precipitation (collected at Hilo, Hawaii) and the steam samples (collected at geothermal test well no. 2) show extremely low dissolved silica contents of about 1 ppm. Anomalously high concentrations of about 99 ppm are found in two coastal warm-water springs located south of the Puna rift zone near the proposed drill site (see Figure 22). The highest dissolved silica concentrations are found in two groundwater wells: geothermal test well no. 3, located on the Puna rift zone near the proposed drill site, with an average content of 174 ppm; and Keller's Kilauea test well, located south of Halemaumau crater, with an average content of 161 ppm. These wells also have the highest recorded in situ temperature of 93° and 83°C, respectively.

The dissolved silica content of hot-spring waters has been used as a geothermometer, indicating the last underground rock-water equilibration temperature (White et al., 1956). However, most if not all of these geothermometers have been calculated for continental acidic rock environments, where quartz

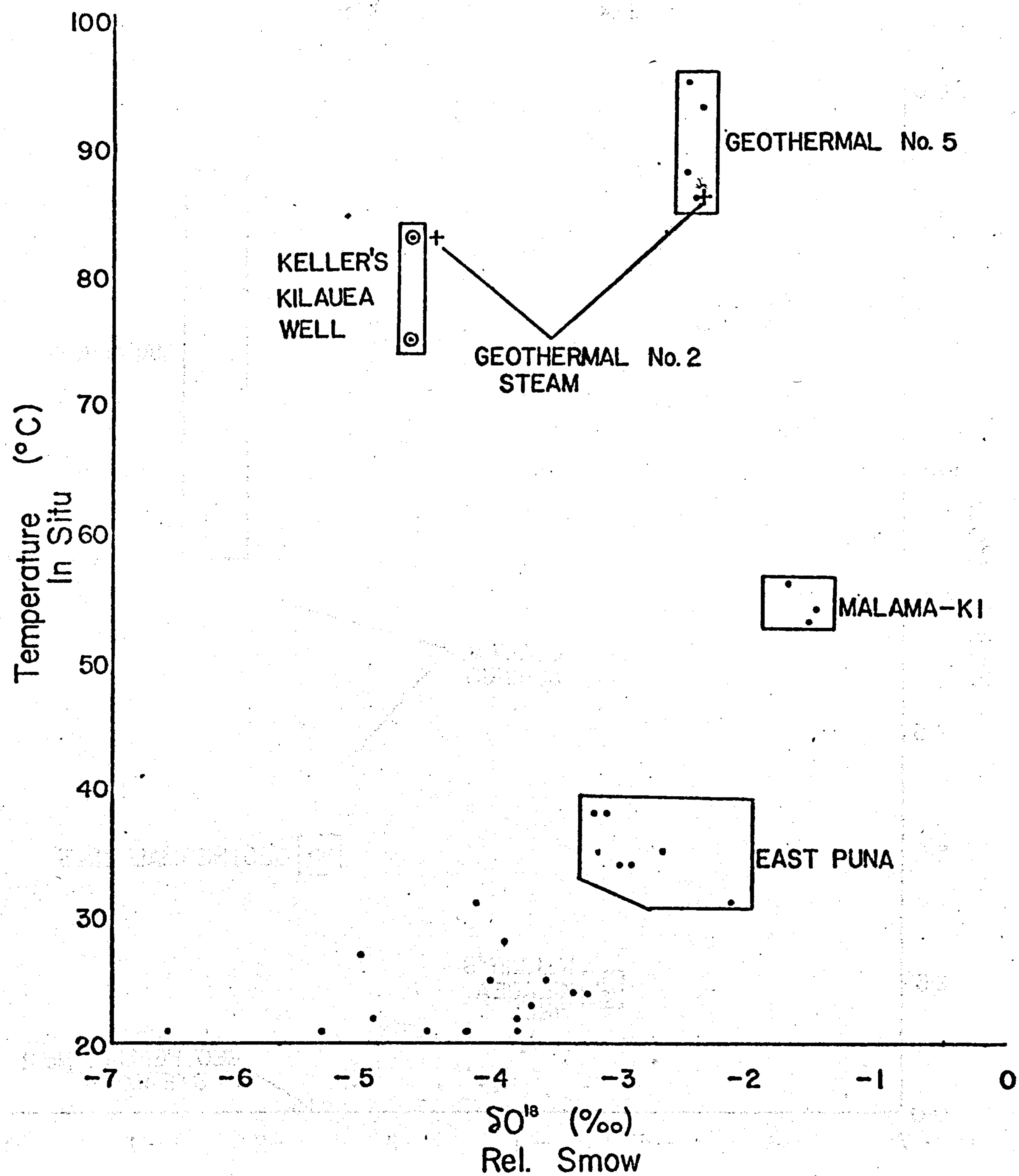

Figure 23 Isotope Content vs Temperature for O^{18}

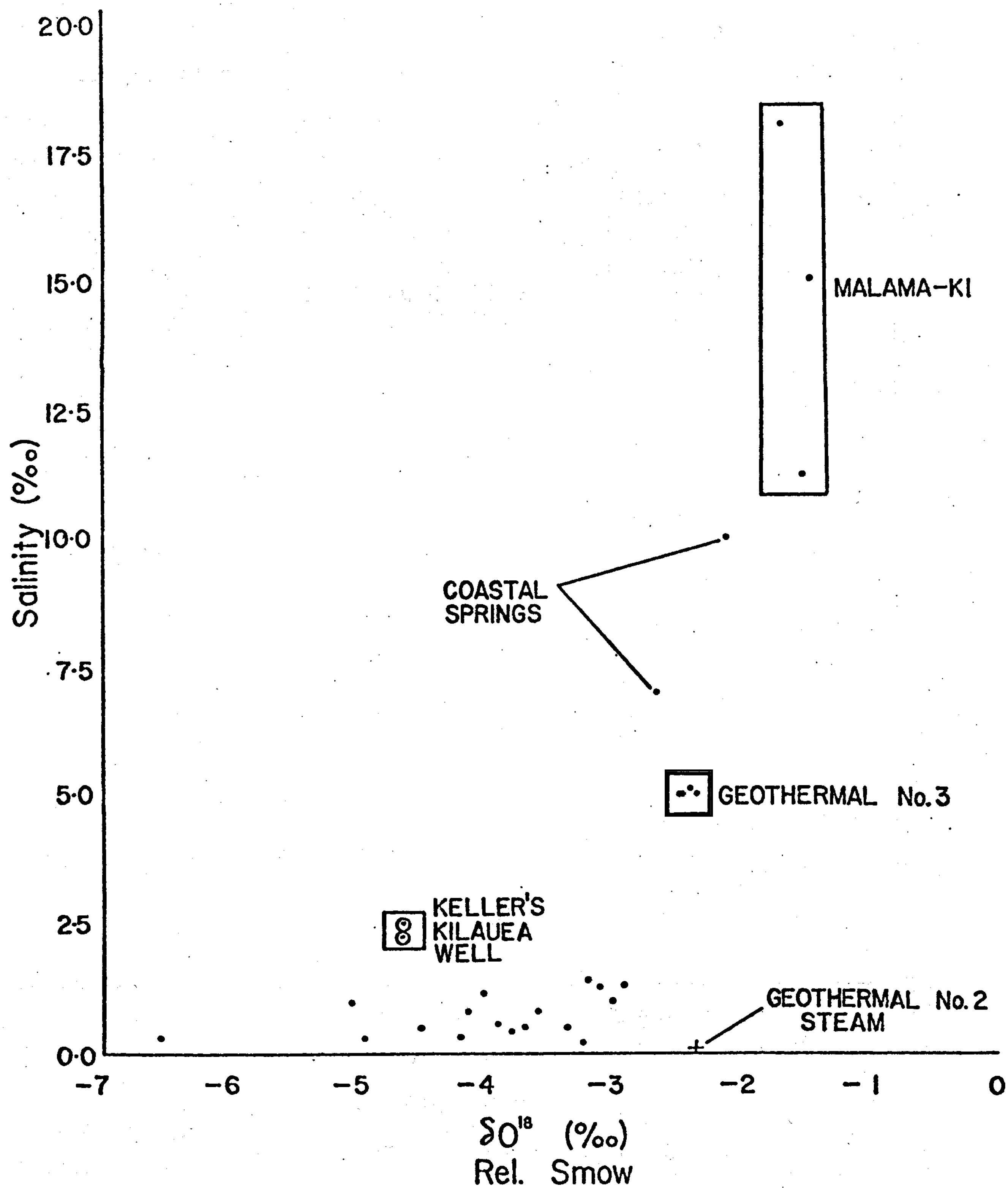

Figure 24 Isotope content vs Salinity for O^{18}

solubility at depth is the major control (Fournier and Rowe, 1966). Therefore, because the Hawaiian groundwaters are exchanging in a basaltic rock environment where free-quartz is rare, these geothermometers cannot be applied. Tholeiitic basalt glass solubility at depth is probably the local control. Experimental data on basalt-water reactions at high temperatures are needed before a local geothermometer can be applied.

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INTEGRATION OF GEOPHYSICAL DATA

A. S. Furumoto

Each of the geophysical tasks provided in its own way a part of the structure of the east rift of Kilauea and the hydrothermal processes associated with it. When the parts are pieced together as in a jigsaw puzzle, a composite picture of the thermal processes emerge. By outlining the dike complex or intrusive zone of the rift the size of the thermal sources was determined and the transfer of energy from magmatic source to hydrothermal processes can be conceptualized.

The Structure of the Dike Complex or Intrusive Zone

The shape and size of the dike complex that make up the spine of the east rift of Kilauea were determined by gravity and seismic data. The dike complex can be approximated by a long horizontal rectangular prism with vertical walls, stretching in a direction of N65°E. With the assumption of a density contrast of 0.6 g/cm^3, the following dimensions were calculated:

width, 3.2 km
vertical extension, about 4 km
depth to top of dike complex, 0.9 km below sea level

The location of the dike complex with respect to the eruptive vents of the east rift is shown in Figure 25. In general, the dike complex as outlined by gravity methods agrees with surface expressions of topography and locations of eruptive vents.

That the bottom of the dike complex is about 5 km below sea level agrees with current concepts of the origin of the east rift of Kilauea. It is generally

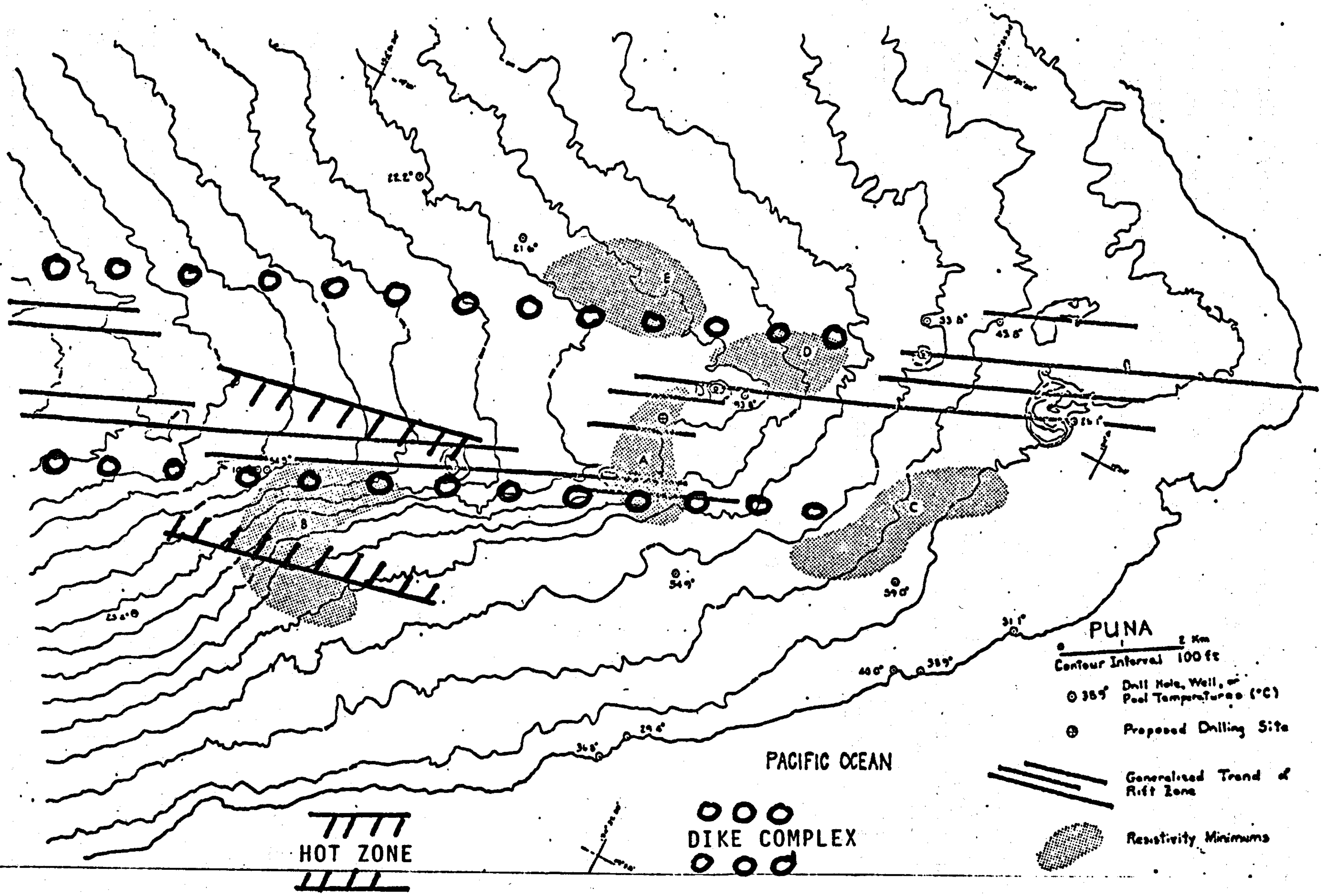

Figure 25 Location of Dike Complex and Hot Section of East Rift of Kilauea

accepted that the magma for Kilauea originates at a depth of about 80 km below sea level and makes its way upward to the summit area through vertical conduits. The magma is stored in a secondary chamber of reservoir under the summit area; some of the magma erupts through the summit caldera and vent, while some works its way laterally through cracks and fissures into the rift zones (Eaton and Murata, 1960). At the very beginning of volcano formation, geological ages ago, the lava began to erupt onto the sea floor through a single vent, which later became the central vent. As the volcano increased in size, rift zones began to form, but these rift zones were formed in the built-up volcano edifice which sat on the sea floor. Hence, as the rift zones were emplaced above the original sea floor, which was about 5 km deep, the bottom of the dike complex would be about 5 km deep.

By assuming that magnetic data are temperature controlled, an attempt was made to determine what part of the dike complex was hot enough to be above the Curie temperature. Although only one magnetic survey traverse has been analyzed so far, the analysis showed that the hot area, about 3.5 km wide, included the southern half of the dike complex and the area immediately to the south of the complex. Another curious factor was the difference in directions of the gravity and magnetic lineations. While the gravity lineations and the line of eruptive vents along the rift trended in a N65°E direction, the magnetic lineations as shown in the maps by Malahoff and Woollard (1965) trended due east, an azimuthal discrepancy of 25°. Toward the eastern end of the rift zone, the dike complex and the magnetic low section did not intersect at all. An attempt to reconcile the offset of magnetic low from the dike complex will be made in the next section when we discuss the hydrothermal processes of the rift zone.

The Hydrothermal Process of the East Rift

The electrical surveys came up with five areas of anomalously low resistivity, shown as areas A, B, C, D and E in Figure 25. Of these the anomaly in area E is attributed to artificial sources, such as water pipes, sewer pipes and cables. The anomalies of areas A and D are probably of hydrothermal origin; as they are both located over the dike complex we shall discuss them together. Areas B and C are located south of the dike complex and hence shall be treated together.

Over areas A and B we have the following geophysical data; a self potential anomaly of about +500 mV (Zablocki, personal communication); low resistivity of 5-10 ohm-m; a ground noise level at 4 hz about 9 db above ambient background; a magnetic high; about a dozen microearthquakes during a three week observation period. Furthermore, gravity data places the dike complex as passing under both areas. The water in Geothermal Well III which is located between areas A and D had a temperature of 93°C, although confined to a rather thin layer. To the south of area A, the water temperature in the Allison Well was 55°C.

The disturbing factor for areas A and D is the rather high magnetic value. Although the dike complex is under these areas, the magnetic data indicate that it is below the Curie temperature. However, the Curie temperature of tholeiitic basalts can be as high as 300°C.

A rather simple model is proposed for areas A and D. Water of meteoric origin percolates downward through the porous and permeable rock, rising in temperature with depth. The temperature probably follows the boiling point with pressure. Also with depth, the rocks become less porous, until a depth is reached where the rocks become impervious enough to prevent further downward percolation. From consulting Archie's law, a temperature of about 140°C is predicted at about the deepest penetration. Now as there are numerous tensional cracks, some of the hot water begins moving upward along the cracks to the top of the water table. At the water table level, the hot water in a thin layer sits on top of the cooler water and begins to flow downhill to the sea. The temperature is lowered as the water moves laterally.

The above model accounts for the low resistivity expression, the temperature profile of wells, the ground-noise, and the self-potential data, if self-potential is due to streaming potential. As the rocks are below Curie temperature, we do not see vigorous action such as steaming vents. The microearthquakes as observed are probably due to southward migration or slipping of the flank of the east rift, in the manner observed by Swanson, Duffield and Okamura (1971) by means of careful surveying. Keller (personal communication) found that the focal mechanism solutions in the east rift conform to dip-slip along fault planes dipping to the south.

The site selection committee for the drilling committee has selected area A for its first hole. Although the area has favorable evidence in the form of self potential data and the underlying dike complex, nevertheless resistivity data delineate a rather limited extent of hydrothermal action and magnetic data indicate a temperature below Curie point. Area A is not as favorable as area B which will be discussed next.

Area B is just to the south of the dike complex but resistivity data indicate a larger extension of low anomaly than area A and magnetic data show rocks beneath to be above Curie temperature. Several small earthquakes have been observed, but the ground noise was no different from ambient background level.

Coincident with resistivity data which says a 5 ohm-m layer exists from 700 m depth to 2000 m depth, the seismic refraction survey by Hill (1969) showed a 3.1 km/sec velocity layer to exist at 700 m depth. Hill did not obtain the surface velocity of the rocks but he presumed it to be low. Now the value of 3.1 km/sec cannot be obtained by compressing surface rocks with pressure equivalent to 700 m depth. The velocity must be attained by other means, such as deposits filling the pores and crevices of the rocks, a very plausible explanation.

In our model for area B, we propose that the 3.1 km/sec velocity is due to a pore filled layer, which traps hot water below it. The pore filled layer is not very thick; it is only thick enough to channel seismic waves to give a velocity of 3.1 km/sec. Below the pore filled layer, the seismic velocity will drop, but the velocity inversion will not be detected by seismic refraction methods.

Another favorable bit of evidence is that Keller (personal communication) calculated from microearthquake data the Poisson's ratio of rocks in area B to be about 0.4. The ratio was lower for the dike complex section. An explanation of the high Poisson's ratio is that the rocks are highly fractured.

The magnetic low for this area indicate that the rocks below the depth of 1000 m are hot enough to be above Curie temperature. The low electrical resistivity is due to heating by the hot source below.

A model for area B is shown in Figure 26. The heat source is partly in the dike complex and partly in the seepage of hot material from the dikes into the fractured rocks. The seepage of hot material accounts for the magnetic low, while the fractured rocks explains the high Poisson's ratio. A pore filled layer traps hot water in the space below 700 m depth. This accounts for the seismic refraction data and the low resistivity anomaly. As the process is rather confined, the absence of upward plumes means low ground noise. There is a self potential anomaly of about 900 mV in the region which can be explained by vents over the dike complex that are 102°C even at the surface. The higher temperature of this area as compared to area A agrees well with magnetic data.

We admit that the proposed model is far fetched and the probability of it to exist is small. Especially will the association of the 3.1 km/sec velocity with a pore filled layer raise mutterings of skepticism. However, we are proposing this model in spite of many reservations, because this is the only place where we can find conditions that approach a utilizable geothermal reservoir, an aquifer heated from below and topped by an impervious caprock.

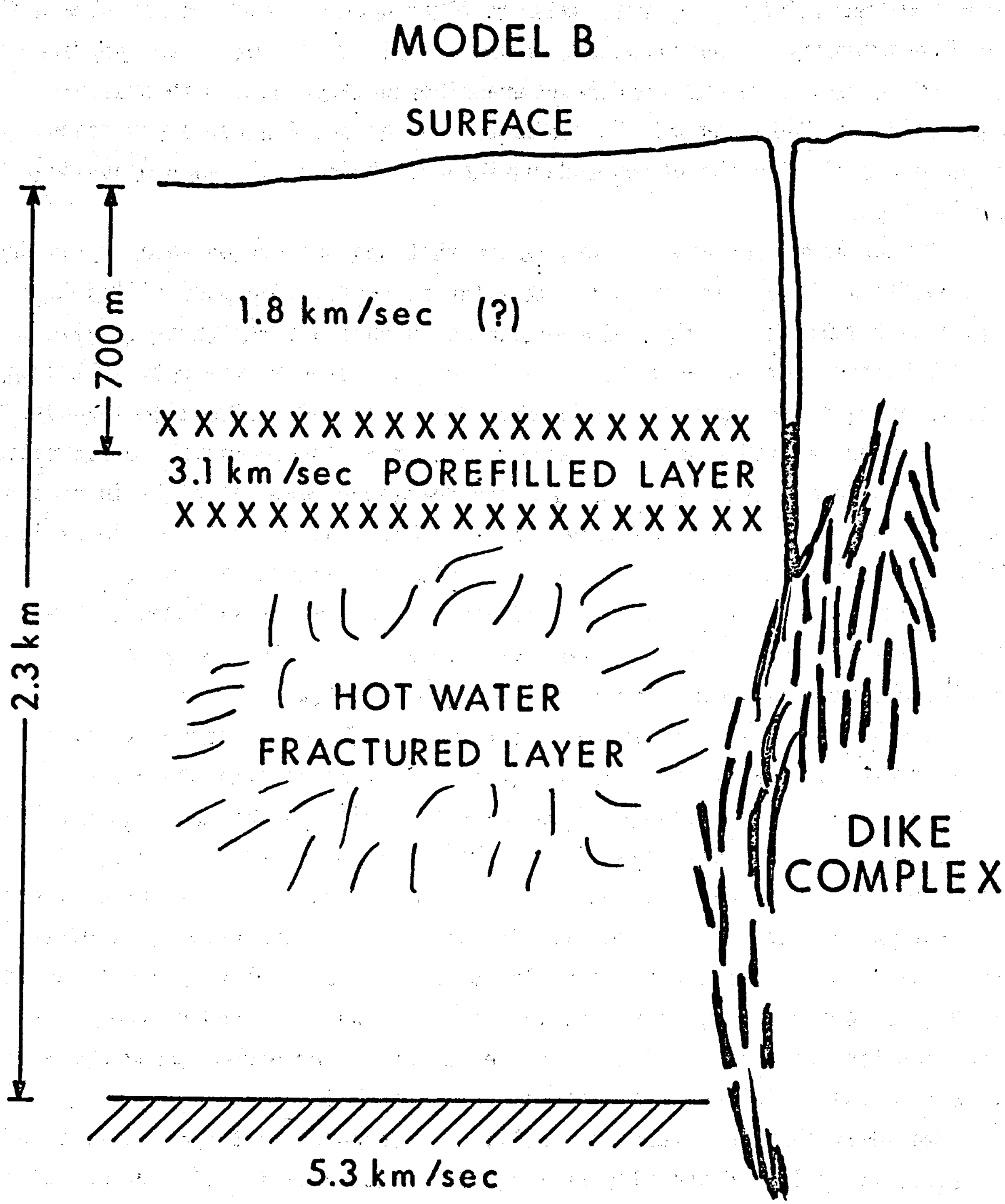

Figure 26 Hydrothermal Process of Area B. The model is very conjectural.

Concluding Remarks

Although electrical surveys had found five areas of anomalously low resistivity, these areas could only be evaluated by considering gravity, magnetic and seismic data. At this point, the value of geochemical data has not been fully appreciated, but we must remember that the study of geothermal resources in basaltic areas is still in its infancy with great room for improvement.

Of the various areas considered, the hydrothermal process associated with area A seems to be rather ephemeral, especially with magnetic data indicating relatively cool sources below as compared to area B. Data for area B indicate that there is a possibility, although a low probability, for a geothermal self-sealing reservoir.

A logical approach to drilling would be to drill in area B to ascertain whether there is a geothermal reservoir or not. If the answer is positive, the project can be turned over to a developer. If negative, further surveys can be planned to locate the best drill site to look for hot rocks or magma.

The geophysical surveys are not completed. Further gravity and magnetic surveys are in the offing to delineate more carefully the dike complex and hot areas; seismic refraction surveys are being planned for examining the 3.1 km/sec layer thoroughly.

