GL03281

RESEARCH PROPOSAL SUBMITTED TO THE NATIONAL SCIENCE FOUNDATION

CONTINUED INVESTIGATIONS OF THE GEOTHERMAL SYSTEM AT KILAUEA VOLCANO

Submitted by

COLORADO SCHOOL OF MINES
Golden, Colorado 80401

Proposed Amount: $167,299
Proposed Effective Date: Oct. 1, 1974
Proposed Duration: 15 months

Co-Investigator G. V. Keller Professor of Geophysics and Head of Department SS No. 578-48-8076	Co-Investigator Philip R. Romig Assistant Professor of Geophysics SS No. 316-36-8551
G. V. Keller	Philip R. Romig
(303) 279-3381, ext. 398	(303) 279-3381, ext. 267

Institutional Administrative Official
James H. Gary
Vice President for Academic Affairs

James H. Gary

ORS Proposal No. 589

June 21, 1974

PROPOSAL FOR CONTINUED INVESTIGATIONS OF THE GEOTHERMAL SYSTEM AT KILAUEA VOLCANO

ABSTRACT

Kilauea Volcano in Hawaii is an excellent field laboratory for studying heat flow from an active volcano because of the extensive studies that have been carried out there in recent decades, largely by the U. S. Geological Survey. In 1973, a borehole was drilled to a depth of 1261 meters at the summit of Kilauea, revealing what appears to be a convective geothermal system at depths to about 1000 meters. We are now proposing a detailed geophysical study of the interior of Kilauea Volcano using the Vibroseis seismic reflection technique and an ultra-deep penetration electromagnetic sounding technique. Both methods are capable of providing information at depths from 2 to 5 kilometers below the surface with far greater precision than any method used previously in similar studies. All available evidence indicates the surface magma chamber of Kilauea lies in the depth range. The proposed study would last for 15 months, from October 1, 1974, to January 1, 1976, with a total cost of $167,299.

PROPOSAL FOR CONTINUED INVESTIGATIONS OF THE GEOTHERMAL SYSTEM AT KILAUEA VOLCANO

Kilauea Volcano on the Island of Hawaii is a mid-ocean basaltic volcano which offers some unique opportunities for studying the mechanisms of heat transfer from molten rock to a geothermal system. Kilauea Volcano has been studied intensively for the past half century, with the research carried out by the staff and associates of the Hawaii Volcanoes Observatory having carried out a wide range of investigations. In addition to studies involving the geology and chemistry of the eruptive rocks, such as have been reported by Macdonald and Abbott (1970), Stearns (1966) and Peterson (1967), there have been investigations involving seismicity. (Eaton, Endo and Koyanagi, 1971; Koyanagi and Endo, 1971), deformation of the earth's surface (Fiske and Kinoshita, 1969; Kinoshita, Swanson, and Jackson, 1974), and determinations of the electrical resistivity of the subsurface (Jackson and Keller, 1972; Keller, 1973). These investigations provided strong evidence for the existence of a near-surface magma reservoir at a depth of 2-1/2 to 3 kilometers beneath the summit of Kilauea Volcano. Because the magma reservoir at Kilauea Volcano is the only one so clearly documented within the United States, in 1972, the National Science Foundation through its program of Research Applied to the Nation's Needs provided funds to the Colorado School of Mines to drill a moderately deep test hole at the summit of Kilauea Volcano, in cooperation with the U. S. Geological Survey (Keller and others, 1974; see also the internal report to NSF, included as an appendix to this proposal).

The intent in drilling the test hole, as stated in an earlier proposal, was to obtain information on the structure and dynamics of a hypothetical convection system which we believed to be present above the Kilauea magma chamber. The test hole was drilled to a depth of 1261 meters from an elevation of 1100 meters. As was expected, the hole penetrated basalt flows as well as more massive units of basaltic rock which may have been ponded flows or intrusive features. The water table was encountered at a depth of 491 meters, and below this level, the temperature distribution observed in the well appears to be best explained as being caused by a convection cell in which the base temperature is between 90° and 100°C. The convection cell has its base at a depth of approximately 1100 meters, with the heat transfer from greater depths being largely by conduction. The permeability required to maintain a convection system of this size at this temperature is of the order of 100 millidarcies (Murray, 1974). It is likely that the permeability is accounted for almost entirely by fractures. Details of the development of a theoretical model for the convection system at Kilauea Volcano are given by Murray (1974) in a report which is appended to this proposal.

It was heartening indeed that the results found on drilling conformed so closely to the model for a convective geothermal system proposed before drilling. As had been hoped, the geologic setting in a Hawaiian Volcano is sufficiently simple that geophysical surveys can be interpreted with little ambiguity. This reinforces the idea we proposed originally that Kilauea Volcano is an exceptional prototype of a volcano, useful in detailed studies of phenomena which must take place in other volcanoes, both of the basaltic type and other types, but which may not be so obvious because of complexities in geologic setting or because of a lack of the abundant supportive data which already exist at Kilauea. Therefore, we are now proposing a new and major phase to the investigation of the internal structure and workings of Kilauea Volcano -- a detailed study of the interior of the volcano at depths between 2 and