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HAWAII GEOTHERMAL PROJECT

ENGINEERING PROGRAM

Paul C. Yuen

The principal objectives of the Engineering Program are 1) to solve important problems related to the extraction of energy from geothermal resources (Task 3.1), and 2) to plan and design an environmentally-acceptable geothermal power plant suitable for Hawaiian geothermal reservoirs (Task 3.6). Research during the past period has been devoted primarily to the theoretical and physical modelling of geothermal reservoirs, preparation for the engineering testing of wells to be drilled on the island of Hawaii, and studies of various methods of converting the heat energy in a geothermal reservoir to electrical energy. Results of the research effort have been reported in five quarterly progress reports and the following technical memorandums and reports:

1. "Modelling of Hawaiian Geothermal Resources," Technical Report No. 1, by P. Cheng and P. Takahashi, January 1974.

2. "Warm Water Wells on the Island of Hawaii," Technical Memorandum No. 1, by S. Shito, January 1974.

3. "Steady State Free Convection in an Unconfined Geothermal Reservoir," Technical Report No. 2, by P. Cheng and K.H. Lau, March 15, 1974. Published in *Journal of Geophysical Research*, Vol. 79, No. 29, October 10, 1974.

4. "Geothermal Reservoir Engineering: State-of-the-Art," Technical Report No. 3, by P. Takahashi, B. Chen, K. Mashima, and A. Seki, March 15, 1974. Submitted for publication in *American Society of Civil Engineers, Power Division*.

5. "Regenerative Vapor-Turbine Cycle for Geothermal Power Plant," by J.C.S. Chou. Published in *Geothermal Energy*, Vol. 2, No. 6, June 1974.

6. "Regenerative Vapor Cycle with Isobutane as Working Fluid," Technical Report No. 4, by J.C.S. Chou, R. Ahluwalia, and E. Woo, June 10, 1974. Published in *Geothermics*, Vol. 3, No. 3, September 1974.

7. "Geothermal Reservoir and Well Test Analysis: A Literature Survey," Technical Memorandum No. 2, by B. Chen, September 1974.

8. "A Parametric Study of a Vertical Heat Exchanger Designed for Geothermal Power Plant Application," Technical Report No. 5, by G. Shimozono, H.C. Chai, and D. Kihara, September 1974.

9. "Characteristics of Vapor Flashing Geothermal Plants," Technical Report No. 6, by R. Ahluwalia and J.C.S. Chou, November 15, 1974.

10. "The Effect of Dike Intrusion on Free Convection in Geothermal Reservoirs," Technical Report No. 7, by K.H. Lau and P. Cheng, December 1, 1974. Accepted for publication in *International Journal of Heat and Mass Transfer*.

Summaries of the research results follow.

TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

INTRODUCTION

The geothermal reservoir engineering research effort, as shown in Fig. 3.1-0, has three subtask groups: computer modelling, physical modelling, and geothermal well testing/analysis. All three subtasks have the ultimate goal of predicting the performance of producing geothermal fields. The computer modelling group will use a mathematical model approach, the physical modelling group will scale model a geothermal system, and the testing/analysis group will evaluate existing geothermal and petroleum/gas hardware and software techniques with the aim of synthesizing optimal measurement and prediction alternatives.

I. Numerical Modelling of Geothermal Reservoirs

Investigators: P. Cheng, K. H. Lau, & L. S. Lau

The primary objectives of the numerical modelling are to predict the performance of geothermal wells under different conditions and to study the environmental impact of the geothermal system, especially the stability of the Ghyben-Herzberg lens when perturbed by the extraction of a fluid from a well below the lens. The results of these studies will aid in the selection of a viable well-site.

A realistic simulation of Hawaii geothermal reservoirs must take into consideration the anisotropic property of rock formation; the irregular geometry of boundaries; the dynamics of the Ghyben-Herzberg lens; and the effects of pumping, reinjection, and freshwater recharging. Mathematically, the problem is a very complicated one since it involves the solution of a set of highly non-linear partial differential equations with non-linear boundary conditions at the water table where its position is unknown. 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. Furthermore, since the numerical solutions for a more realistic model will probably involve iteration, the results of the simplified models can be used as input data for the first iteration to guarantee convergence of the

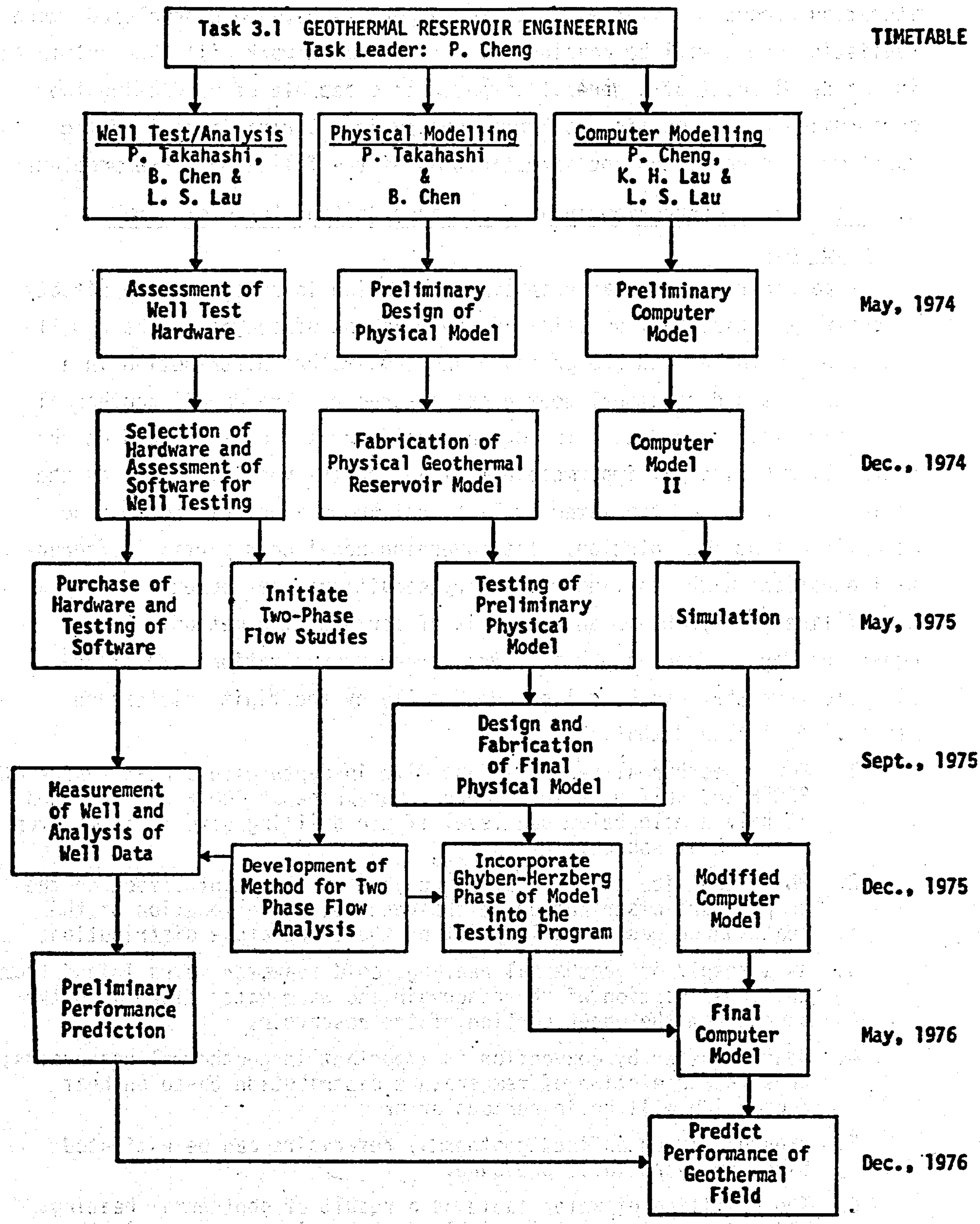

FIG. 3.1-0 ORGANIZATIONAL PLAN FOR THE TASK ON GEOTHERMAL RESERVOIR ENGINEERING

iteration process. After maturity and expertise have been developed, more realistic models will be considered. The research work will then culminate in the development of a general computer code capable of predicting the performance of a specific geothermal reservoir. During Phase I of the grant we have completed the investigation of the following three problems:

A. Steady Free Convection in an Unconfined Rectangular Geothermal Reservoir

A parametric study has been completed which investigates the effects of geothermal heating from below on the movement of seawater, the upwelling of water table, and the pressure and temperature distribution in a rectangular two-dimensional geothermal reservoir. The Hawaii geothermal reservoir is idealized as a two-dimensional porous medium bounded on the bottom by a horizontal impermeable wall and on the vertical sides by the ocean. The shape of the water table is not known a priori and must be determined from the solution. The governing non-linear partial differential equations with non-linear boundary conditions are approximated by a set of linear subproblems on the basis of perturbation method. The equations for the zero-order and first-order approximations are of the elliptic type that can be solved numerically by the finite difference method. It is found that:

1. For a geothermal reservoir one mile in depth with a heat source at 800°F and half mile in diameter, hot brine at 400°F can be found at half a mile below sea level if the drilling site is at the top of the heat source.
2. While the size of the heat source has an important effect on the temperature distribution in the reservoir, the location of the heat source has a small effect on the temperature distribution.
3. As a result of geothermal heating, cold seawater moves inland from the lower portion of the reservoir and warm water flows into the ocean from the upper portion of the reservoir.
4. Heat transfer by convection is important in geothermal reservoirs; thus the prediction of temperature distribution based on heat conduction will be in serious error.
5. Pressure in unconfined geothermal reservoirs can be estimated based on hydrostatic pressure.
6. The upwelling of water table as a result of geothermal heating, which is predicted analytically for the first time, is in the order of 100 feet for a reservoir of one mile in depth.

The perturbation method is used in the present analysis. The major advantages of the application of the method to the present problem are a) the problem becomes linear and the difficulty in the non-convergence of iteration associated with the numerical solution of non-linear finite difference equations does not exist, b) the unknown position of the water table is explicitly determined from the first-order problem, thus the usual practice of the iteration of position of water table is avoided, and c) a clearer physical picture emerged with regard to the driving forces and the role played by various parameters in heat transfer and fluid flow characteristics in a geothermal reservoir. This work is published in the *Journal of Geophysical Research* [1].

B. <u>The Effects of Vertical Heat Sources on the Upwelling of Water Table</u>

The perturbation approach discussed earlier was extended to investigate the effect of vertical heat sources on the upwelling of water table. The purpose of the analysis is to assess in a qualitative manner whether the upwelling of water table of 2000 feet above sea level reported by Keller [private communication] is due to vertical heat sources.

Suppose a dike exists in the reservoir as shown in Fig. 3.1-1A with the idealized situation shown in Fig. 3.1-1B. The parameters for the present problem are L the width to height ratio, D ($D \equiv K\rho_s gh/\alpha\mu$ where K, ρ_s, g, h, α, and μ are the permeability, the density of water in the ocean, g, the gravitational acceleration, h, the depth of the aquifer, the thermal diffusivity and the viscosity of the fluid), and ε ($\varepsilon \equiv \beta(T_c - T_s)$ where β is the coefficient of thermal expansion, T_c is the maximum temperature of the impermeable surface, T_s is the temperature of the ocean) the perturbation parameter.

Computations were carried out up to the second-order approximation for D = 500 (upper bound for which the perturbation method is valid) with $L = 4$, $\varepsilon = 0.1$, and $\theta_a = 0.02$ for the following three cases with different prescribed temperatures of the dike (θ_d) and the bottom impermeable surface (θ_L).

<u>Case A</u>. One vertical heat source. For the problem of geothermal heating due to a hot dike 0.5 unit in height and 2 units in width located at the center of the aquifer with a cold impermeable surface at the bottom, the prescribed temperatures are:

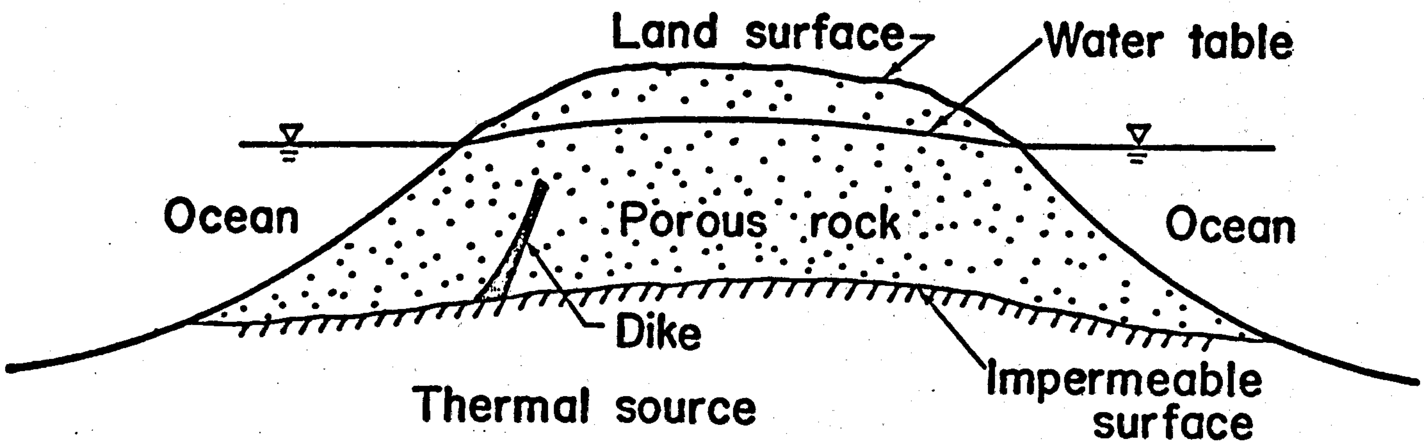

FIG. 3.1-1A AN UNCONFINED AQUIFER IN A VOLCANIC ISLAND WITH DIKE INTRUSION

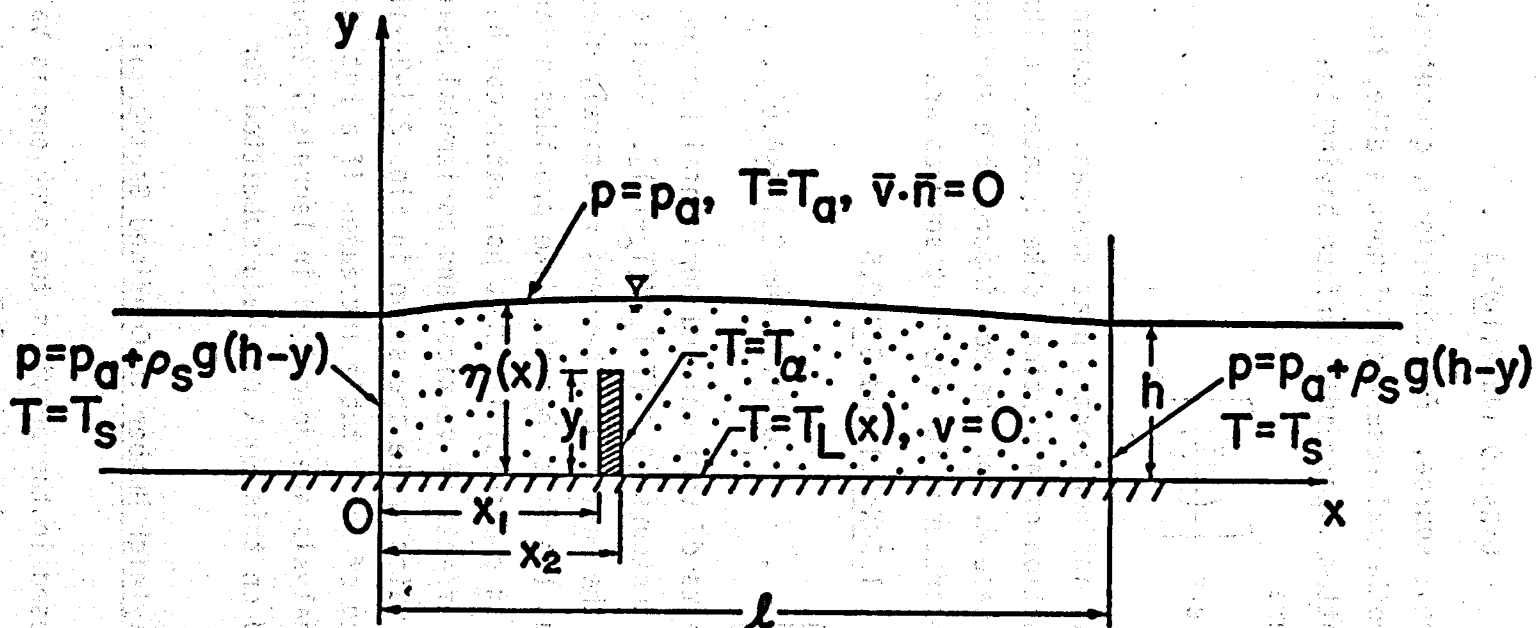

FIG. 3.1-1B IDEALIZED MODEL OF A GEOTHERMAL RESERVOIR WITH DIKE INTRUSION

$$\theta_d = 1 \quad , \qquad 1.9 \le X \le 2.1 \text{ and } 0 \le Y \le 0.5$$

$$\theta_L(X) = 0 \quad , \qquad 0 \le X \le 1.9 \text{ and } 2.1 \le X \le 4 \ .$$

Case B. One horizontal heat source. For comparison, computations were also carried out for a geothermal reservoir without a dike, but with geothermal heating from the bottom impermeable surface having the following prescribed temperature

$$\theta_L(X) = \exp\left[-\left(\frac{X-2}{0.5}\right)^2\right] .$$

Case C. Combined vertical and horizontal heat sources. Heating in this case is due to the combination of a vertical dike located at the center of the reservoir as in Case A, and the hot impermeable surface as in Case B. The prescribed temperatures for the heat sources are

$$\theta_d = 1 \quad , \qquad 1.9 \le X \le 2.1 \text{ and } 0 \le Y \le 0.5$$

$$\theta_L(X) = \exp\left[-\left(\frac{X-2}{0.5}\right)^2\right] \quad , \qquad 0 \le X \le 1.9 \text{ and } 2.1 \le X \le 4.0 \ .$$

Fig. 3.1-2 shows the effects of vertical and horizontal heating on the dimensionless temperature contours $[\theta \equiv (T-T_s)/(T_c-T_s)]$. When a hot dike exists in the reservoir, the heat source becomes relatively close to the water table. This, plus the fact that the dike provides a larger area for heat transfer, makes it a possibility that hot water can be found at shallow depths. The effects of vertical and horizontal heating on the amount of upwelling of water table are shown in Fig. 3.1-3--it can be seen here that upwelling of water table increases if a hot dike exists. The details of the analysis are described in Technical Report No. 7 [2]. A manuscript based on this work has been submitted for publication.

C. Free Convection at High Rayleigh Number in Confined Geothermal Reservoirs

The perturbation method used in the previous two problems is valid for small ε and for small and moderate values of D. Thus, the method is applicable for reservoirs with low permeability. In the present study, we shall focus our attention to reservoirs with high permeability. For this purpose it is convenient to express the governing equations in terms

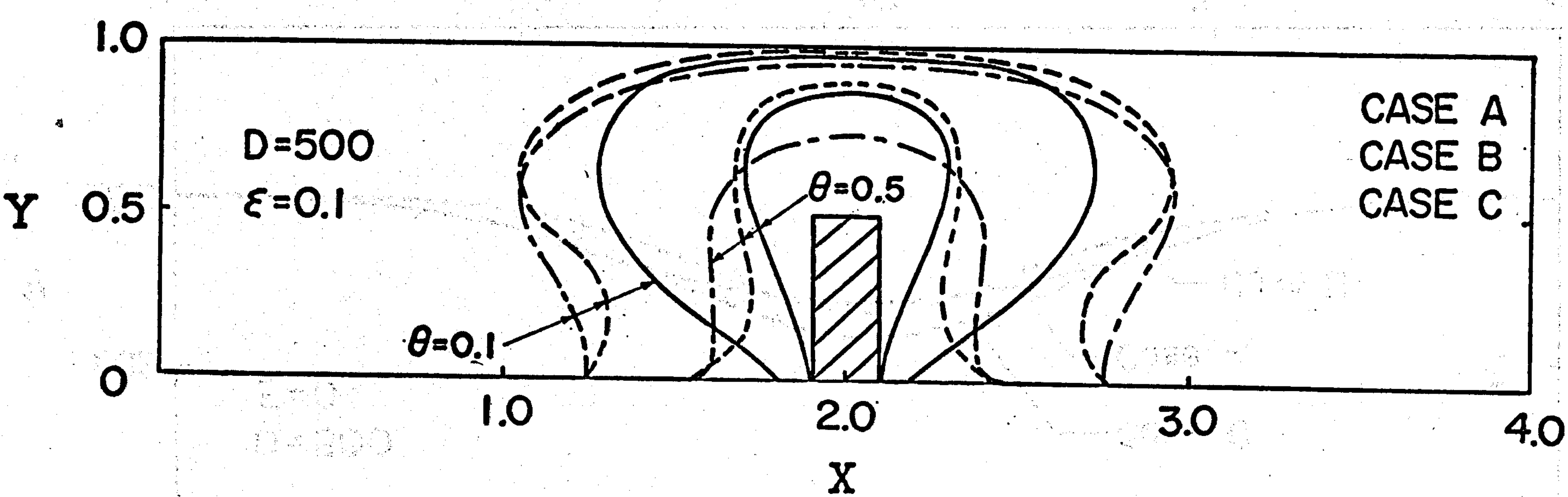

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FIG. 3.1-2 EFFECTS OF VERTICAL AND HORIZONTAL HEATING ON TEMPERATURE CONTOURS IN UNCONFINED GEOTHERMAL RESERVOIRS

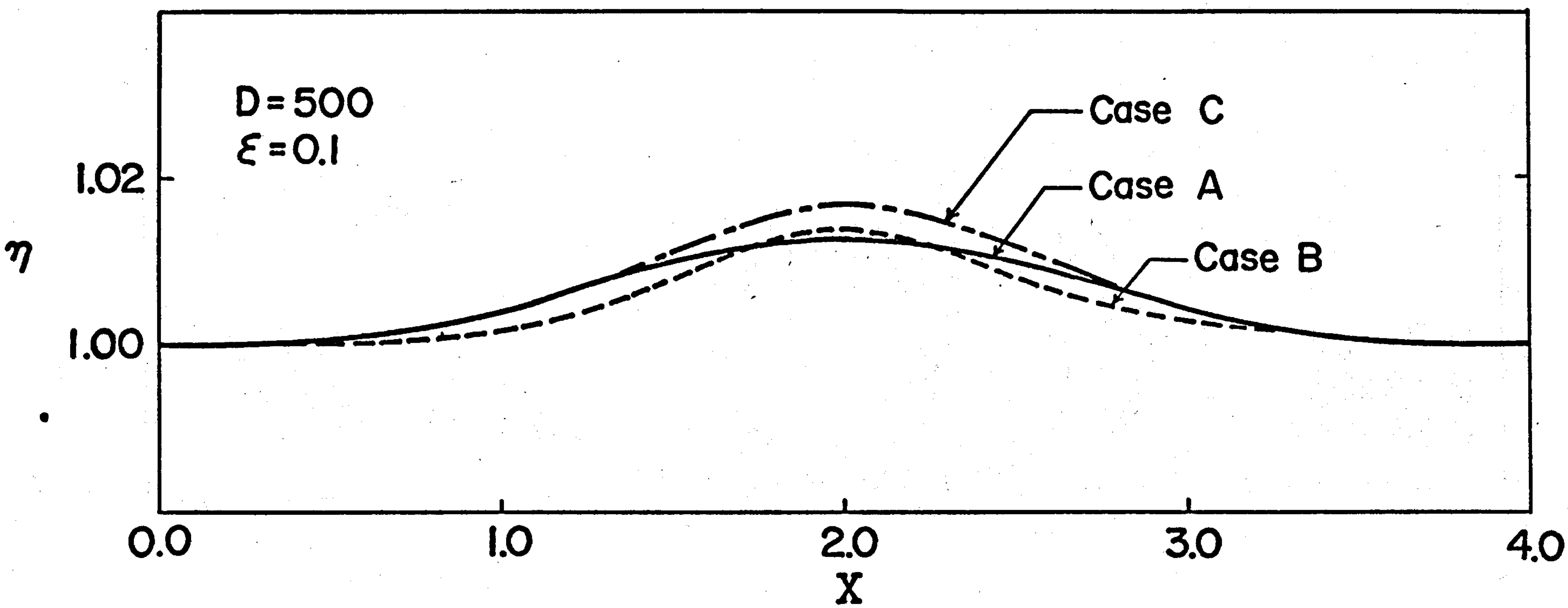

FIG. 3.1-3 EFFECTS OF HEAT SOURCES ON THE UPWELLING OF WATER TABLE FOR CASES A, B, AND C

of dimensionless stream function ($\Psi = \frac{\mu\psi}{\rho_s ghK}$, where μ, the viscosity of the fluid, ρ_s, the density of the fluid at some reference condition, g, the gravitational acceleration, h, the depth of the reservoir, and K, the permeability of the aquifer) and dimensionless temperature $\theta \equiv \frac{T-T_s}{T_c-T_s}$. The resultant set of non-linear partial differential equations are of elliptic type that can be approximated by a set of non-linear, algebraic equations by the finite difference method. The parameters in the equations are the aspect ratio L, and the Rayleigh number Ra where $Ra \equiv K\rho_s gh\beta \frac{(T_c-T_s)}{\mu\alpha} = \varepsilon D$. Computations were carried out for L = 4 and for Ra from 0 to 2,000 with the following two different boundary conditions.

Case 1. <u>Cylindrical and rectangular island aquifers with caprock temperature specified</u>. Consider an island aquifer bounded by ocean on the sides, confined by caprock at the top, and heated by a horizontal impermeable surface at the bottom. The temperature of the ocean and the caprock are given by $\theta_s = 0$ and $\theta_a = 0.02$, and that of the heated surface is given by

$$\theta = \exp\left[-\left(\frac{R}{0.5}\right)^2\right] \quad \text{for cylindrical reservoirs,}$$

$$\theta = \exp\left[-\left(\frac{X}{0.5}\right)^2\right] \quad \text{for rectangular reservoirs.}$$

The temperature contours in a cylindrical island aquifer are shown in Fig. 3.1-4. For small values of Ra (Ra = 50, for example), the temperature contours are similar to those by conduction. As the value of Ra is increased, temperature contours develop into mushroom shapes. The results have important implications on the selection of a drilling site. It indicates that for a reservoir at a large value of Ra and having a hot heat source, a large amount of hot water is indeed available at shallow depths. Fig. 3.1-5 shows the vertical temperature profiles in a cylindrical island aquifer. At the location directly above the heat source (R = 0), temperature increases rapidly from nearly zero at the caprock to almost unity at a small vertical distance from the caprock. The vertical temperature profile at R = 0 is dramatically different from the rest of the profiles which have a temperature reversal at a vertical distance not too far from the caprock. It is worth mentioning that the

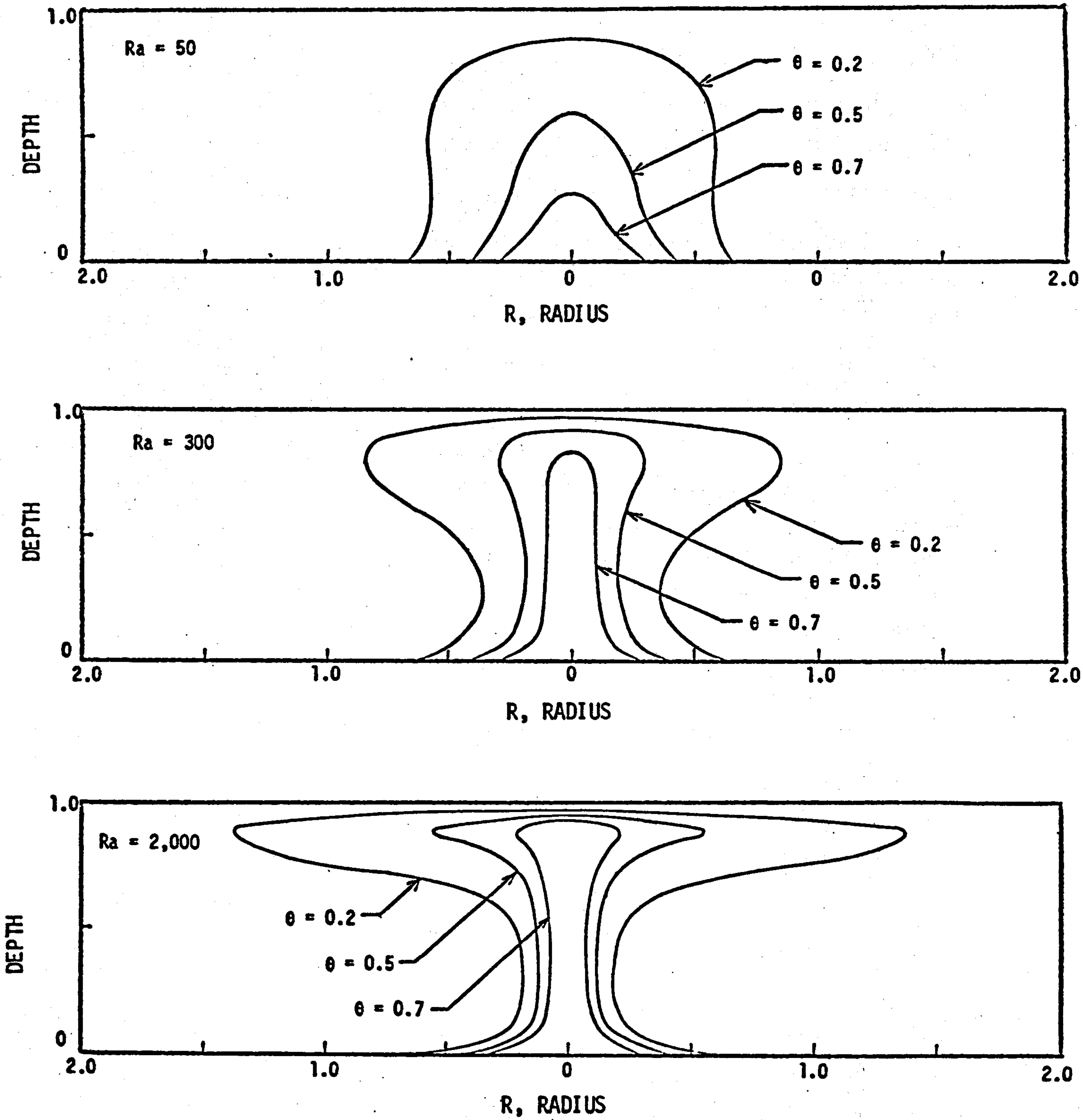

FIG. 3.1-4 TEMPERATURE CONTOURS IN A CYLINDRICAL ISLAND AQUIFER WITH CAPROCK TEMPERATURE SPECIFIED

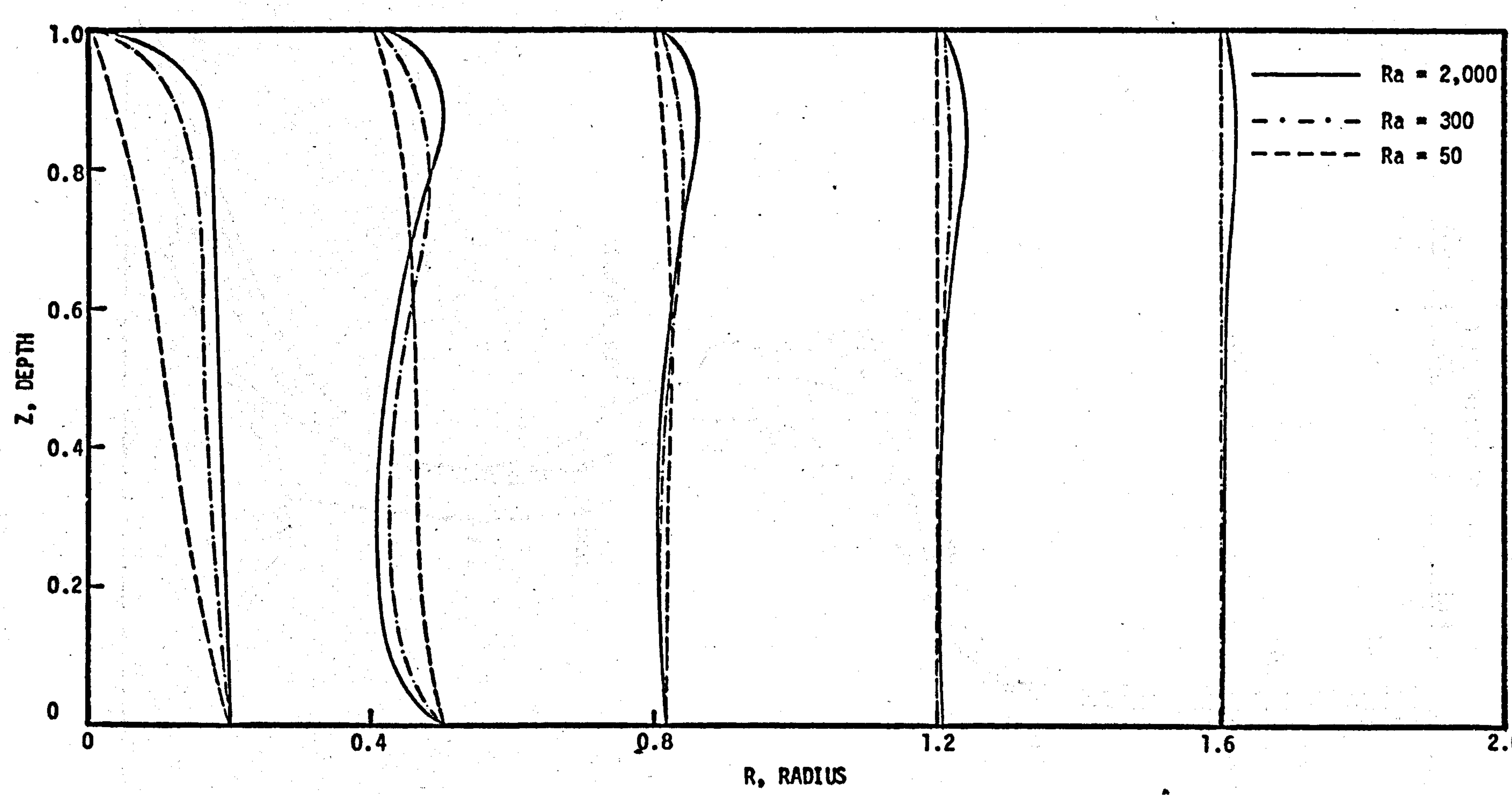

FIG. 3.1-5 VERTICAL TEMPERATURE PROFILES IN A CYLINDRICAL ISLAND AQUIFER WITH CAPROCK TEMPERATURE SPECIFIED

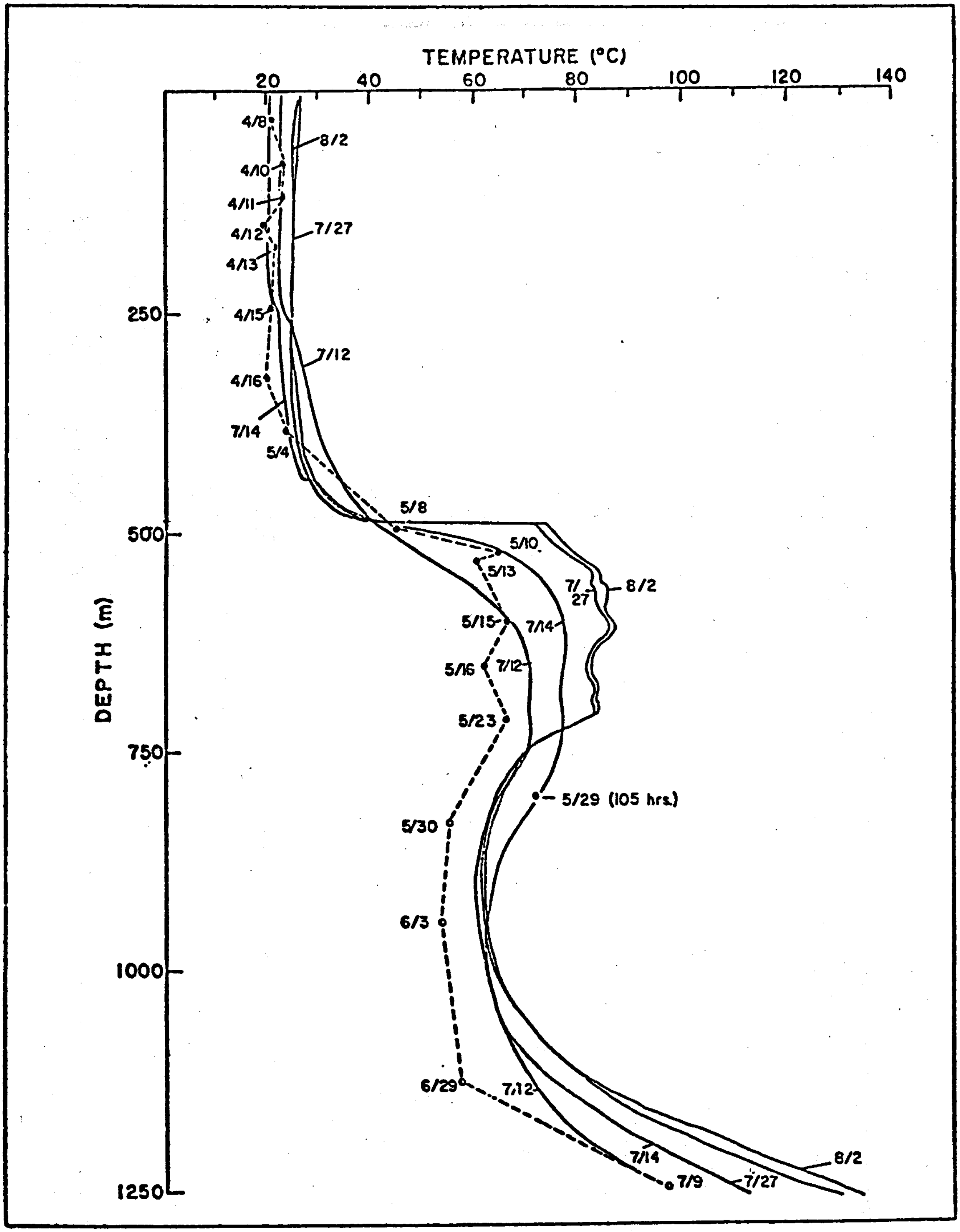

FIG. 3.1-6 TEMPERATURE PROFILES IN THE KILAUEA DRILL HOLE MEASURED BY KELLER

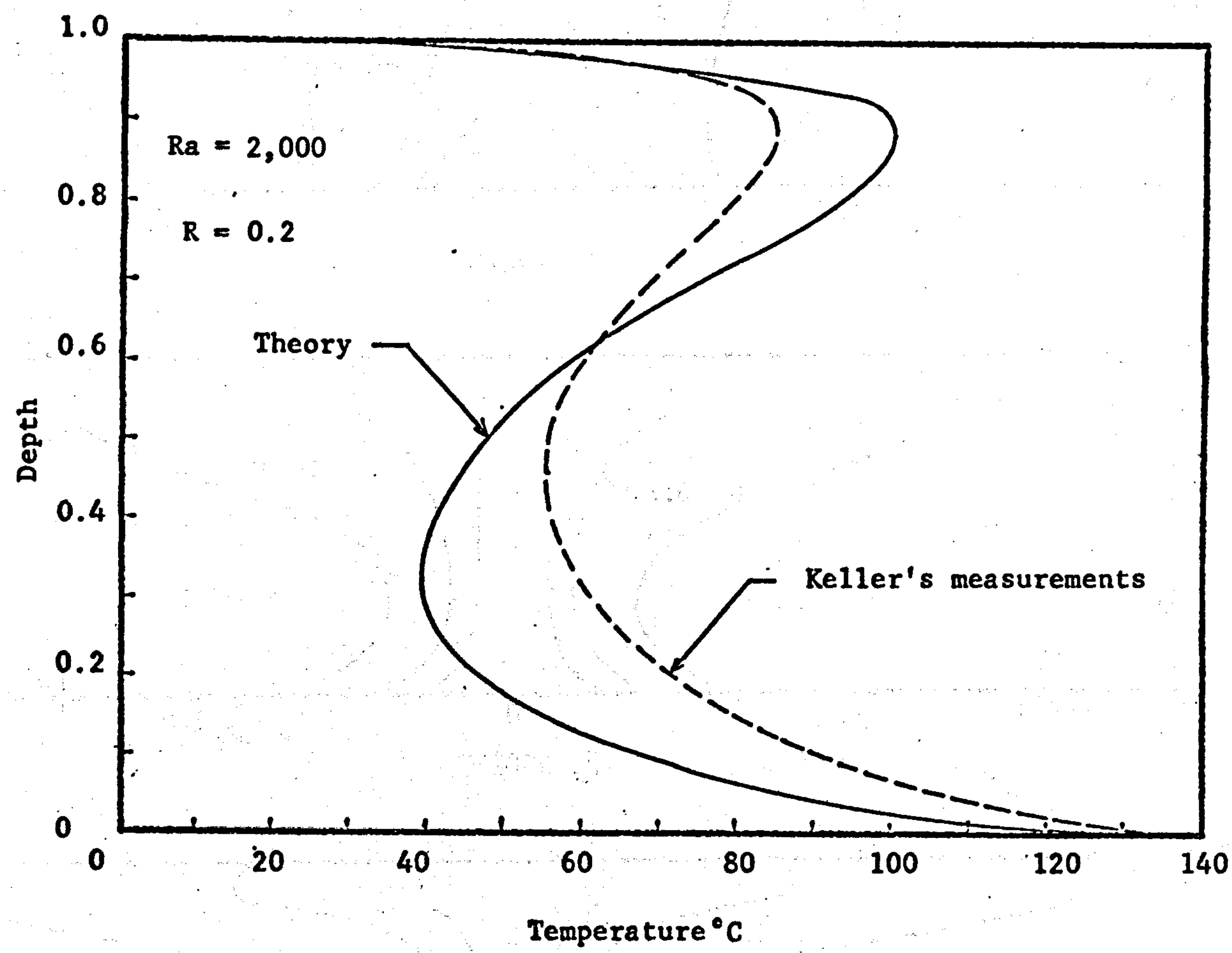

FIG. 3.1-7 COMPARISON OF THEORY AND MEASUREMENTS

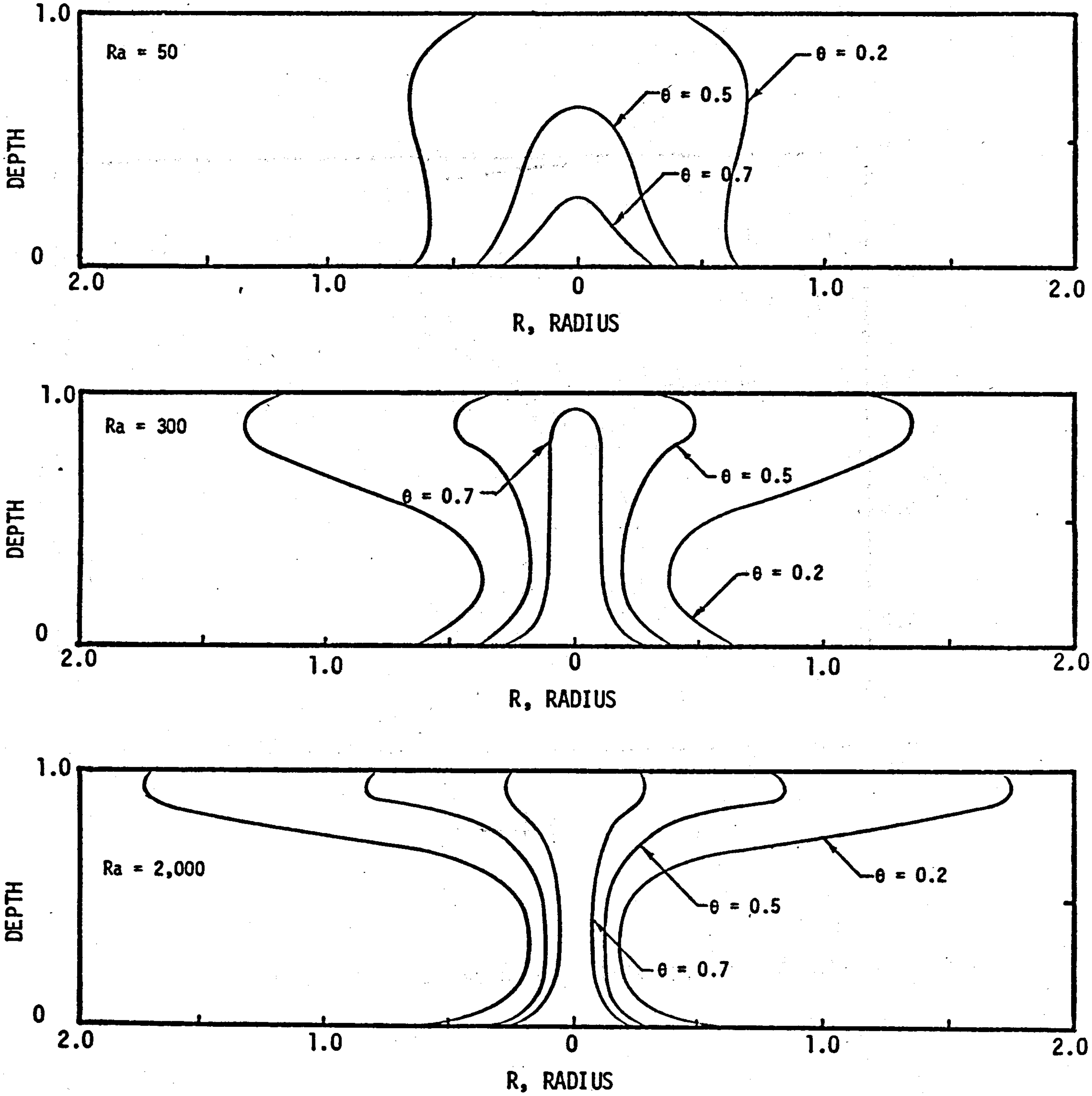

FIG. 3.1-8 TEMPERATURE CONTOURS IN A CYLINDRICAL ISLAND AQUIFER WITH ADIABATIC CAPROCK

temperature reversal occurs because of the discharge of warm water toward the ocean. The behavior of temperature reversal is most pronounced for large Ra at a horizontal distance near the heat source. It is interesting to note that temperature vs. depth measurements obtained by G. Keller [3] show also a temperature reversal behavior (Fig. 3.1-6). A comparison between theory and measurements shows a striking similarity (Fig. 3.1-7), although the island of Hawaii is supposed to be an unconfined aquifer.

Case 2. Cylindrical and rectangular island aquifer with nonheat conducting caprock. The geometry is similar to Case 1 except the thermal boundary condition of the caprock is changed to an adiabatic surface. The temperature contours of this case are plotted in Fig. 3.1-8. A comparison of Fig. 3.1-8 and Fig. 3.1-4 shows that a substantially larger amount of hot water at shallow depth is available for Case 2 because of the nonheat conducting caprock. A manuscript covering this work is now under preparation for publication.

II. Well Testing and Analysis

Investigators: P. Takahashi, B. Chen, & L. S. Lau

A. The Nature of a Geothermal Reservoir

Speculations on the nature of geothermal reservoirs can be found in the literature. Legally, in the United States, the U. S. Geological Survey defines a geothermal reservoir to be contained in either a known geothermal resource area (KGRA) or a potential geothermal resource area (PGRA). Geothermal reservoirs can be characterized in several other ways:

1. Depletable (self-sealed) or regenerative (recharged),
2. Physical state: vapor-steam, liquid-hot-water (normally two-phased at wellhead), solid-hot rock, liquid magma,
3. Physical condition: temperature/pressure, size/depth, production rate,
4. Degree of dissolved solid content.

In California, vapor-dominated wells are considered to be depletable. A tax allowance is permitted under this classification. A decision has not yet been made on other types of wells. There is some reason to believe that all wells are at least partially regenerative because of the meteoric (rainwater) origin of geothermal fluids [5]. Furthermore, reports of measurable pressure drops in steam-dominated geothermal fields seen after rainfall lead one to suspect that perhaps fluid recharge could be significant.

Although vapor-dominated geothermal wells are generally contaminated with CO_2 (primarily) and H_2S, there is little dissolved solid content. On the other hand, some of the hot water well samples in the Imperial Valley have shown as much as 30% dissolved solids by weight.

There seems to be no clear-cut answer to a universal definition of a geothermal reservoir. A geothermal reservoir generally requires: heat source (magma or geopressure); to be confined in an aquifer, although nonpermeable hot rocks can be transformed into an aquifer through hydro-fracturing/thermal cracking and the addition of water; and caprock--to hold the hot fluid in place . . . although the latter requirement is controversial. Speculations on geothermal reservoirs have been advanced by White and Muffler [5], Facca [6], Elder [7], and Hayashida [8].

For the island of Hawaii, it is generally believed that the system is self-sealed and liquid-dominated. Fig. 3.1-9 is a conceptualization of the expected system for Hawaii. It should be noted that magma is generated at the crust-mantle interface. For the Hawaiian Islands, there is belief that the production of magma could be as close as 20 miles from the surface of the earth [9, 10].

George Keller, discussing results of his drilling program at Kilauea Volcano [11], concluded that evidence favored the existence of hydrothermal convection cells and, most importantly, suggested the action of self-sealing within the porous island medium. The supposition advanced, therefore, is that Hawaiian geothermal reservoirs are sealed with the heat source being magma at depth, which with time either: 1) induced abnormally high circulation rates resulting in flashing or thermal deposition, effectively capping the reservoir, perhaps even above sea level; or 2) intruded above the magma chamber and released energy to the surrounding aquifer, in effect forming a system composed of a cooling, vertical dike surrounded by hot fluid, which through the physical phenomenon as described in "1" has been capped into a self-sealed reservoir.

Although it has been reported that hot water reservoirs are twenty times more prevalent than vapor-dominated ones [12], technical difficulties in the former have resulted in considerably more production from the

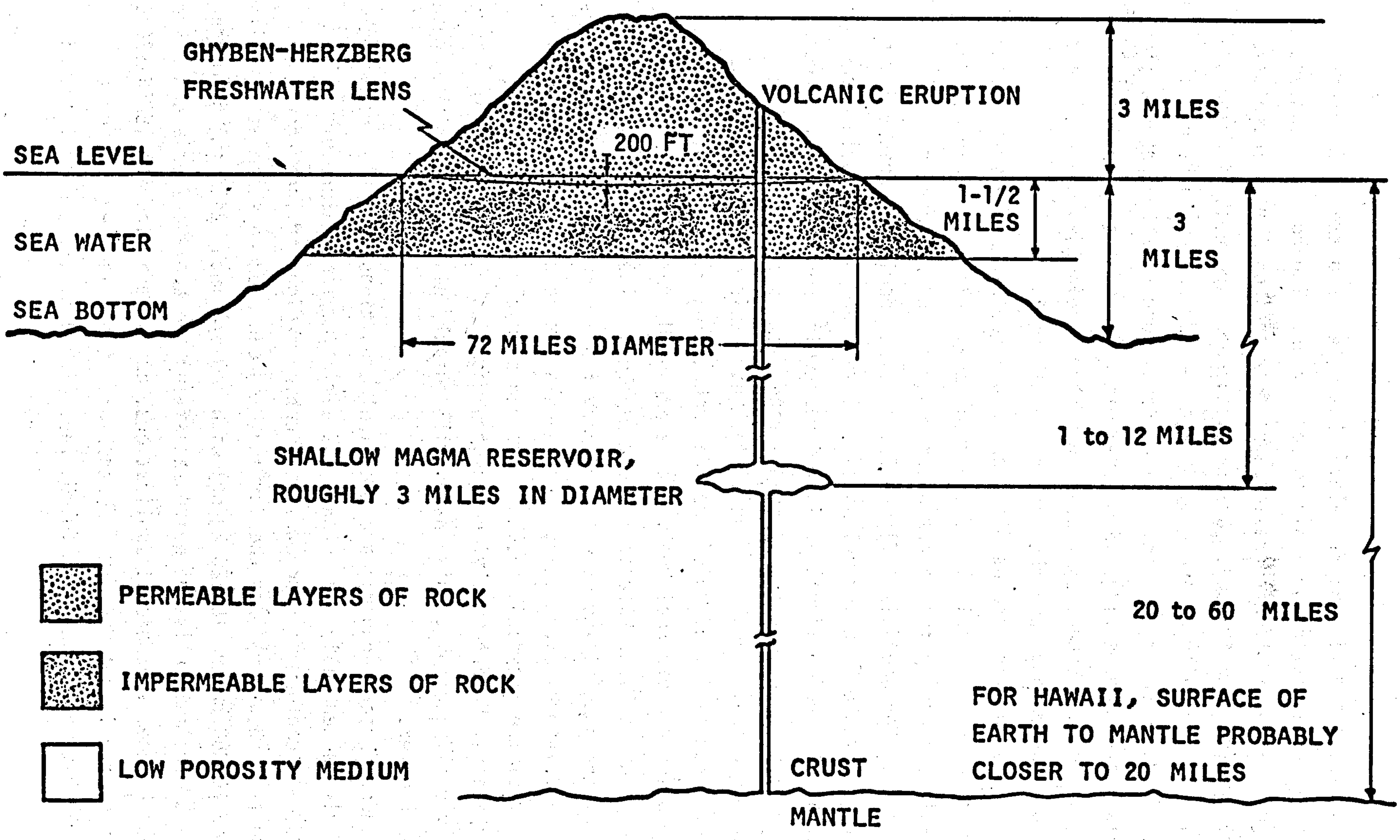

FIG. 3.1-9 SPECULATIVE CROSS-SECTIONAL VIEW OF THE ISLAND OF HAWAII

latter. There are five vapor, eleven hot water, and two binary cycle plants either operating or close to completion. The hot rock concept is undergoing investigation by researchers from the Los Alamos Scientific Laboratory (for New Mexico). A fourth concept, direct utilization of magma, was originally advanced by George Kennedy and David Griggs in 1960 [13]. A recent conference on volcano energy supported the reasonability of this latter scheme [14]. Some preliminary work, mostly in the proposal stage, is being advanced by researchers from Sandia (New Mexico), Lawrence Livermore Laboratory, and the University of Hawaii.

When calculating the usable energy in a geothermal reservoir, one should be aware that only 1% of the total available energy can be converted to electrical energy from a hot-water reservoir using present proven technology. The equivalent figure from a vapor-dominated reservoir is 2-5% [5]. It should nevertheless be realized that on an absolute energy scale, a self-sealed liquid-dominated reservoir, per cubic foot of reservoir, will produce more energy than a vapor-dominated one. A quick comparison of water and steam densities bears this out. Secondly, the thermal conductivity of rock precludes conduction as a mechanism for regenerating a geothermal well. For example, H. Ramey has reported that the net heat recharge rate in the Big Geysers is less than 0.6% [15]. However, the possibility of extraordinary fluid convection through porous media as driven by circulating magma should not be discounted--thermal cracking of the receding, cooled magma can possibly result in high permeability. Unfortunately, unless the magma chamber is extremely large or self-sealing occurs, this energy will quickly dissipate with recharging meteoric water.

Under present economic and technical conditions a viable geothermal reservoir is generally one which: has a minimum temperature of 356°F (180°C)--to conform to current steam turbine design, is located within 10,000 feet (3,050 m) from the surface, and can produce steam at a minimum rate of 40,000 lb/hr (18,120 kg/hr) with a 9-5/8 inch (24.4 cm) diameter hole. Geothermal wells not quite satisfying the above criteria can nevertheless be used for special applications, as for example, the 158°F (70°C) binary system in the U.S.S.R. Furthermore, there is every reason to believe that wells exceeding 10,000 feet (3,050 m) will, with improved drilling technology and increasing energy fuel prices, become economically feasible.

The general nature of a geothermal reservoir is contentious. The question of its being self-sealed or regenerative has not been completely answered.

B. International Questionnaire

A questionnaire on the nature of geothermal reservoirs and well testing and analysis was sent to a number of workers in the field. Over twenty replies were received from companies, institutions, and government agencies from all of the prominent geothermal energy nations. While some of the responses were received through oral communication, the majority of them were in the form of personally written correspondence. Many of the individuals chose to answer the questions by citing published technical literature. All responses were evaluated and the most appropriate ones were tabulated in a matrix arrangement as shown in Table 3.1-1. This table should be a convenient guide for quick reference to geothermal reservoir engineering.

C. Geothermal Reservoir Engineering: Well Measurement and Analysis

Geothermal reservoir engineering begins with exploration and progresses through stages of drilling, well testing, analysis and performance prediction. Investigators in the engineering phase of the program have worked closely with the geophysical effort in activities that impact engineering. The "well test analysis" team has progressed in two well-defined but closely interrelated sequential areas. Close to completion is a master's thesis on formation evaluation, the interface region connecting geophysics and engineering. This initial probe has categorized the various techniques utilized in geophysical exploratory programs, especially with respect to engineering relevant data. All activities in the region of the geothermal well, from speculations into most probable reservoir configurations to fluid flow properties in the well itself, to measurement of the necessary parameters, have been considered. Study #2, well test analysis, logically extends the first. Methods used by the petroleum industry have been studied for adaptation to geothermal fluids.

The purpose of a reservoir engineering study is to collect enough information to reveal the nature of the reservoir and to determine the pertinent physical parameters which control the behavior of fluids in the reservoir. Some of the questions that need to be asked are:

What are the temperature and pressure ranges of the fluid?

What is the nature of the fluid; i.e., vapor, liquid or a mixture of both?

What is the chemical composition of the fluid?

What is the expected production rate and expected life of the reservoir?

After the geologists and geophysicists have decided on the drill site and drilling has commenced, a reservoir testing program should be outlined. Well tests are performed in two phases. In the first phase tests are performed during open-hole drilling operations. They consist of fluid temperature measurement, fluid sampling, core analysis, and formation logging. After completion, the production well must undergo a second phase of tests to determine the thermodynamic condition of the fluid and the adequacy of the reservoir. Measurements are taken both at the wellhead and downhole.

1. Hardware

The following list outlines the hardware to adequately measure a geothermal reservoir [13, 16-20].

a. Subsurface formation condition

Permeability: resistivity logs, core samping.

Porosity: resistivity logs, core sampling, density logs, neutron logs, sonic logs.

Water saturation: resistivity logs, porosity measurements.

b. Evaluation of well casing: inclination for deviation survey, wellbore calipering, casing condition.

c. Downhole fluid condition

Pressure: Amerada-Kuster RPG-3 gauge, pressure transducer, gas purge tube with pressure element.

Temperature: expansion thermometer, resistance thermometer thermocouple, geothermograph, maximum registering thermometer, temperature sensitive paint, metal, and ceramic pellets.

Flow rate: mechanical spinner, electronic flowmeter.

Fluid sampling: Kuster sampler, Schlumberger sampler, gas purge tube with fluid sampler.

TABLE 3.1-1 RESPONSES TO INTERNATIONAL QUESTIONNAIRE

NAME AND AFFILIATION	WHAT IS THE NATURE OF A GEOTHERMAL RESERVOIR	WELL TESTING AND ANALYSIS HARDWARE	SOFTWARE
B. C. McCabe Magma Power Company USA	In geothermal reservoir engineering, the theoretical information to determine the size or longevity of a geothermal field is a very inexact science. For steam and hot water reservoirs, no one knows what the % of replaceable heat is coming into the reservoir in proportion to the amount being withdrawn. Probably, the replacement heat is much greater than it is generally imagined.	No reply	No reply
W. K. Summers New Mexico Bureau of Mines USA	Geothermal fluids consist of two components: 1) meteoric water and 2) gases (H_2S and CO_2), rising from great depths. The mixture of the components occur in fractures. If the fractures are sufficiently close together, a well will produce routinely. Otherwise, only occasional wells will produce.	Petroleum or groundwater hydrology equipment can be used, as modified to incorporate temperature.	Computer technology is generally adequate, but software is dependent on adequate sampling of the flow continuum and the proper incorporation of the parameter temperature.
Giancarlo E. Facca Registered geologist Italy and USA	Geothermal fields are composed of: 1) a deep sequence of layers, heated by an underlying magmatic stock and which, in turn, heats the overlying porous strata, and 2) a very permeable layer with thickness, porosity and permeability of such an order as to allow the formation and the permanence of a system of convection currents in the water filling the pores of the rock, and 3) an impermeable layer over the reservoir.	Refer to United Nations and UNESCO publications [26, 27, 28, 29, 30].	Refer to United Nations and UNESCO publications [26, 27, 30, 31, 32, 33].

TABLE 3.1-1 (CONTINUED)

W. E. Allen Oil and Gas Conservation Commission (Arizona) USA	References 26 - 36.	References 26 - 36.	For the purpose of predicting well performance, there are no marketing companies in Arizona.
Robin Kingston Kingston, Reynolds, Thom, and Allardice, Ltd., New Zealand	Refer to United Nations publications in References 26 - 36.	Refer to articles by D.K. Wainwright [34] and A.M. Hunt [27].	Prediction of well performance is a composition of permeability, temperature, reservoir capacity, and rate of flow. Permeability in geothermal terms depends on fracture zones much more than on porosity. Oil reservoir assessment techniques can in some applications be modified for geothermal applications.
Enrico Barbier International Institute for Geothermal Research Italy	Refer to United Nations and UNESCO publications [35, 36].	Equipment and other hardware are generally not available.	The evaluation of the quality of a geothermal well is uncertain. Analogies are generally made with existing wells.
J. L. Guiza Geothermal Resources Cerro Prieto Mexico	Geothermal fields are classified into two major groups: 1) sedimentary fields and 2) volcanic fields. In a sedimentary field the productive strata is a permeable sandstone interbedded by impermeable clay layers. The sandstone is saturated with meteoric water, and the heat flow is due to the faults and fissures of the granitic basement. In volcanic fields the possible production mechanism is due to the water flow through fissures in the volcanic rocks being heated by a cooling magmatic body.	For the determination of reservoir parameters such as permeability index and porosity, the synergetic log named SARABAND is used. For temperature, pressure, and flow measurements the conventional systems (Kuster RPG and KTG instruments) are employed.	The performance in a well can be predicted by means of a hydrologic model modified by the temperature effect and taking into account the physical characteristics of the productive sandstone as well as the physical-chemical properties of the geothermal fluids. For the purpose of optimizing well locations, computer programs are used to simulate field production.

d. Surface fluid condition

Pressure: aneroid barometer, mercury column, glass manometer, pressure recorder.

Temperature: filled thermal measuring systems, resistance bulbs, thermocouples.

Flow rate (and enthalpy): separator, orifices, and weirs for separate vapor and liquid flow, beta ray, gas method, magnesium sulfate injection, critical lip pressure, conductivity, calorimetry.

In fluid measurment the data obtained from one particular downhole instrument are not always reliable due to its operational characteristics. Combined readings from two or more instruments for a certain parameter are desirable to predict a specific subsurface condition. Data generated from these measuring devices are cross-verified to determine the probable downhole condition.

2. Analysis

Although the two types of analyses to be described are closely related, they are being separated because part "A" is the classical method used by geologists and petroleum engineers. This technique has an empirical foundation and is not conducive to the analytical/computer solutions to be developed in part "B."

a. Formation Evaluation

The proper interpretation of data from well tests will determine the feasibility of utilizing a geothermal well. Both open-hole nonflowing and cased-hole production tests are used to aid in characterizing a reservoir. The required data includes formation thickness, permeability, porosity, water saturation, viscosity, compressibility, fluid and rock density, temperature and formation fluid pressures. The values for these parameters can be obtained in different ways depending upon the developmental phase of the well. For practical purposes, it is important to understand the ways in which these values are obtained.

In early logging the previously described analytical methods were done manually to obtain the desired subsurface information. However, with significant advances by well service companies, the process is now performed by applying computer programs for specific types of formations. The two common types of complete open-hole interpretation programs are the SARABAND and the CORIBAND techniques, both developed by the Schlumberger Company. SARABAND is applicable for shaley sands while CORIBAND is used primarily for complex lithologies.

b. Well Test Analysis

In order to evaluate a geothermal reservoir, whether it be drilling, development or production, various data on certain parameters are needed. Pressure is a particularly important parameter for use in materials heat balance calculations of geothermal liquid in place and determination of reservoir characteristics: compressed liquid, saturated liquid and steam or superheated steam. Extrapolation into the future is best made by using the method which relates future production to future average pressure. Tests to be conducted include pressure drawdown and buildup, with specific determination of skin effect, interference and other desired features.

In the general sense, software encompasses both computer programs and the standard type curve analysis. It appears that the methods of analysis used in the petroleum and gas industries cannot be naively applied to geothermal systems. A geothermal reservoir has temperature as the dominant parameter. Most petroleum reservoir analyses are based on isothermal conditions. Whiting [4] and Ramey [15] have successfully demonstrated that the regular volumetric balance method in petroleum engineering does not apply to geothermal reservoirs, but rather a material and energy balance method is needed. However, in most cases, the principles of petroleum reservoir engineering for single-phase liquid flow can be applied with certain modifications to hot water reservoirs [21].

III. Physical Modelling

Investigators: P. Takahashi & B. Chen

The physical model is a necessary balance to the ongoing software investigations. The physical model will not only serve as a convenient check on the math model, but will simulate conditions not easily attempted by software. The objectives of the initial physical model studies will be to bring together known information about related laboratory studies, analyze the state-of-the-art, design the hardware system required for simulation, and initiate fabrication and preliminary tests.

Very little physical modelling work has been reported in the literature. The significant studies related to geothermal reservoirs include those of G. Cady [22], F.G. Miller [23], H. Henry and F. Kahout [24], and the remotely related work of J. Bear [25]. However, none of the reported investigations approached the problem on a total systems basis while considering the high [2012°F (1100°C) for magma, 527°F (275°C) at wellhead] temperatures expected.

In movement of fluid through a geothermal reservoir, the driving force is primarily the buoyant force. This force is created by heat within the geothermal system which decreases the fluid density. The dimensionless number determined to be of prime interest to the study is the Rayleigh Number (Ra). The Rayleigh Number is the product of the Grashof (Gr) and Prandtl (Pr) Numbers, where

$$Gr = \frac{\text{buoyant force}}{\text{viscous force}}$$

To insure similarity between the physical and mathematical models and the actual reservoir, a modified Rayleigh Number will be used. This dimensionless number is defined as follows:

$$\text{mod Ra} = Ra \frac{k}{L^2}$$

where Ra = Rayleigh No.

k = permeability (units of length squared)

L = characteristic length

since

$$Ra = \frac{\beta g \Delta T L^3}{\alpha \nu} ,$$

$$\text{mod Ra} = \frac{\beta g \Delta T L K}{\alpha \nu}$$

where β = coefficient of thermal expansion

α = thermal diffusivity

ν = kinematic viscosity

g = gravitational constant

ΔT = difference in temperature between the reservoir and ocean

L = height of aquifer

Convection is initiated at a modified Rayleigh Number of 40; mod Ra's up to 1,000,000 can be expected for actual conditions in Hawaii. Calculations showed that it is possible to obtain mod Ra's up to 1,000 using the full scale unpressurized model. This model is tentatively planned to have a seawater capacity of 450 gallons, a variable (in size and temperature) heat source and glass bead permeable medium. As the model will be two-dimensional, one face will be used to insert temperature measurement devices to obtain the temperature profile.

Three glass bead mesh sizes will be used to vary permeability. Various researchers have speculated that macroscopic fractures will result in aquifer permeabilities in the order of several hundred darcies. It was fortuitous that glass bead permeabilities were available to stradle this range and yet provide for reasonably high modified Ra numbers. Glass beads having mesh size/permeability of 12-14/1490, 20-30/319, and 40-50/80 were selected. Lower permeabilities can be obtained by using higher mesh sizes consolidation, or artificial dike formation.

A preliminary 50-gallon (1/3 size) model will be initially built. This smaller tank will give an economical means of testing construction and operational costs. Certain design questions such as to pressurize or unpressurize will also be answered. The heat source and temperature measurement and recording instruments will be the same for both the preliminary and final models. Materials and equipment for the preliminary model have been ordered and fabrication has commenced.

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TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

Investigators: H. C. Chai, J. Chou & D. Kihara

INTRODUCTION

The efforts of Task 3.6 have been concentrated on studies of geothermal power plant configurations which might be considered for use in moderate temperature, low salinity fields. Emphasis has been placed on vapor flashing plants and binary fluid, vapor turbine cycles--focusing on the major parameters and criteria for selecting the particular configuration once the geothermal source is located and tested.

I. Vapor Flashing Plants

A. Selecting Flashing Pressures

In a vapor flashing system hot water is flashed to steam at a pressure lower than the wellhead pressure. The vapors thus generated may be used to drive a mixed pressure turbine. Flashing may be done in a centrifugal cyclone separator. Bengma [2] discusses the development and selection of a steam water separator. Chierici [4] draws some important conclusions about the feasibility of using a condensing plant.

Work output from the turbine is the product of steam flow rate and the available energy. In a simple flashing system, the lower the flashing pressure, the higher the steam production rate. However, available energy associated with each pound of steam decreases with the lowering of the separator pressure. Therefore, there exists an optimum flashing pressure for obtaining maximum power from the hot water. At a pressure higher than the optimum, work output is small due to minimal available energy. At a pressure lower than the optimum, low turbine work results because of the diminished steam flow rate.

By employing multi-stage flashing, the temperature of discharged water is lowered and thus the work output of the plant can be greatly increased. The number of stages of flashing is a matter of economic justification. Power contribution of an additional stage decreases as the number of stages increases, and specific volume of steam increases rapidly at low pressure to cause high cost of the multi-stage arrangement. An advantage of multiple admission of steam to a mixed pressure turbine is to improve the quality of the exhaust steam, thereby reducing erosion of the turbine blades. Also, steam flashed from separated water is practically free of gases. The percentage of gas content in the exhaust steam can be lowered by blending the flashed steam with the steam directly from the well. In a mixed-pressure turbine, there are separate inlets for steam at different pressures, and each inlet is equipped with its own control valve.

Hansen [7] stated that for a simple flashing cycle, optimum flashing pressure corresponds to a saturation temperature halfway between the well water temperature and saturation temperature of the condensate in the condenser. For example, for 400°F well water and 120°F condensate, the optimum flashing temperature should be 260°F. He extended the rule to the multi-stage flashing plant. For well water at 400°F, condensate at 120°F, and three-stage flashing, optimum intermediate pressures should correspond to saturation temperatures of 330°F, 260°F, and 190°F, respectively. A procedure, based on mass and heat balances has been worked out to determine the exact optimum flashing pressure with numerical methods; the results confirm Hansen's rule of approximation. The steepest ascent method utilizing a digital computer was used to determine the optimum flashing temperatures.

For saturated well water at 400°F and condensing temperature of 120°F, the total turbine work per pound of well water is tabulated in Table 3.6-1 for one- to four-stage plants. With reasonable amounts of heat losses through the flashing tanks, Hansen's rule of approximation yields nearly the same amount of work as obtained by the exact method. As expected, the power contribution of an additional stage diminishes as the number of stages increases. Also, the specific volume of steam increases rapidly to cause difficulty in turbine design. Thus the number of flashing stages is likely to be limited to two. Because of the pressure drops through pipes and the high cost of low pressure equipment, the most economical flashing temperatures should be slightly higher than the calculated optimum temperatures.

B. Optimum Wellhead Pressure

The wellhead pressure affects the sizes of pipeline and plant components, the total flow rate of fluid from the well, and the specific steam consumption for power production. The power output can be enhanced

TABLE 3.6-1 FLASHING TEMPERATURES AND TOTAL WORK FOR SATURATED WATER AT 400°F AND CONDENSING TEMPERATURE AT 120°F.

Index	t_1°F	t_2°F	t_3°F	t_4°F	Work, Btu Per Pound of Well Water
1	280	-	-	-	22.377
	260	-	-	-	23.085+
	240	-	-	-	22.89
	220	-	-	-	21.743
2	307	213	-	-	29.33+
3	330	260	190	-	32.034+
	326.6	257.1	186.04	-	32.068
	322.91	255.23	183.31	-	32.084*
	313.94	248.04	173.94	-	31.979
4	344	288	232	176	33.173+
	335.24	276.37	216.02	170.93	33.681
	332.56	275.0	218.71	167.80	33.713*
	334	168.65	221.46	161.67	33.615
5	330	260	190	-	31.193+
	322.02	253.57	185.33	-	31.267
	316.83	247.10	180.75	-	31.271*
	304.92	224.22	172.18	-	30.962
6	330	260	190	-	27.035+
	315.12	247.25	181.36	-	27.513
	300	228	169	-	27.7 *
	287.6	173.8	132.64	-	20.563
7	330	260	190	-	17.088+
	301.67	253.3	174.09	-	19.571
	267	192.29	146.39	-	20.892*
	254.62	173.8	132.64	-	20.562

\+ Equal distribution of temperature difference.

* Optimal flashing temperatures.

1 1-stage flashing, no heat loss, zero moisture content of flashing vapor, saturated water leaving tank.

TABLE 3.6-1 (Continued) FLASHING TEMPERATURES AND TOTAL WORK FOR SATURATED WATER AT 400°F AND CONDENSING TEMPERATURE AT 120°F.

2	2-stage flashing, no heat loss, zero moisture content of flashing vapor, saturated water leaving tank.
3	3-stage flashing, no heat loss, zero moisture content of flashing vapor, saturated water leaving tank.
4	4-stage flashing, no heat loss, zero moisture content of flashing vapor, saturated water leaving tank.
5	3-stage flashing, no heat loss, 3% moisture content of flashing vapor, superheated water leaving tank ($z = 0.015$).
6	3-stage flashing, with heat loss ($y = 0.97$), 3% moisture content of flashing vapor, superheated water leaving tank ($z = .015$).
7	3-stage flashing, with heat loss ($y = 0.90$), 3% moisture content of flashing vapor, superheated water leaving tank ($z = 0.015$).

Turbine efficiency is assumed to be 75%.

by employing a multi-stage flashing plant. To evaluate the effect of wellhead pressure and number of stages on power output, the optimum wellhead pressures have been calculated for four different arrangements. The typical flow rates of wells for the purpose of calculations are given in Fig. 3.6-1, which shows that the well flow rate decreases as the wellhead pressure increases. The power output is the product of the flow rate and the work per pound of fluid, whose available energy decreases correspondingly with the decrease in wellhead pressure. There exists an optimum wellhead pressure for the maximum power output of each arrangement. The optimum flashing pressures can be determined by using the rule discussed in Section 1.

In Fig. 3.6-1, the curves near the points of maximum power output are flat. It appears desirable to select a wellhead pressure higher than the optimum pressure since the sizes of pipes and equipment can be lowered by increasing the working pressure. However, Usui et al. [13] argued that it is not advisable to select a wellhead pressure higher than the pressure which gives the maximum power because 1) such a design is apt to suffer power decrease by scale deposition on the nozzles and blades of the turbine, and 2) the well flow rate does not remain constant with time. At low wellhead pressure, the drop of flow rate may be retarded, and the underground paths of water are less likely to be blocked.

C. Heat Balance of a Hypothetical Plant

The heat balance of a two-stage vapor flashing plant is given in this section. Fig. 3.6-2 shows the flow diagram of the plant, for which the basic assumptions are as follows:

Power output	=	8 MW
Number of cyclone separators	=	2
Wellhead pressure	=	100 psig
Number of wells	=	2
Water flow	=	10^6 lb/hr
Gas flow	=	3000 lb/hr
Enthalpy of water	=	400 Btu/lb
Pressure drop in main pipeline	=	10 psi
Condensation loss	=	3% of the heat content of water
Turbine-generator efficiency	=	73%

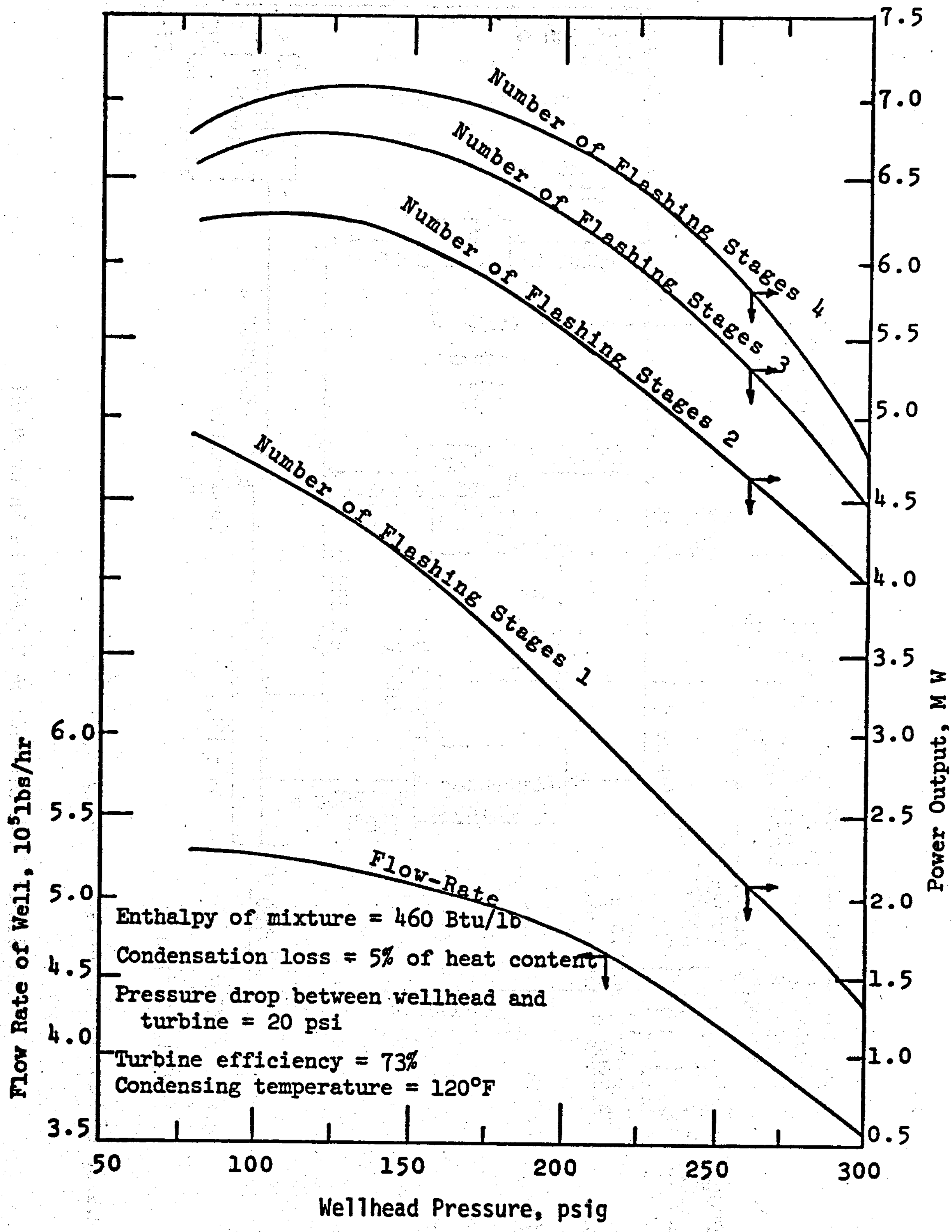
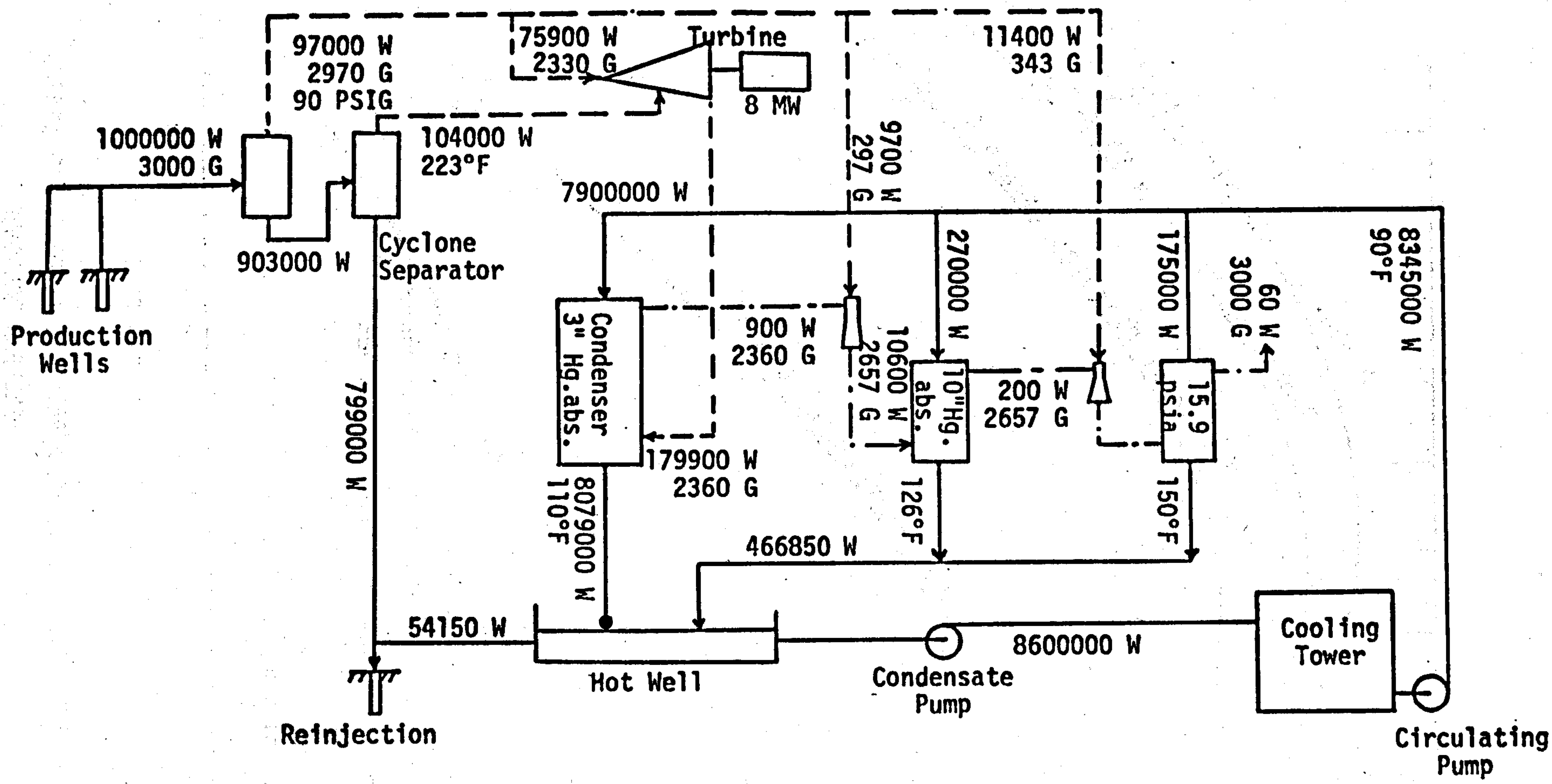


FIG. 3.6-1 WELL FLOW RATE AND POWER OUTPUT VERSUS WELLHEAD PRESSURE



W = lb. water and steam per hr., G = lb. gas per hr.

FIG. 3.6-2 FLOW DIAGRAM OF A VAPOR FLASHING PLANT

Pump efficiency	=	75%
Fan motor efficiency	=	90%
Ejector efficiency	=	5.6%
Condensing pressure	=	3 in. Hg. abs.
Wet bulb temperature	=	75°F
Approach of cooling tower	=	15°F

The process of heat balance involves the selection of the optimum flashing temperature, the energy and material balances of geothermal water, non-condensable gases and cooling water. The optimum flashing temperature of this example is 223°F, as determined by the rule stated in Section 1. After the temperature in the second cyclone separator is selected, the steam productions of the two separators can be determined. They are 97,000 lb/hr and 104,000 lb/hr, respectively.

The wellhead pressure affects the flow rate of fluid from the well and the specific steam consumption for power production. To evaluate the effect of wellhead pressure on the specific steam consumption, Fig. 3.6-3 has been constructed for different enthalpies of well water. The graph shows that the pressure which yields the highest power output per million pounds of water, i.e., the lowest specific steam consumption, increases as the enthalpy of well water increases.

D. Using Deep Ocean Water as Cooling Water

In Hawaii, the average temperature of seawater is 81°F at the surface and 41°F at a depth of 1,600 ft. For a geothermal plant near the sea, the cost of using sea water as cooling water in a condenser is likely to be lower than the cost of recycling the cooling water through a cooling tower. Assuming the back pressure of a steam turbine is 2.0 in. Hg for a plant using the surface sea water as cooling water, the back pressure could be lowered to 0.5 in. Hg with the same condenser design if the cooling water is taken from the deep ocean. The variation of turbine output with cooling water temperature is illustrated in Fig. 3.6-4. Since the isobutane turbines have higher efficiencies than the steam turbines, the gain in power output of an isobutane plant should be more impressive than that of a steam plant. It is intended to expand the study on extracting more energy from geothermal fluids by taking advantage of deep ocean water.

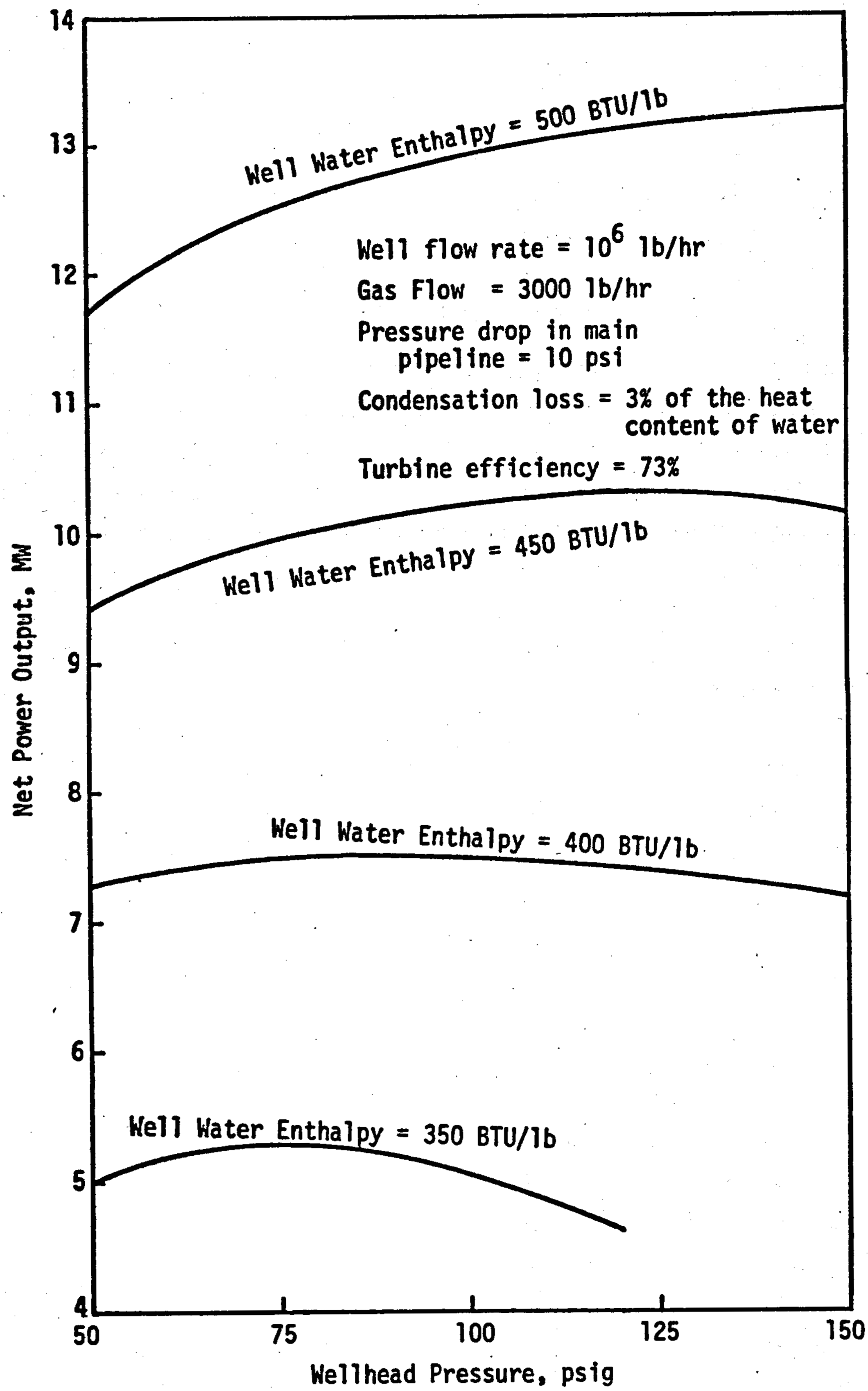


FIG. 3.6-3 VARIATION OF SPECIFIC POWER OUTPUT WITH WELLHEAD PRESSURE FOR A TWO-STAGE VAPOR FLASHING PLANT

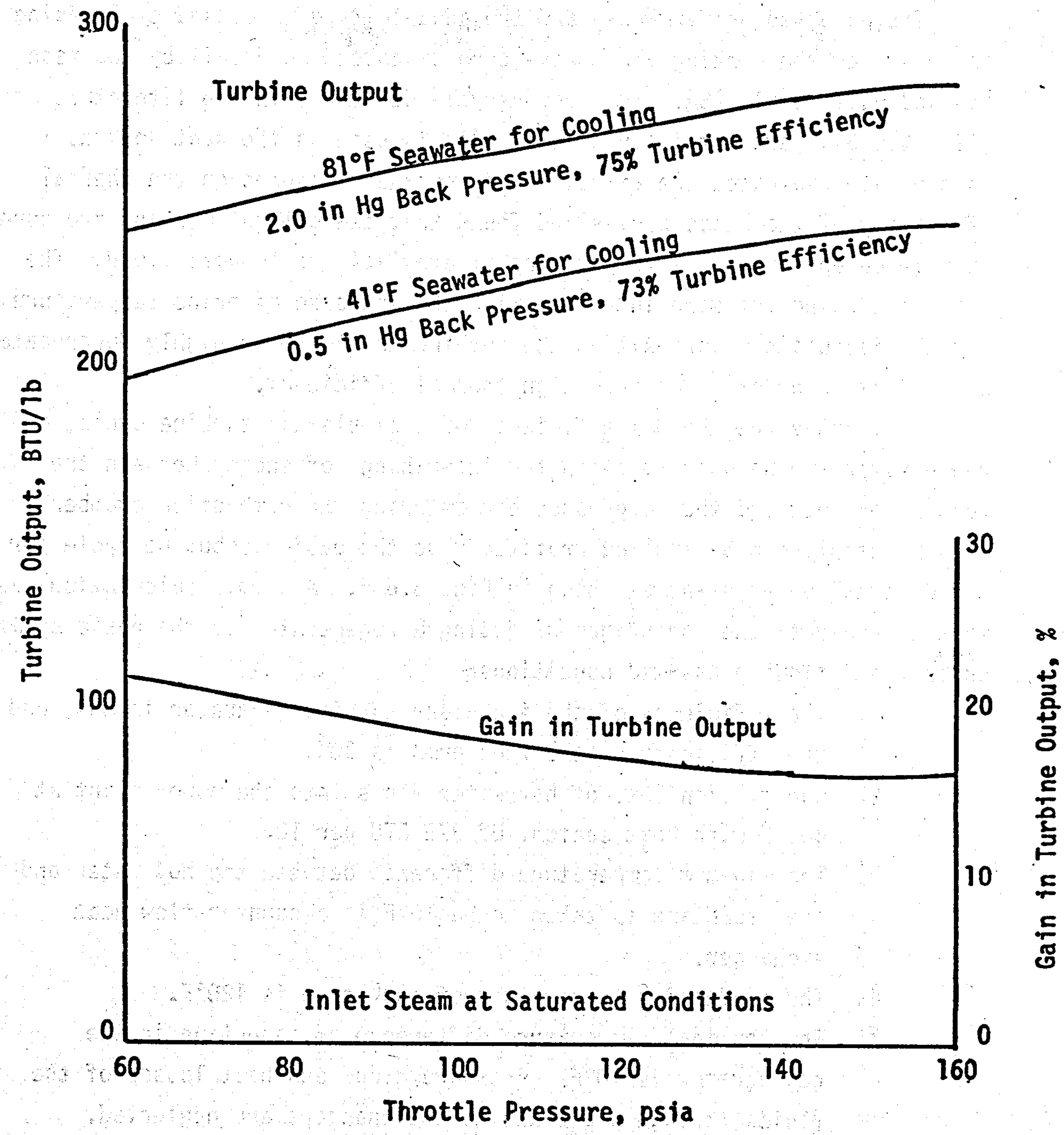


FIG. 3.6-4 EFFECT OF TEMPERATURE OF COOLING WATER ON TURBINE OUTPUT

II. Binary Fluid, Vapor Turbine Cycles

A. Simultaneous Fresh Water Production and Electrical Power Generation with a Regenerative Binary Fluid Cycle

The expected performances and the advantages of a closed cycle using isobutane as the working fluid have been discussed in detail by Anderson [1] and Holt et al. [8]. In a basic cycle described in the literature (Fig. 3.6-5), geothermal fluid from wells is used as the heat source. Holt et al. evaluated the effects of isobutane pressures on the thermal efficiency of the basic cycles and found that the optimal working pressure largely depends upon the temperature of available geothermal fluid. The optimal working pressure increases with the increase of brine temperature, and the isobutane vapor exiting the turbine has to be at highly superheated conditions in order to achieve high thermal efficiency.

To improve the thermal efficiency of a simple gas turbine cycle, a regenerator may be used to allow the interchange of energy between the turbine exhaust and the compressed air entering the combustion chamber. This principle can be applied profitably to the basic isobutane cycle for a geothermal power plant as shown in Fig. 3.6-6. A sample calculation was made to evaluate the advantages of adding a regenerator to the basic cycle under the following assumed conditions:

1. The efficiency of the isobutane turbine-generator is 85%, and the efficiency of the feed pump is 80%.
2. One million lbs. of hot water flows into the power plant at 400°F with heat content of 375 BTU per lb.
3. The minimum temperature difference between the hot water and the isobutane is taken to be 10°F in a counter-flow heat exchanger.
4. The condensing temperature of isobutane is 120°F.
5. The terminal temperature difference of isobutane in the regenerator is 10°F. Pressure drops and heat losses of the fluids through pipes and heat exchangers are neglected.

The mass flow rate of isobutane and the throttle temperature at various operating pressures are shown as follows:

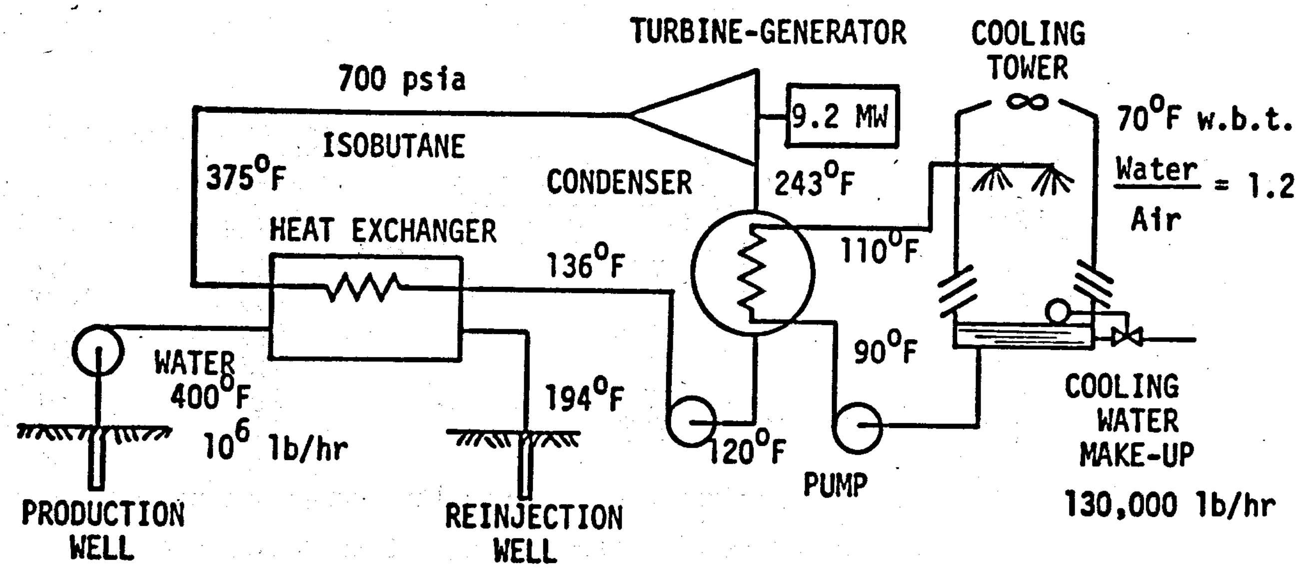


FIG. 3.6-5 BASIC ISOBUTANE CYCLE

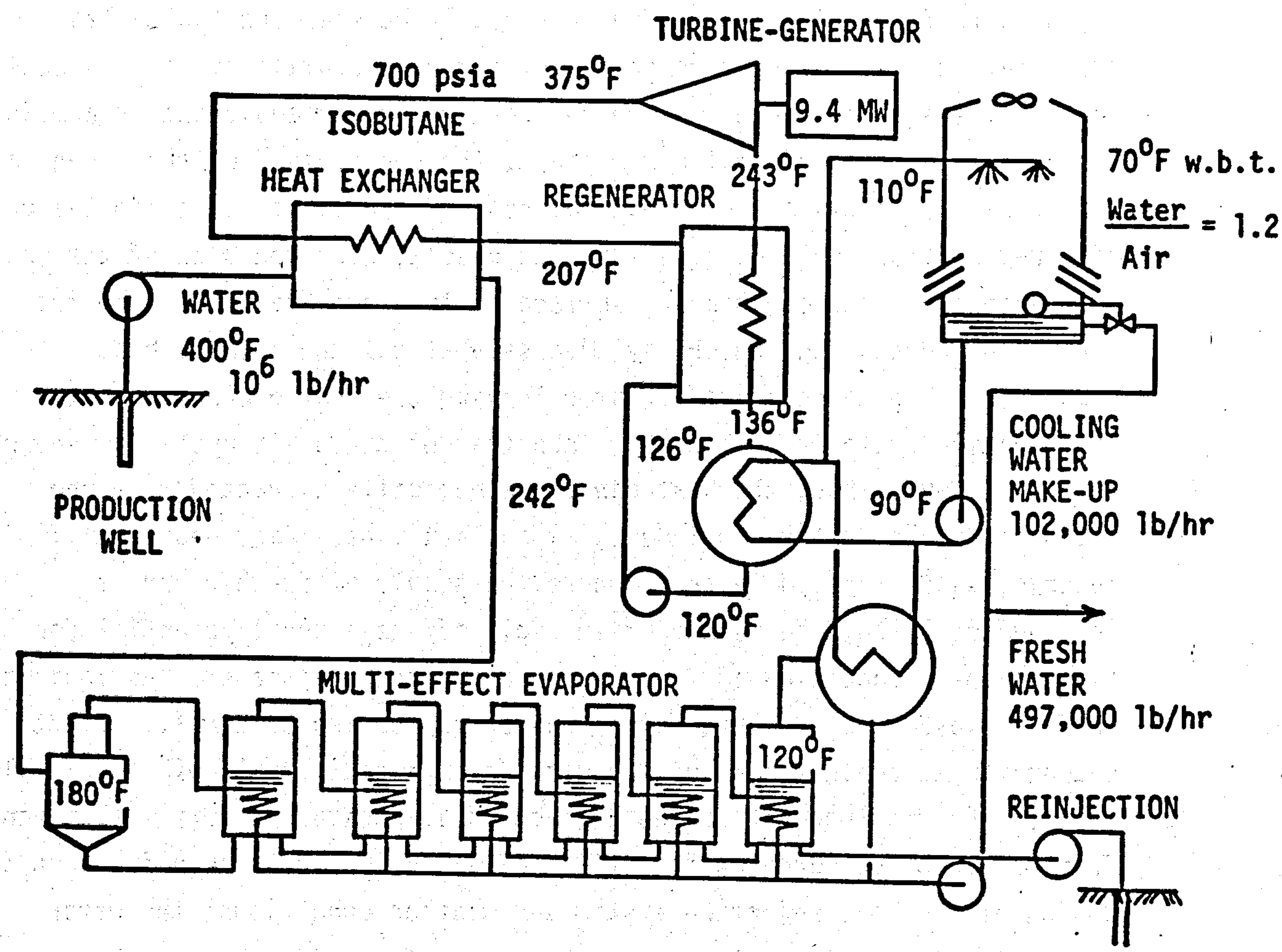


FIG. 3.6-6 REGENERATIVE VAPOR-TURBINE CYCLE AND MULTI-EFFECT EVAPORATOR

OPERATING PRESSURE, PSIA	THROTTLE TEMPERATURE, °F	MASS FLOW RATE, 10^3 LB/HR	
		Basic Cycle	Regenerative Cycle
900	380	1000	1015
800	375	998	1006
700	375	919	933
600	390	913	925
500	380	914	916
400	390	855	856

To illustrate the significance of the results, power production, heat rejection and temperature of water leaving the heat exchanger are plotted in Figs. 3.6-7, 3.6-8, and 3.6-9, respectively. The increases in power production by using a regenerator are insignificant; the maximum gain is in the order of 2% of the power produced by the basic cycle at the optimum operating pressure of 700 psia. However, the rates of heat which must be rejected to the environment differ noticeably between the two cycles. At 700 psia, the rate of heat rejection of the regenerative cycle is reduced to 72% of the basic cycle. Since the heat rejection equipment is a major cost item in the geothermal power plant, the application of the regenerator should significantly affect the total cost of the plant. The capital cost of a regenerator could be offset by the reduction of the size of the main heat exchanger, and the heating surface of the regenerator is free from corrosion and scaling, which may adversely affect the primary heat exchanger. The temperature of water leaving the heat exchanger of the regenerative cycle is much higher than that of the basic cycle, as shown in Fig. 3.6-9. Thus, the heat can be economically extracted from the discharge of hot water for industrial applications. Many geothermal reservoirs are located in areas where the supply of fresh water is inadequate; if so, the regenerative cycle offers a great potential for simultaneous production of fresh water and electrical power. As indicated in Fig. 3.6-6, the discharge of hot water may be led to a multi-effect evaporator to convert part of the water from a geothermal well to distilled water. The knowledge of designing such an evaporator is very well advanced from research sponsored by the Office of Saline Water. Depending upon the design of the heat rejection system and weather conditions, the water evaporated in cooling water is in the order of 102,000 lbs. per hour for a 10 MW regenerative isobutane plant operating at 700 psia. With a six-

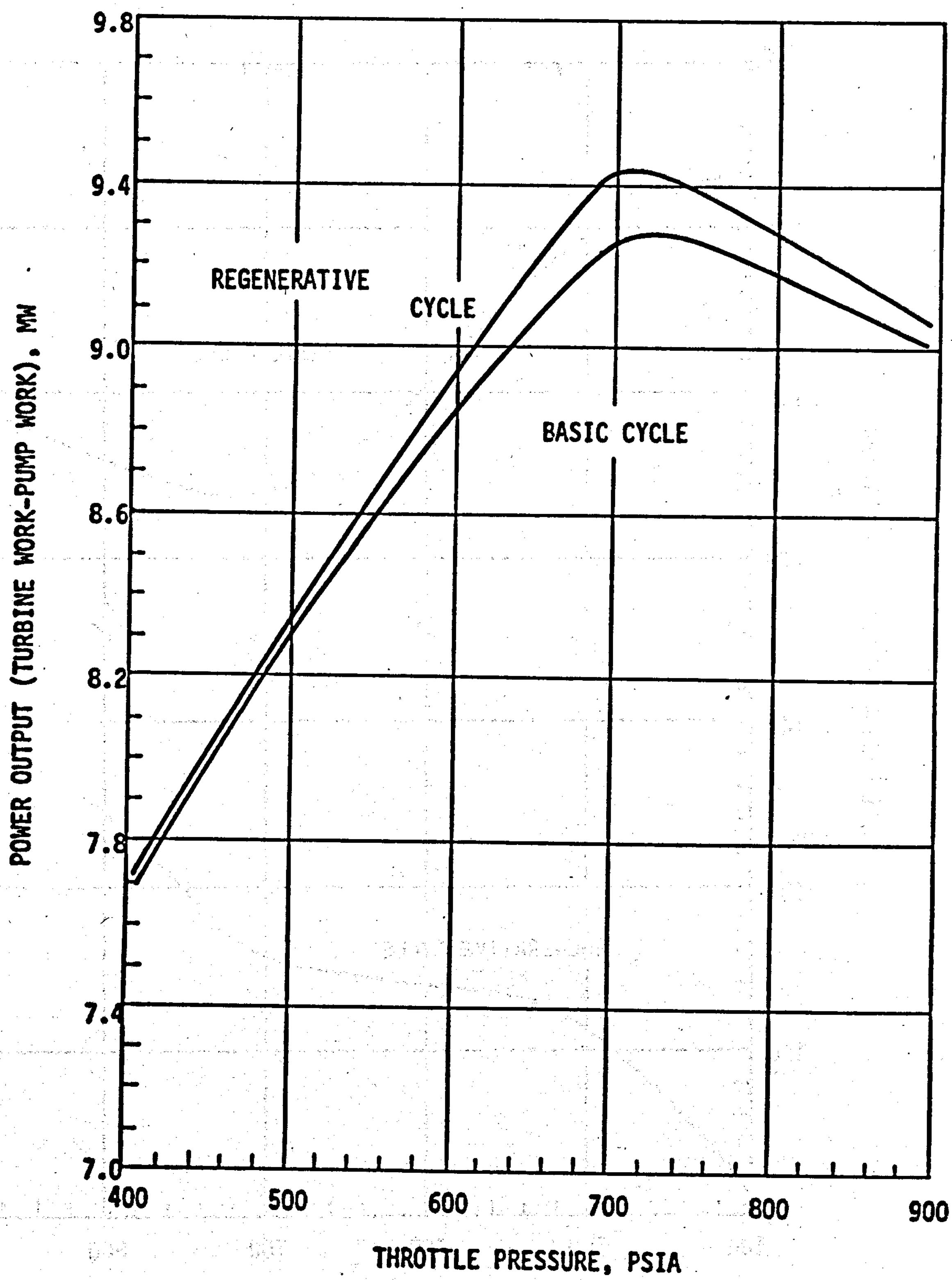


FIG. 3.6-7 POWER OUTPUT

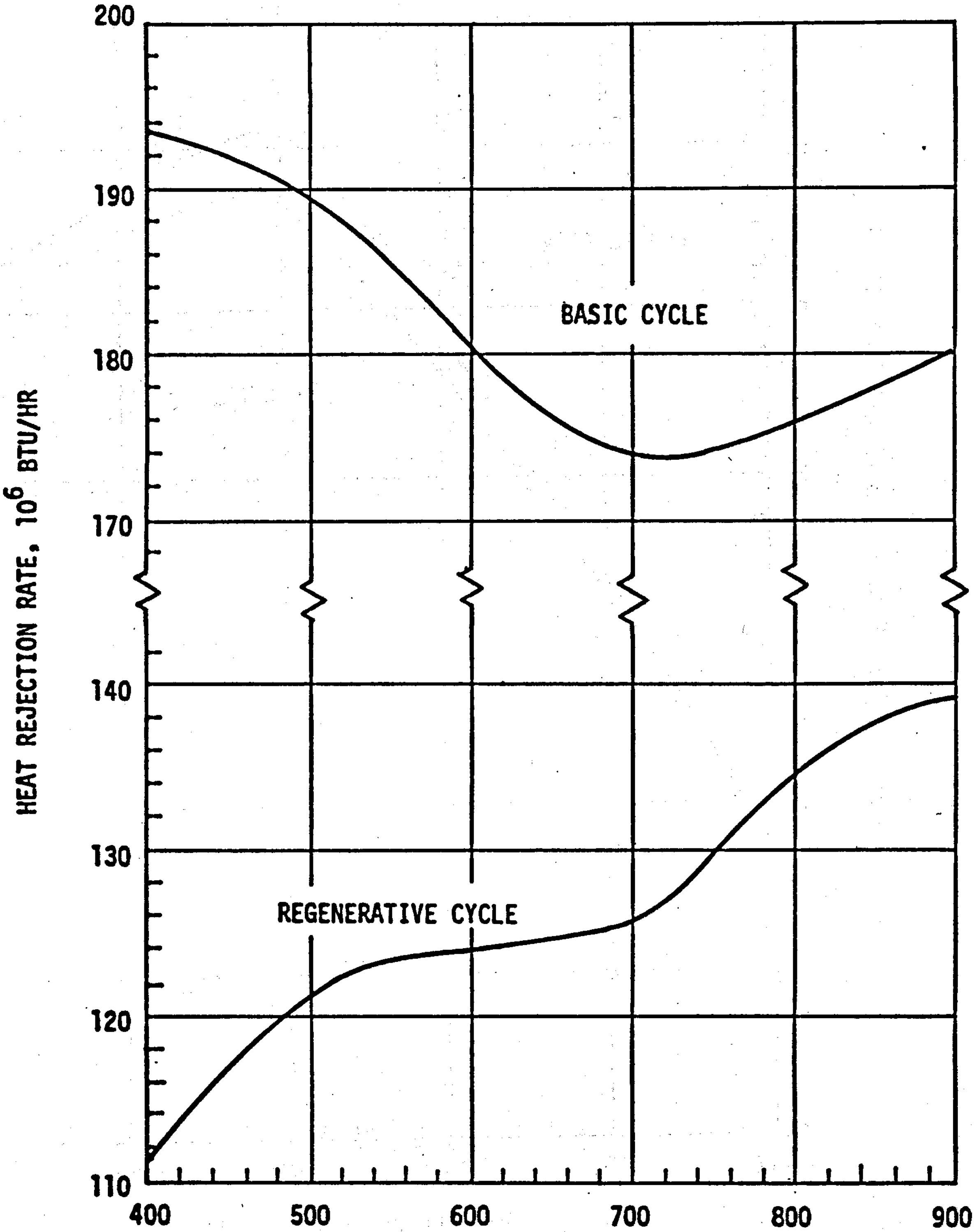


FIG. 3.6-8 HEAT REJECTION RATE

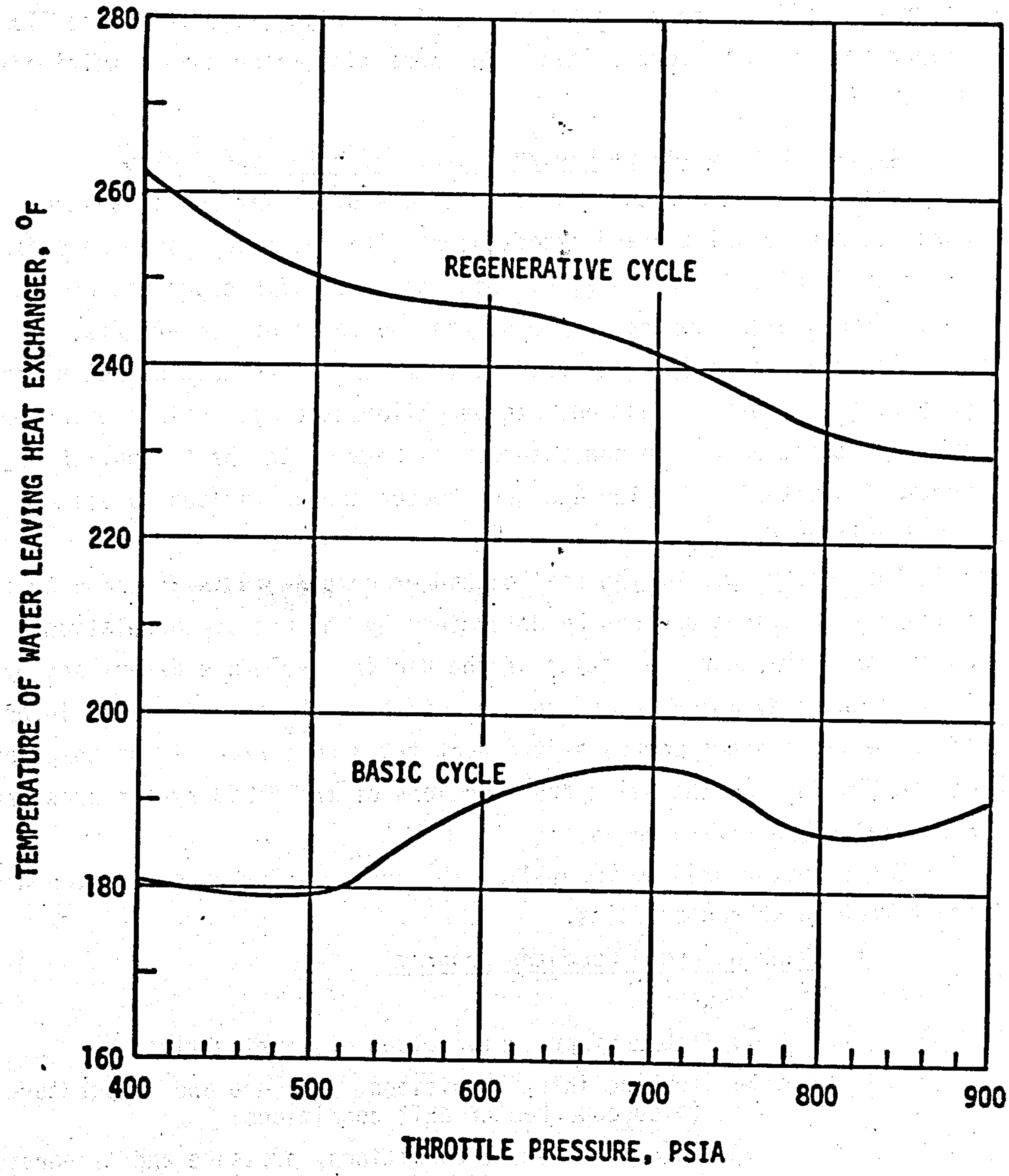


FIG. 3.6-9 TEMPERATURE OF WATER LEAVING THE HEAT EXCHANGER

effect evaporator, it is possible to export 497,000 lbs/hr of fresh water for the arrangement shown in Fig. 3.6-6. Should the seawater or brackish water be available from nearby sources for cooling, a multi-stage flashing evaporator might be more suitable for desalting water than a multi-effect evaporator.

B. Computer Simulation of Binary Fluid, Vapor Turbine Cycles

Computer programs to study the effects of variations of system parameters were written and prooftested. The specific system considered is shown in Fig. 3.6-5. A simple Rankine cycle with superheat and heat input from a high temperature brine was the focus of our efforts.

Since a task objective would be to minimize the cost of net power output, i.e., well production rate per kilowatt electrical power output, primary attention was on the interaction between the heat input through a vertical counterflow boiler and superheater and on various parameters of the Rankine cycle.

The performance of the heat exchanger components is governed by the transport equations and can be determined by the use of correlation equations. The characteristics of the Rankine cycle are determined by the laws of thermodynamics and properties of the working fluid. The interface of these two systems occurs at the heat transfer surfaces--the temperatures of the fluids on either side are functions of the fluid system pressure, and relative mass flow rates.

The computer programs modelling the system under consideration have the following characteristics:

1. Rankine Cycle Computer Program
   a. Input
      1) Table of property values of working fluid
      2) Turbine inlet conditions, pressure and temperature (also superheater exit conditions)
      3) Condenser outlet conditions, pressure and temperature
      4) Component efficiencies
      5) Required net power output
   b. Output
      1) Property values of working fluid at all points in the cycle
      2) Cycle efficiency

3) Mass flow rate for required power output
4) Heat rejection rate

2. Boiler and Superheater Computer Program

a. Input
1) Properties of working fluid
2) Properties of brine
3) Brine inlet temperature and velocity
4) Working fluid inlet temperature
5) Pinch point temperature difference
6) Tube material, diameter, spacing
7) Fouling factors

b. Output
1) Convective heat transfer coefficients on both sides
2) Number of tubes
3) Length of tubes
4) Total heat transfer rate across tube walls
5) Ratio of mass flow rates--brine to working fluid

The vertical configuration was first considered primarily because of the availability of suitable heat transfer equations for its design. Correlation equations for boiling heat transfer for a single tube are available for both vertical and horizontal tubes. However, the effect of tube spacing and number of tube rows on the average heat transfer coefficient for horizontal heat exchangers is not known. This was discussed by Palen et al. [10] but no quantitative results were presented.

In the design of these vertical heat exchangers, Chen's [3] correlation equation is used for the boiling section. The equation is not shown here because it is long and so many terms are included. Chen's correlation equation was used for the boiling section because 1) his experimental results seem to be accurate, 2) the equation applies to boiling heat transfer of fluid flowing in vertical tubes with quality ranging from 0 to 100%, and 3) his results agree very well with the experimental results of other investigators [5, 6, 11, 12]. For the nonboiling region, the equation recommended by Kays [9] is used.

Hot brine is circulated inside the tubes because of cleaning considerations. Use of finned tubes has not been considered because the inside and outside convective heat transfer coefficients are approximately the same magnitude and there is no need to artificially increase one or the other.

Currently no specific input data are available for the complete design of the heat exchanger equipment. The brine inlet temperature will be known only after a production well is drilled. The inside fouling factor will be determined by the brine temperature and the contents of minerals in the brine. Working fluid inlet temperature will be determined by whether a dry or wet cooling tower is going to be utilized. Because of this situation, a general computer program was written, and all the required terms are included in the program for the design of the heat exchanger. As soon as specific information becomes available, these data will be fed into the program, and the dimensions of the heat exchanger and other information such as mass flow rates, transfer coefficients, number of tubes required, etc., will be computed and printed. The design procedure used to determine specifications for the boiler-superheater is based on an overall heat balance of the heat exchanger, and as a first approximation, heat losses are neglected.

C. Selection of a Working Fluid

A short list of possible working fluids with a wide range of properties was initially studied for possible utilization in a simple Rankine cycle. The analysis of the power producing cycle was conducted for the following set of conditions:

Net power output	=	10 MW
Condenser outlet conditions	=	Saturated liquid at 100°F
Heat source	=	Liquid brine at temperature indicated
Turbine efficiency	=	85%
Pump efficiency	=	75%
Pinch point temperature difference	=	20°F
Pressure losses and heat losses neglected		

If the consumption of hot brine is to be the governing factor, Figs. 3.6-10 and 3.6-11, which show the required brine flow rate as a function of turbine inlet temperature, are essential. These figures are for brine temperatures of 325°F and 375°F. There are some interesting

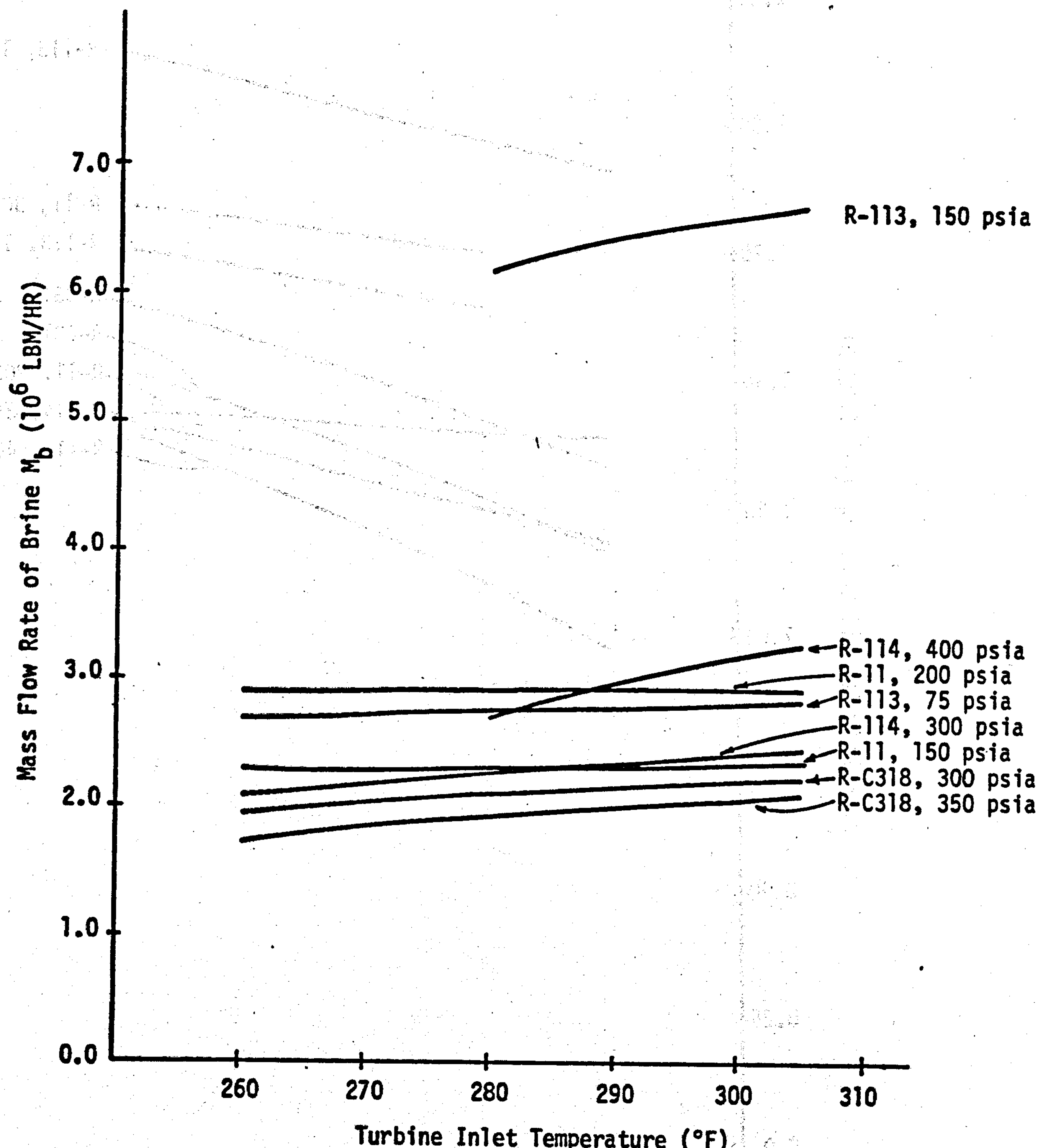


FIG. 3.6-10 BRINE FLOW RATES USING VARIOUS WORKING FLUIDS WITH BRINE AT 325°F

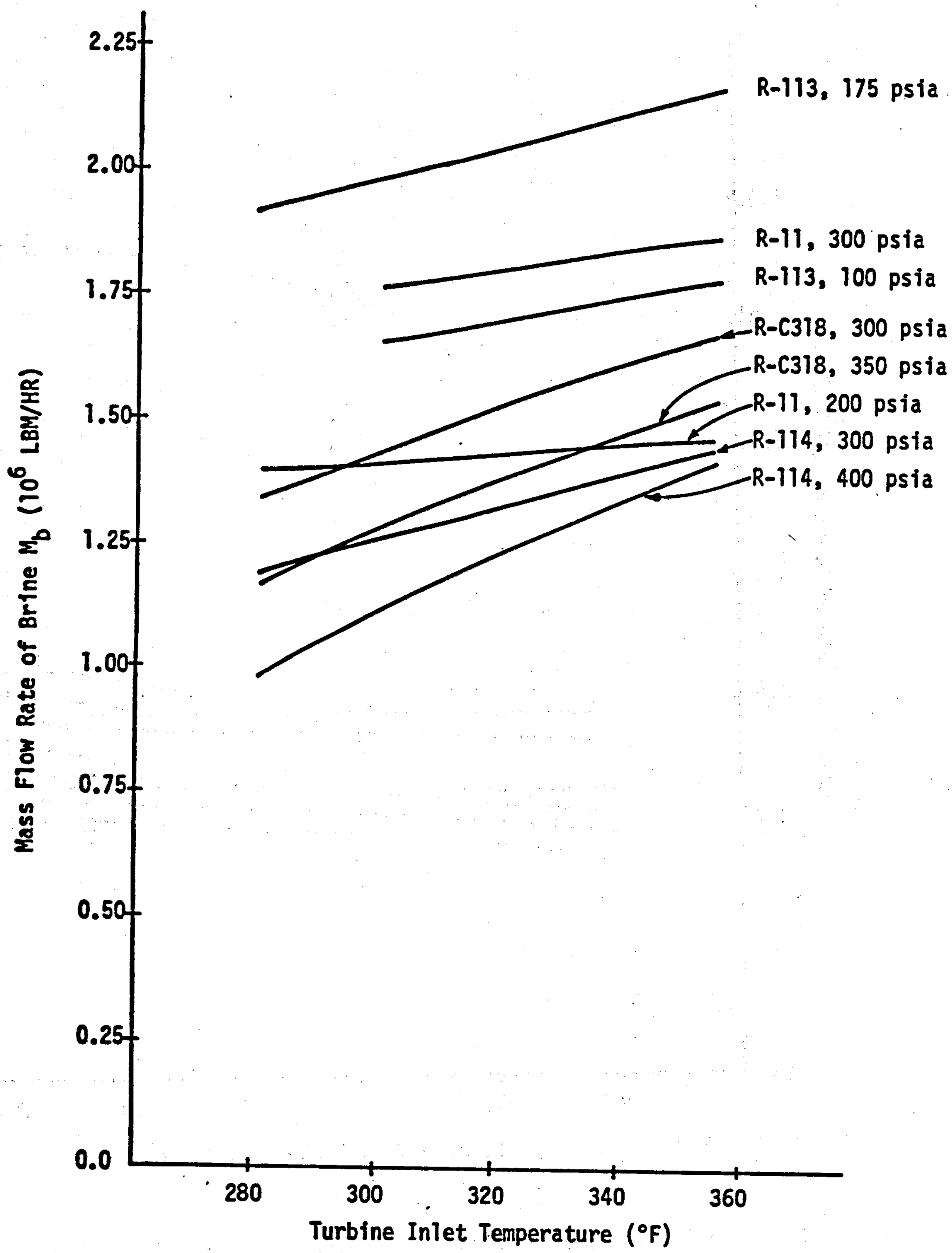


FIG. 3.6-11 BRINE FLOW RATES USING VARIOUS WORKING FLUIDS WITH BRINE AT 375°F

observations to be made from Figs. 3.6-10 and 3.6-11. In general, all curves have positive slopes, which indicates that as turbine inlet temperature is increased, a greater flow rate of brine is required. This trend becomes more pronounced as the brine temperature increases.

The effect of using system pressures greater than the critical pressure is shown in Figs. 3.6-12 and 3.6-13. Fig. 3.6-12 shows the effect of system pressure and turbine inlet temperature on the rate of consumption of the primary resource, brine. In general, higher system pressures lead to a reduced brine mass flow rate, although a minimum does appear to exist for a system pressure of 700 psia and turbine inlet temperature of 300°F (see Fig. 3.6-13).

D. Parametric Study of a Vertical Counterflow Heat Exchanger

The details of a parametric study of a vertical counterflow heat exchanger just concluded are detailed in Hawaii Geothermal Project Engineering Program Technical Report No. 5. However, a summary of some of the results is presented here. In this parametric study, one parameter was varied while all of the others were kept constant. In this fashion significant trends could be more easily detected.

The variation of total length required as a function of turbine inlet temperature is shown in Fig. 3.6-14. This was part of the standard design but is shown here to give an indication of the lengths to be expected in a heat exchanger of this type. It is interesting that a minimum for the required tube length exists at a temperature of approximately 290°F. In Fig. 3.6-15, the inside tube diameter is the parameter varied. As the diameter is decreased, the total tube length decreases but the number of tubes increases to compensate for the decrease in surface area per tube.

The following conclusions were drawn from the results of the subcritical pressure and supercritical pressure cases:

1. Systems using supercritical pressures will require significantly more tube material than systems employing subcritical pressures.
2. Pumping requirements will generally be less for supercritical pressure conditions than for subcritical pressure conditions.

Under subcritical pressure conditions, variations in turbine inlet temperature will produce the following effects:

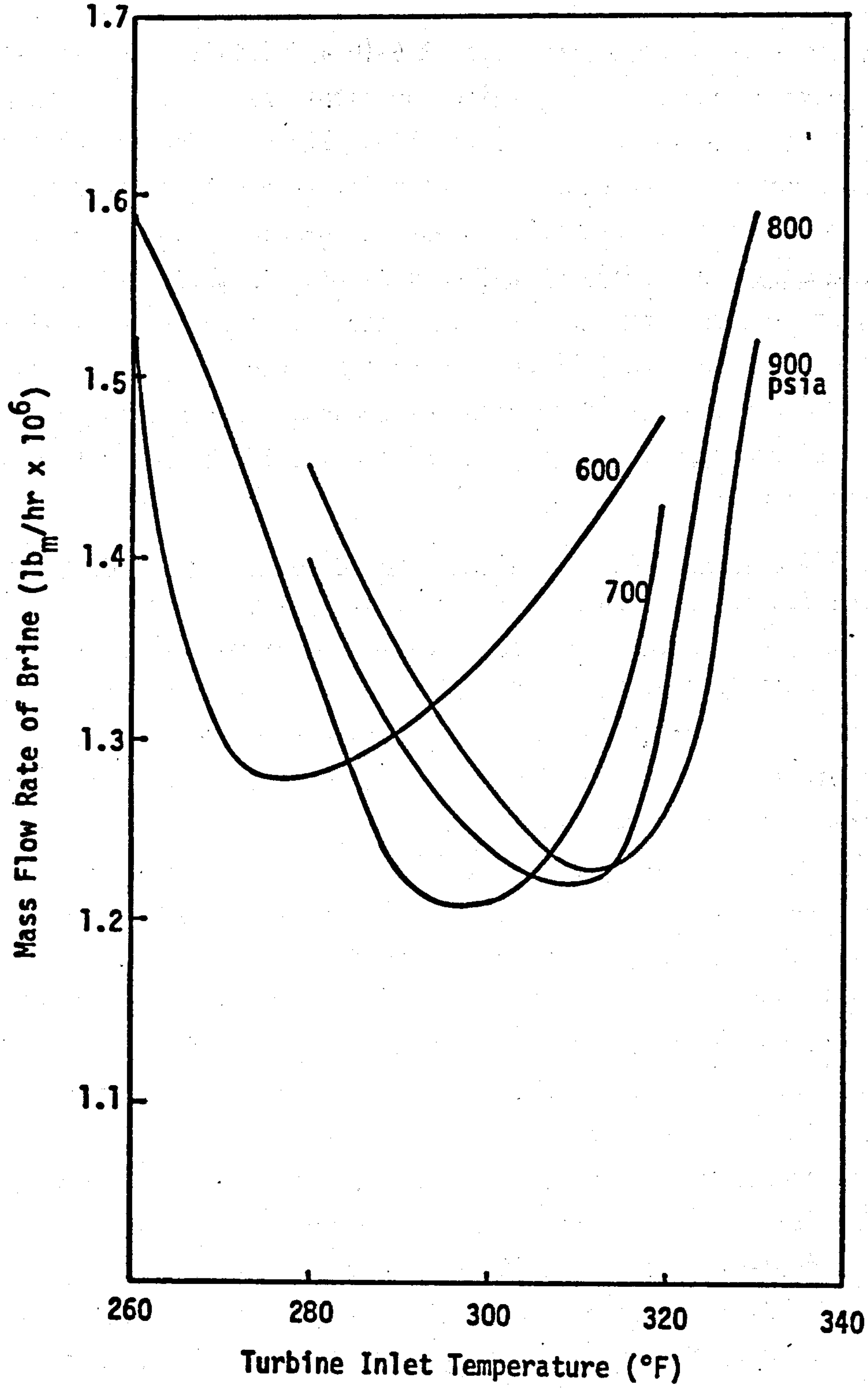


FIG. 3.6-12 BRINE FLOW RATE REQUIRED AS A FUNCTION OF TURBINE INLET TEMPERATURE FOR SUPERCRITICAL PRESSURES

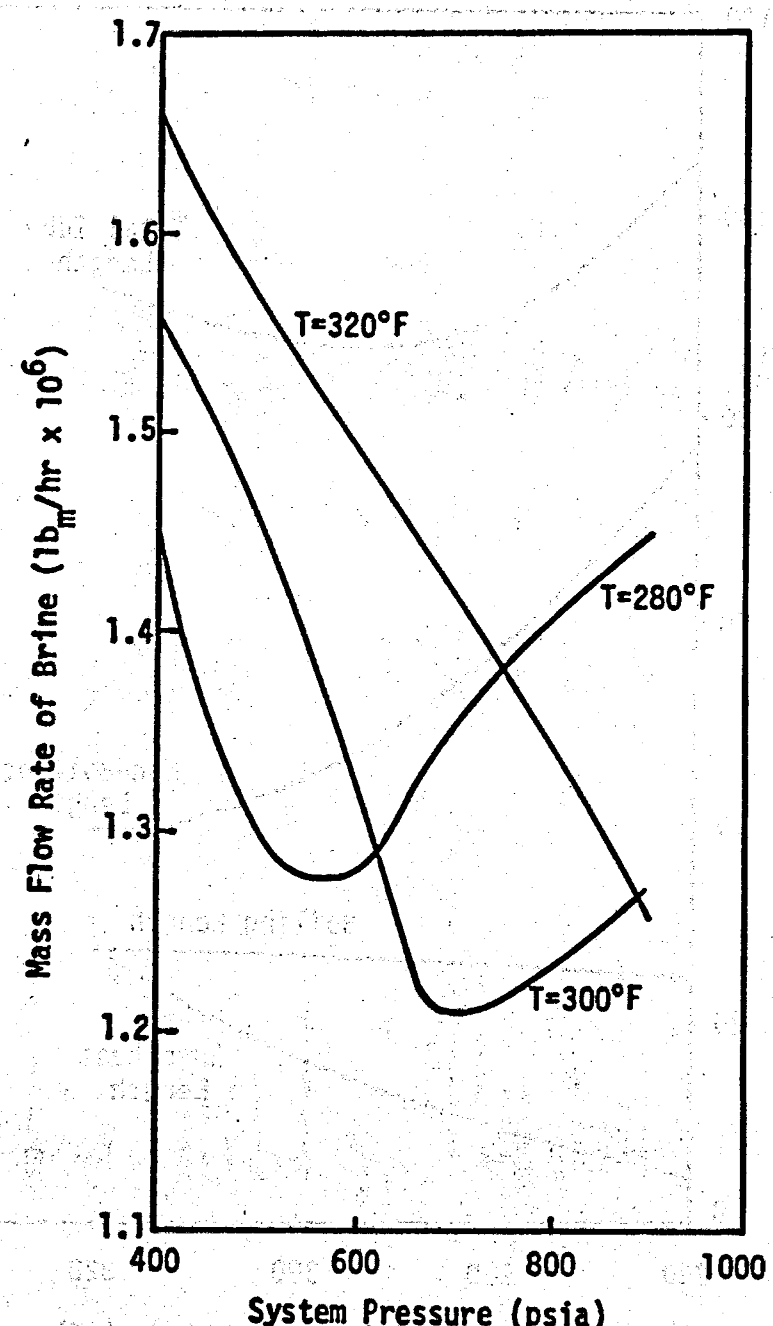


FIG. 3.6-13 BRINE FLOW RATE AS A FUNCTION OF SYSTEM PRESSURE

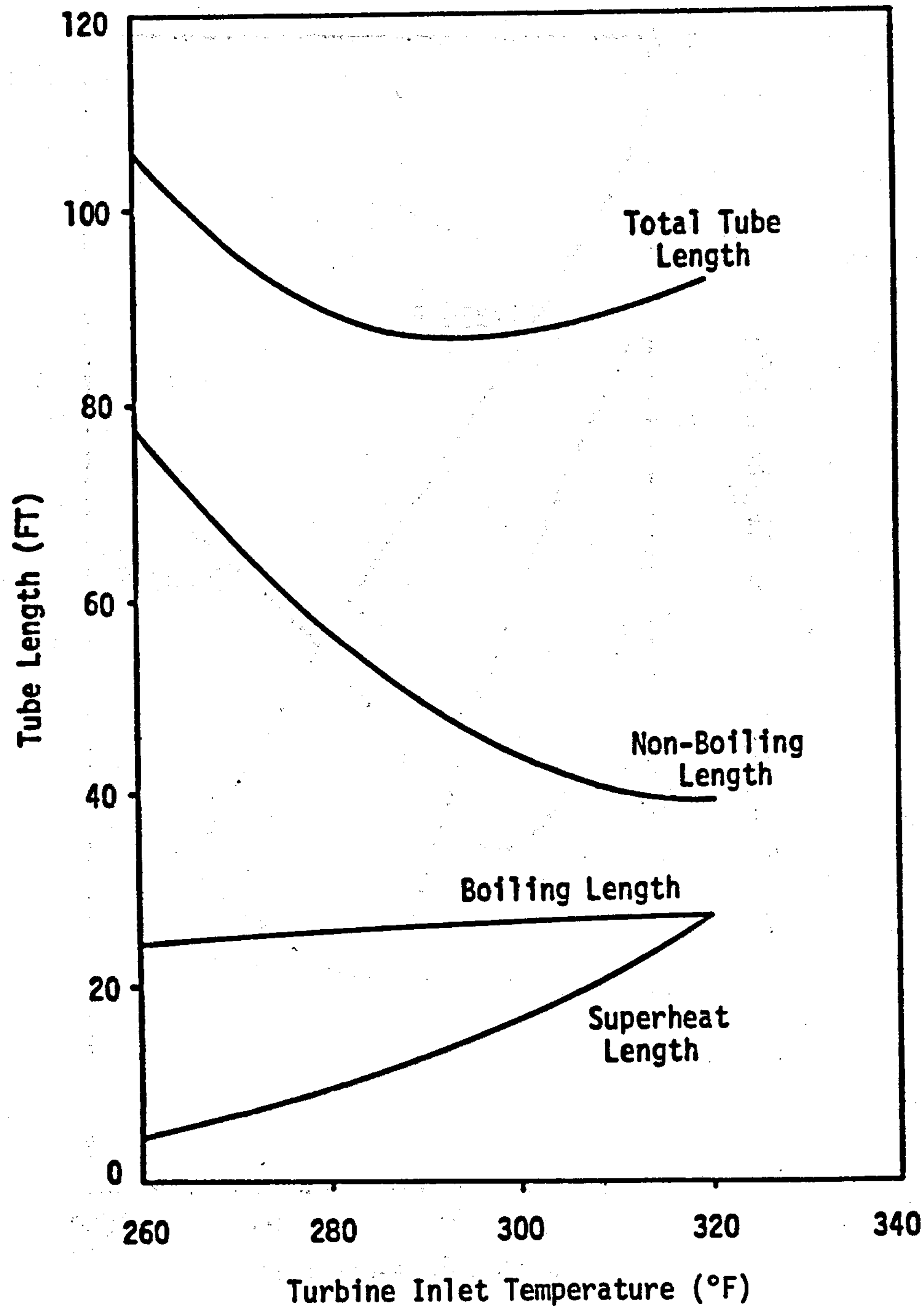


FIG. 3.6-14 THE EFFECT OF TURBINE INLET TEMPERATURE ON TUBE LENGTHS

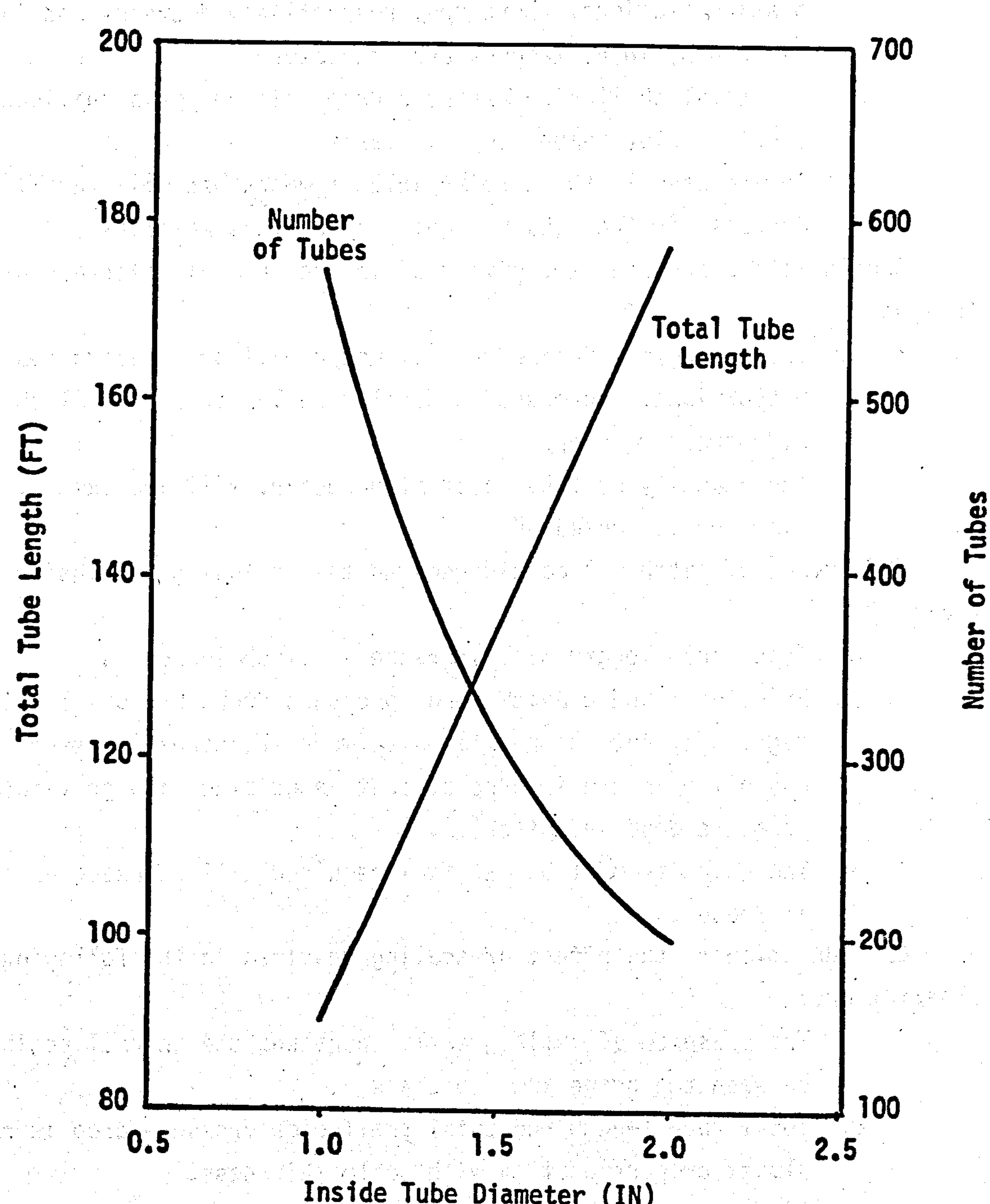


FIG. 3.6-15 THE EFFECT OF TUBE DIAMETER ON TUBE LENGTH AND NUMBER OF TUBES

1. Tube lengths change significantly in the nonboiling and superheating sections, where they respectively decrease and increase as turbine inlet temperature increases.
2. The total shell side pressure drop will change significantly as turbine inlet temperature is varied.
3. An increase in the turbine inlet temperature will result in a decrease in the required quantity of tube material.

Conclusions concerning the effect of inside tube diameter are as follows:

1. Increasing the inside tube diameter will bring about nearly proportional increases in total tube length and total shell side pressure drop.
2. The quantity of tube material necessary will increase if tube diameter is increased.

The effect of pitch was considered and the following conclusions were drawn:

1. Total tube length will increase as pitch increases.
2. Frictional and gravitational pressure drops are similar in magnitude, but the relations between frictional pressure drop and pitch is the inverse of that associated with gravitational pressure drop and pitch.
3. The quantity of tube material required will decrease as pitch increases.

Consideration of the effect of scaling resulted in the following observations:

1. The presence of scale greatly increases the thermal resistance between the brine and isobutane.
2. Total tube length and total shell side pressure drop increase almost proportionately with scale thickness.
3. Since tube number is unaffected by the presence of scale, required tube material quantity is proportional to tube length.

Consideration of the effect of pinch point temperature difference led to the following conclusions:

1. Brine mass flow rate increases as the pinch point temperature difference increases.

2. An inverse relationship exists with pinch point temperature difference for both total tube length and total shell pressure drop.
3. Since tube number is not a function of pinch point temperature difference, tube material quantity is proportional to tube length, and therefore has an inverse relationship with pinch point temperature difference.

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HAWAII GEOTHERMAL PROJECT

ENVIRONMENTAL-SOCIOECONOMIC PROGRAM

Robert M. Kamins

SUMMARY

The objectives of the Socioeconomic Program are: (1) identifying the major impacts of geothermal development on the economy and society of Hawaii; (2) identifying potential legal, administrative and economic impediments to the development of geothermal resources in Hawaii; (3) identifying alternative public policies toward geothermal development in Hawaii (as in defining ownership and setting regulation of the resource, in tax policies, subsidies, land use regulation); (4) ascertaining potential impacts of geothermal development on the environment, and establishing benchmarks prior to development by which to measure that impact. As concurrent functions, the Program: (1) is working with legal officers of the State of Hawaii to obtain a right-of-entry permit for the drilling on the Island of Hawaii planned by the Project in 1975; (2) maintains liaison with agencies of the State and County governments particularly concerned with the Project, namely the Office of the Attorney General, the State Department of Land & Natural Resources and the Department of Planning & Economic Development and the Hawaii County Department of Research & Development.

Work has progressed on the following three tasks which were funded among those originally proposed:

Task 4.1 Environmental
Task 4.2 Legal and Regulatory
Task 4.4 Economics

Task 4.1
Environmental

A. Ground Water Analysis

The geographical scope of the environmental task -- to ascertain potential impacts of geothermal development on the environment and to establish benchmarks by which to measure that impact -- is limited by the drilling program, which provides the first impact. After a decision was made to confine exploratory drilling to a site in the Puna District, it was possible to make an initial appraisal of the environmental factors likely to be significant and concentrate on them.

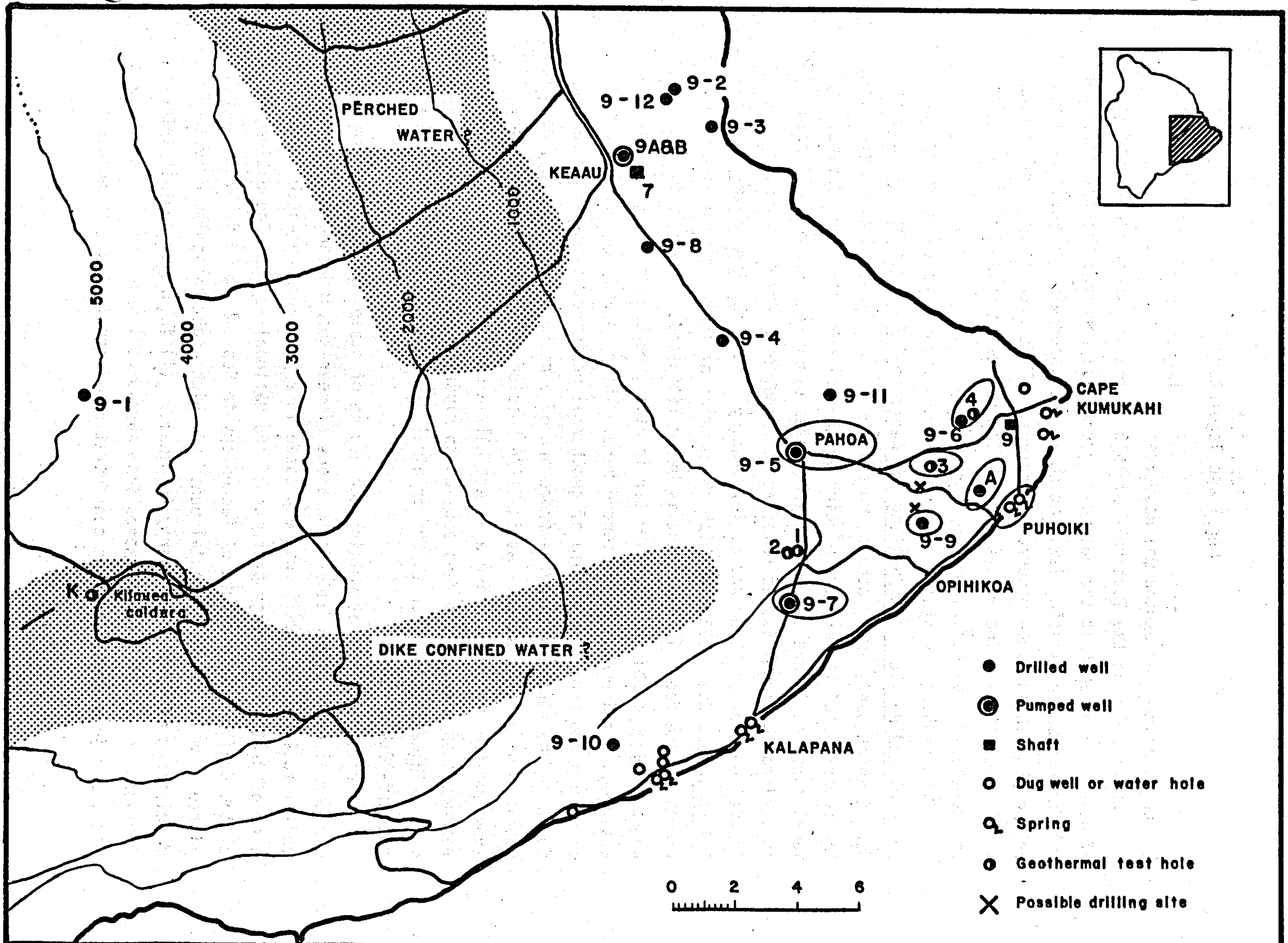
Since the Puna area selected for the drilling site is only sparcely populated and in fact largely consists of lava fields overgrown with staghorn fern, grasses, flowering ginger, wild orchids, and occasional trees -- none, by initial appraisal, of rare or endangered species, and since only a limited amount of land disturbance will be made by the drilling -- the concentration of environmental concern is on the possible impact on the ground water supply. While the supply of ground water in this section of Puna presently developed is limited, and what is there is frequently highly saline, it is important to ensure that the Ghyben-Herzberg lens underlying the area is not polluted by the drilling.

To establish what the water conditions are, prior to drilling, the director of the University's Water Resources Research Center and an associate are at this writing testing the water of six wells and two springs within a five-mile radius of the proposed drill site. (The water sources to be analyzed are circled on the map which follows this page.) The deep-well sampling procedures used will yield an analysis of salinity and other chemical characteristics, pH, temperature, selected nutrients and coliform bacteria. As drilling proceeds, the same water sources will be checked to determine what changes, if any, occur at these wells and springs.

B. Checklist of Decision Points, Including Environmental Controls

Looking beyond the exploratory well to the environmental impact of a possible geothermal field, in Puna or elsewhere, we are working with the project "State Management of Geothermal Energy in Hawaii" to ascertain the key decision points which would occur -- from site selection and preparation of an environmental impact statement to power production and utility regulation -- as geothermal development progresses. The checklist now in first draft will locate the points at which the federal government, State of Hawaii and County of Hawaii will be able to influence the course of development, and its pace, by the administrative, executive and legislative actions they take, either on their own initiative or in response to initiatives of private enterprise.

In the present situation of preparing for exploratory drilling, we are keeping the state Office of Environment Quality Control, Department of Planning and Economic Development, Office of the Attorney General and Department of Land and Natural Resources apprised of the project and its drilling program.



Approximate location of water sources in the Puna area, island of Hawaii.

Task 4.2
Legal and Regulatory

A. Legal Regime for Geothermal Resources

Analysis during the last half of 1973 of the statutory and common law of Hawaii revealed that the potential geothermal resources of the state were not defined under existing law, and so it was uncertain who would have property rights in any such resource discovered. That uncertainty would remain until a definitive finding was made by the courts or unless a legal regime for geothermal was established by statute.

This finding was stated in a preliminary report, dated February 1974, on Legal and Public Policy Setting for Geothermal Resource Development in Hawaii which went, among others, to members of the Hawaii State Legislature. The report noted the manner in which geothermal resources were defined for legal purposes in the twelve western states other than Hawaii. It also summarized the legal issues relating to resource ownership raised by the federal Geothermal Steam Act of 1970 and by a case (United States v. Union Oil Co., N.C. Cal. 1973) in which the portion of that act reserving mineral rights to the federal government is being litigated. Court decisions concerning ownership of ground water in Hawaii were examined as the closest analogous legal problem experienced here. The pros and cons of private ownership and public ownership of geothermal resources in Hawaii were set forth in the report within the framework of a policy of encouraging resource development in this state. At its 1974 session, the Hawaii Legislature subsequently enacted a measure -- Act 241 -- which defined geothermal resources as mineral and thus subject to mineral reservations by the government of Hawaii going back to the original division of lands by the King in the mid-19th century.

A rationale for determining the degree of state participation in geothermal development under conditions of near-total dependence on imported fossil fuel, as in Hawaii, was expressed in a paper presented to the conference of geothermal energy projects of the National Science Foundation, held at the California Institute of Technology in September, 1974. The paper listed some of the major social benefits which might be achieved by the development of geothermal energy in Hawaii: (1) insurance against interruptions of fossil fuel shipments from abroad; (2) provision of an economic base, and jobs, away from the concentration of population in Honolulu;

(3) substitution of less-polluting fuels for oil. It noted that these benefits may not be fully reflected in market value calculations which private enterprise might make in determining the feasibility of investment in geothermal development and stated that optimization of such development might require support by the state.

B. Regulation of Geothermal Production

Since Hawaii is without experience in regulating the production of either oil or minerals, the project requested David N. Anderson, Geothermal Officer of the California Department of Conservation, to advise it on the manner and scope of regulations which the State of Hawaii would require in the event that geothermal resources were used to generate electricity or for other commercial purposes. Mr. Anderson drafted a set of regulations, based on the experience of California, but with Hawaii's different circumstances in mind.

The draft regulations cover the following general areas and potential problems:

1. Places regulatory authority over geothermal development with the State Department of Land and Natural Resources, with responsibility for encouraging the "greatest ultimate recovery of geothermal resources", subject to safe and beneficial methods of production.

2. Establishes a system of control over drilling to ensure safety and conservation, utilizing applications and bonds -- generally similar to California's system -- with appropriate fees.

3. Prescribes minimal conditions for well spacing (including directional drilling), requirements for casing (with wide discretion to the Department), blowout-prevention gear and other elements of production facilities.

4. Requires logging of production wells and the keeping of specified records of drilling and production.

5. Provides for periodic surveillance of equipment and lines to check on corrosion and other conditions prejudicial to life, health and property at the geothermal field.

6. Sets conditions for reinjection wells and other modes of disposing of waste water.

7. Proposes environmental safeguards for geothermal development beyond the preliminary exploration stage.

8. Provides for appeals from administrative actions under the proposed regulations.

The draft was made available to the project on "State Management of Geothermal Energy in Hawaii", which is administered in the Department of Planning and Economic Development, as well as to the Department of Land and Natural Resources.

C. Right-of-entry for Drilling

In the last quarter of 1974, the drilling program within the Hawaii Geothermal Project identified in the Puna district of the Island of Hawaii the site it proposes for exploratory drilling. Once the location was made, the Socioeconomic Program served to identify the owners of the land around the target area, to ascertain if the patents of title to the land contained a reservation of minerals (and hence of geothermal resources under the 1974 legislation referred to above) -- they do -- and to contact the owners of the two large parcels in the immediate vicinity of the site proposed for drilling to determine if they would be agreeable to permitting entry on their lands for this purpose.

We then obtained the services of a University attorney to draft a right-of-entry permit agreement for the property closest to ground zero in the target area identified by the drilling program, and arranged to have the draft examined by the Office of the Attorney General for legal correctness. At this writing the document is being considered by one corporate landowner, following conversations with their attorney. The availability of an alternative site is also being checked out, should the first landowner not agree to drilling on its property.

Task 4.4
Economics

A. Data Gathering: Hawaii Energy Situation

Data has been gathered showing the energy consumed in the State of Hawaii in 1962 and 1972, by source and use, showing that almost 100 per cent of all energy used in commerce and industry in Hawaii derives from petroleum (against approximately 46% for the entire U.S. in 1972).

Other sets of data, provided by the electric companies operating on each major island within the state, show generation capacity and energy sales back to 1960 and projected to 1990. Source data for the Island of Hawaii shows the amount provided by hydroelectric generation plus the quantities of electricity purchased by the Hawaii Electric Light Company from sugar plantations derived from the burning of bagasse at the mill. The latter component of electrical energy supply on the Island of Hawaii will comprise about 3 per cent of the island total in 1975, by far the largest contributor of commercial energy other than petroleum in the state energy network.

B. Data Gathering: Geothermal Production Elsewhere

An inventory of geothermal production centers around the world is being developed by recording significant data -- on record of flow, number and depth of wells, well life, costs and income where available, by-product utilization, etc. -- noted in the large and growing literature on geothermal resource utilization. Thus far, there are 65 pages in the inventory, each relating to one production center.

C. Annotated Bibliography

From the literature searched for inventory data, plus others read, an annotated bibliography on geothermal energy economics has been prepared. To this date two volumes have been reproduced and distributed to interested persons: Volume I, dated February 1974, includes 192 items with 32 annotations; Volume II, dated September 1974, has 198 items, with 15 annotations. In most instances the "annotations" are lengthy, amounting to summaries.

D. Non-electrical Uses of Geothermal Resources

Data is being gathered on the use of geothermal resources for purposes other than generating electricity, such as space heating and cooling by utilization of the geothermal water directly; industrial uses of geothermal waters, as in wood pulp and paper processing; agricultural uses; geothermal waters in spas. The inventory and annotated bibliographies are useful in gathering this data, as well as materials obtained from the conference on this subject held at the Oregon Institute of Technology in Klamath Falls, Oregon, in October 1974, attended by a researcher in this program. This data will be especially valuable if a geothermal resource is located in Hawaii which is large in quantity but too low in heat to serve as an economic source of electric power generation.

E. Input-output Analysis of New Energy Source Impact

To ascertain the possible impact of new energy supplies on the economy of Hawaii County, should a viable input for the generation of electricity be found on the Big Island, the industries now in existence there are being analyzed to determine which are the most energy, or rather electricity, intensive. An industry ranking high on this list is a likely candidate for possible utilization of significant amounts of new energy.

Since production activities use energy either by direct purchase or by purchasing inputs which incorporate some amount of energy, the secondary, tertiary and subsequent impacts of any single activity are relevant to this question. Even though a given industry uses relatively modest amounts of energy directly, it may, through its raw materials and intermediate inputs, be a significant contributor to aggregate energy demand in the region.

Input-output analysis emphasizes the structural interdependence of an economy and in the process accounts for such indirect effects as just mentioned. Total sales of any given industry are classified according to where its sales go: to any one of the other producing sectors of the local economy, or to final purchasers -- consumers, government, foreign countries or to net capital formation. Since each sale to another producing sector is also a purchase, the tables also show the distribution of each sector's purchases from other producing sectors, and its expenditures for "primary" inputs -- labor and capital -- and for imports. We thus have distributions of both sales and purchases -- outputs and inputs. Treating this system of interconnections as a set of linear equations allows derivation of various summary measures of not only the direct impact of a change in demand for any one sector's product, but the secondary and subsequent impacts as well. The latter impacts are measured not only by the absolute values of estimated energy use, but through multipliers. One set of multipliers compares direct-to-total energy use in each sector; another compares value added (income) generated per unit of energy use.

The Hawaii County I/O Model

The recently completed input-output model for the County of Hawaii is an adaptation of a statewide model, which in turn is derived from the national I/O tables. The many differences in interindustry trade patterns between the state and national economies were accounted for in the state study by surveying 22 local industries and adjusting the appropriate coefficients from survey results. The most important of these adjustments are for the two sugar sectors (growing and milling), pineapple growing, canning, bakery products, textiles and apparel, petroleum and fabricated metal products. Similar though less extensive surveys were undertaken to adapt the state model to the county level. The published state model is based on 1967 data. A revision (as yet unpublished) provides a 1970 edition. The Hawaii County model uses the later edition for its origin.

The state model deletes all but 54 of more than 400 sectors defined in the most extensive of the national I/O tables. While in principle the same 54 sectors remain in the Hawaii County version, seven* have zero output in the county and thus fall out before inverting and solving the model. Thus 47 interindustry sectors enter the county analysis. Sector definitions are slightly altered, however, in three agricultural industries: "other field crops" are included with sugar in sector 1; fruits, nuts and vegetables enter into sector 2 (which retains the "pineapple" label although no pineapple is grown on the Big Island); and sector 3 incorporates canned sea foods with fruits and vegetables.

Data; Computation

Electrical energy usage is brought into the analysis through attaching electricity demand coefficients to the matrix of direct + indirect energy requirements. Each coefficient represents the number of kwh used by a given sector, per dollar of that sector's output. Industry-by-industry data on energy usage consistent with published estimates of output is not readily available, but three data sources have been exploited for the tentative figures used in this report:

1. With the cooperation of Hawaiian Electric Company and Hawaii Electric Light Company, electricity use figures for hotels and possibly construction are being developed.

2. A study by John W. Wilson (American Economic Association Meeting 1973) presenting estimates constructed from the Census of Manufacturers for manufacturing sectors only.

3. The 1967 edition of the 367-sector national I/O table. One row of this table is devoted exclusively to electric utilities, showing the value of electricity purchased by each of the 367 sectors per dollar output. Aggregating these figures to conform with the sector definitions of the state

*Paper and paper products (#19); petroleum refining (#22); rubber, misc. plastic and leather products (#23); primary metals (#25); electrical machinery, equipment and supply (#28); transport equipment (#29); and instruments (#30).

and county I/O models, and applying Hawaii electricity prices, yields an estimate -- admittedly rough -- of the physical quantity of energy used per dollar output for each sector.

The third source provides tentative estimates for all sectors of our model until the other figures are completed.

Computer programming was much simplified by the existence of a set of routines designed to produce all the standard input-output results plus figures for water analogous to those we are after here for electricity. With minor adaptations, these routines produce the desired electricity interactions table as well as the multipliers.

Energy-related results of the input-output model solution are contained in three tables of the computer printout. One table lists the requirement of each industry for electricity via its purchases from other industries per dollar of output of the purchasing industry's product, incorporating both direct and indirect demand. The sum of these elements is the total requirement, direct and indirect, for electricity per dollar of output.

A second table displays three electric energy coefficients. The first coefficient shows a given sector's direct requirement for electricity per dollar of output. The direct + indirect requirements coefficient is next. The ratio of these two coefficients appears in the third column. The electricity use multiplier can be taken as a measure of the degree of interrelatedness, with respect to energy consumption, of the given industry with the rest of the economy. If one were to seek to identify those industries which would be stimulated by more abundant energy supplies, one might concentrate on those with high multipliers.

The third table shows measures of the beneficial economic impacts of a given amount of energy used in each sector: data indicates the amount of "value added" or income per unit electricity purchased by each industry, showing indirect energy use (by suppliers) as well as that used directly by each sector.

Although not derived in the current version of computer programs, measures relating energy use to employment, rather than income, can also be devised.

Further application

From the electrical energy coefficients, and electricity-use multipliers derived from them, we will be able to identify existing industries in Hawaii

County which would be particularly stimulated by the addition of new electric energy supplies.

To estimate the degree of such stimulation, assumptions will have to be made as to how the price of electricity may be affected by a new energy source and consideration made of the increase, at the margin, of production in energy-intensive sectors which would be stimulated. Further, research would be needed into industries identified in the Hawaii State model or in national input-output models as having particularly high energy coefficients, and which are potential industries for the Island of Hawaii though not yet developed. Two examples are wood products -- since the island has a capability for lumber and wood products frequently noted in economic surveys -- and refinement of metals from the manganese nodules reported as abounding on the ocean bottom off Hawaii.

Technical Outline for Input-Output Analysis

Technically speaking, the procedure is as follows. The basic input-output relation for "selling" sector i is

$$\sum_{j=1}^{n} a_{ij}X_j + f_i = X_i \qquad i = 1, 2, \ldots, n \qquad (1)$$

where a_{ij} is the direct coefficient for purchases by industry j from i; f_i is final demand for sector i and X_i is total output. Substituting matrices as usual and solving for total output yields

$$X = (I - A)^{-1}f \qquad (2)$$

For ease of exposition, the Leontief inverse matrix will be denoted $B = (I - A)^{-1}$ with elements b_{ij} expressing direct + indirect requirements for output of sector i per dollar increase in deliveries by sector j to final demand.

If we now multiply each b_{ij} by an energy use coefficient, say e_i, denominated in, say, kwh/\$ j, we have the direct + indirect requirement for energy used by sector j via sector i in delivering one dollar output j to final demand. To generalize, if I is an identity matrix and e a column vector of energy use coefficients (electrical energy, in particular), the matrix

$$Ie(I - A)^{-1} \qquad (3)$$

shows direct + indirect energy requirements of each purchasing industry via each selling industry, and

$$\sum_{i=1}^{n} e_i b_{ij} \tag{4}$$

represents the total energy required by the j^{th} industry, directly and indirectly, to deliver one additional dollar of output j to final demand.

Attaching units of measure to (4) is instructive. e_i is in kwh (or some such quantity measure) energy per dollar of sector i output; b_{ij} is purchases directly and indirectly, of commodity i for use in producing commodity j. Thus

$$e_i b_{ij} = \frac{\text{kwh}}{\$\ i} \cdot \frac{\$\ i}{\$\ j} = \frac{\text{kwh}}{\$\ j} \quad \text{via sector i.}$$

Consider for example the sugar growing sector, denoted by j = 1. Expression (3) would yield*

$$e_1 b_{11} = \frac{\text{kwh}}{\$\ \text{sugar}} \cdot \frac{\$\ \text{sugar}}{\$\ \text{sugar}} = \frac{\text{kwh}}{\$\ \text{sugar}}$$

$$e_2 b_{21} = \frac{\text{kwh}}{\$\ \text{pineapple}} \cdot \frac{\$\ \text{pineapple}}{\$\ \text{sugar}} = \frac{\text{kwh}}{\$\ \text{sugar}}$$

$$\vdots$$

$$e_{39} b_{39,1} = \frac{\text{kwh}}{\$\ \text{utilities}} \cdot \frac{\$\ \text{utilities}}{\$\ \text{sugar}} = \frac{\text{kwh}}{\$\ \text{sugar}}$$

$$\vdots$$

and so on through the list of sectors. Thus expression (4), when i denotes the sugar sector of the Hawaii model, is the sum of numbers whose units of measure were just outlined and is denominated entirely in terms of kwh/$ sugar. Similar expressions exist for all other industries of I/O model.

Note that if j is the index of an electrical energy sector, each of the terms $e_i b_{ij}$ represents merely the inverse of the price of electricity:

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*Subscripts here refer to sectors of the State of Hawaii I/O model.

$$\frac{\text{kwh}}{\text{\$ sector i}} \cdot \frac{\text{\$ sector i}}{\text{\$ electricity}} = \frac{\text{kwh}}{\text{\$ electricity}} = \frac{1}{\text{price}}$$

In addition to the energy flows matrix of equation (3), an energy "multiplier" and several value added coefficients can be calculated:

-- an energy use multiplier for each sector, the ratio of direct + indirect to direct use alone. This figure essentially demonstrates the degree of interconnection between energy use in the given sector and in the rest of the economy;
-- value added directly by any given sector per unit of energy use;
-- value added directly as well as indirectly by the given sector per unit energy use.

The first of these measures is useful in identifying industries which themselves exercise relatively light energy demand, but which use inputs with relatively heavy electrical energy content. The other two measures will bring to light those sectors with the greatest beneficial (in terms of creating value added, that is, income) economic impact per unit of energy use.

The multipliers are calculated as follows. Again letting e_j designate the direct use coefficient, the multiplier for sector j is the ratio of direct + indirect energy use per dollar output to direct use alone:

$$m_j = \frac{\sum_{i=1}^{n} e_i b_{ij}}{e_j}, \qquad j = 1, 2, \ldots, n \tag{5}$$

The first value added coefficient is simply the ratio of direct value added* v_j, to energy use in sector j:

$$u_j = v_j / e_j \qquad j = 1, 2, \ldots, n \tag{6}$$

The second coefficient may be calculated as

$$T_j = \frac{\sum_{i=1}^{n} b_{ij}(v_i/X_i)}{\sum_{i=1}^{n} b_{ij}e_i} \qquad j = 1, 2, \ldots, n \tag{7}$$

*Determined in conjunction with the data required for equation (1).

where X_i is total output for the i^{th} sector. The numerator represents direct + indirect value added per dollar output from sector j; while the denominator is direct + indirect energy use by sector j. Hence T_j is defined as direct + indirect value added per unit of energy by the sector in question.

Publications generated by the Socioeconomic Program:

1. El-Ramly, Peterson, Seo. GEOTHERMAL ENERGY ECONOMICS: AN ANNOTATED BIBLIOGRAPHY, Volume I, February 1974, 79 pp.

2. Grabbe and Kamins, STATE POLICY CONSIDERATIONS FOR GEOTHERMAL DEVELOPMENT IN HAWAII, April 1975, 19 pp.

3. Kamins, Kornreich, Sheets. LEGAL AND PUBLIC POLICY SETTING FOR GEOTHERMAL RESOURCE DEVELOPMENT IN HAWAII, 1974, 42 pp. (being revised).

4. Peterson and Seo, GEOTHERMAL ENERGY ECONOMICS: AN ANNOTATED BIBLIOGRAPHY, Volume II, September 1974, 66 pp.

5. Peterson, R.E., ECONOMIC FACTORS IN THE LONGEVITY OF RESOURCES, December 1974, 19 pp. Published in Geothermal Energy, March 1975 issue.

6. Peterson, R.E., ECONOMIC FACTORS IN THE OPTIMAL DEPLETION OF RESOURCES, March 1975, 19 pp.

7. Peterson, R.E., THE REICH CASE: ECONOMIC IMPLICATIONS OF DEPLETION ALLOWANCES, January 1975, 35 pp. (in draft, being revised).

HAWAII GEOTHERMAL PROJECT

DRILLING PROGRAM

Agatin T. Abbott

Resume of Activities of the Site Selection Committee

The Site Selection Committee was formed in the spring of 1974 to advise on the proposed exploratory drilling program on the island of Hawaii. The Committee consists of the following members, with area of interest noted:

Agatin T. Abbott -- Committee Chairman -- Geology
Professor and Chairman of the Department of Geology and Geophysics, University of Hawaii (U.H.)

Pow F. Fan -- Geochemistry
Professor of Geology, U.H.

Augustine Furumoto -- Geophysics
Professor of Geophysics, U.H.

Gordon A. Macdonald -- Geology
Senior Professor of Geology, U.H.

Donald Peterson -- Geology
Formerly Chief Scientist at the U.S. Geological Survey (U.S.G.S.) Volcano Observatory

Charles Zablocki -- Geophysics
Geophysicist, U.S.G.S. Volcano Observatory

Recently Dr. Robert Tilling, Chief Scientist at the U.S.G.S. Volcano Observatory, with interest in both Geology and Geochemistry, was added to the Committee. Drs. Peterson and Zablocki will be leaving Hawaii in the summer of 1975.

In its early stages the drilling program was envisioned as 10 or 12 exploratory holes at three selected sites on the island. Because of funding restraints, this type of program had to be abandoned. The decision was reached to concentrate attention in the Puna district of Hawaii, which showed the greatest promise based on work completed up to that time. It was also decided by the Site Selection Committee to use the available funds for the drilling of one deep hole, rather than expending the money for two or more shallow holes.

The first official meeting of the committee was held on April 15, 1974, at the U.S.G.S. Volcano Observatory on the island of Hawaii. An exploratory drilling schedule proposed by the chairman in three areas of the Big Island was reviewed, and places for further exploration were made. The feasibility of employing a drilling management team, such as that provided by Rogers Engineering of San Francisco, was discussed and the idea approved.

The next meeting was in late May 1974 at the Volcano Observatory. Mr. James Kuwada of Rogers Engineering Company of San Francisco was in attendance to discuss the role of a drilling manager and to make on-site visits to the three potential areas. These areas were the SW rift of Mauna Loa, the SW rift of Kilauea, and the East rift of Kilauea (Puna). At that time the Puna area for numerous reasons was appearing to be a good deal more favorable than the other two areas.

In early September Dr. Paul Kruger and Ritchie Coryell visited the campus and indicated that NSF was not planning to fund an exploratory drilling program, and that $500,000 would probably be a maximum we could expect for research drilling.

The Site Selection Committee next met at the University of Hawaii in October 1974 and made several important decisions:

1) With the reduced level of funding it would be necessary to reduce the drilling program drastically -- it was the consensus that all the funds should be concentrated in the drilling of one deep hole, rather than dissipate the funds in shallow drilling.

2) It was decided that we could not afford to employ a firm as drilling manager because the usual 10% commission charge would seriously reduce our already curtailed drilling plan. It was agreed that the money would be better spent in drilling as deep as possible, although this decision may prove to have been questionable as the need for a drilling manager becomes more apparent.

3) The location of the hole based on several lines of geophysical, geological, and geochemical evidence was spotted fifteen hundred feet north of Puulena Crater, in a general area that has since been designated as Area A. The preferred site was later moved about 1600 feet northeast of that point because of land ownership difficulties.

Location of the drill site in Area A was questioned as additional geophysical data came in during the fall, and over the holiday season. In order to reassess the whole site selection under the new sets of data on this and other locations in the Puna district, the Site Selection Committee was assembled again in late January 1975 for a thorough review of the data as it was known up to that time. Again the opinion of the Site Selection Committee was that the initial site selection was sound.

This decision was reached in full cognizance of a letter dated December 3, 1974, from Dr. George Keller to Dean John Shupe that he (Keller) did not feel that Area A was a favorable location because of possible dike concentrations and reliance on self-potential anomalies in the area. The general opinion of the committee was that other factors of geology and geochemistry, as well as an extension of a resistivity low into Area A, still made it the more promising of the two areas.

During the week of January 20, 1975, Mr. Paul English was sent by NSF to Hawaii to confer and advise on the procedures of preparing invitation to bid by drilling contractors. Land arrangements were continued with the Lyman estate and plans to submit the Bid Sheet and Well Specifications to twenty five potential drilling contractors were well underway.

At a meeting of the HGP executive committee on April 21, Dr. Furumoto first indicated that he had doubts that Area A was indeed the best drill site. This ultimately led to a third meeting of the Site Selection Committee on May 1, 1975, to which Dr. George Keller was invited to present his views of the geophysical data of each of the two areas. Dr. Furumoto also presented his data, as did all the other members of the committee. Also represented were a number of interested geologists, geophysicists and geochemists -- many of them members of the HGP Geophysical Program -- who took an active role in the review. After a full afternoon of discussion, which has been transcribed from the tapes but not included in this summary, it was decided by all committee members except Dr. Furumoto, as well as by those observers mentioned above, that the weight of all evidence -- geophysical, geological, geochemical, and thermal tests on neighboring wells -- indicated that Area A still appeared to hold the most promise. It was felt that an exploratory hole in Area A would provide more meaningful research data than one in Area B, and that the likelihood of encountering a geothermal anomaly was at least as great at A as it was at B. This evaluation is consistent with the statement by geophysicist Douglas Klein in his report of Task 2.2 in the section on the Geophysical Program.

In conclusion, it should be reiterated that the chairman and most of the members of the Site Selection Committee maintain a position of cautious optimism for either area. It should also be emphasized that one drill hole does not suffice to prove or disprove a potential geothermal resource in the Puna area. A multiple hole drilling program is essential to verify the presence or absence of a commercial geothermal field.

At the present moment, invitation to bid and copies of a tentative contract are being prepared by the University of Hawaii Procurement Office and will be mailed to potential contractors very shortly.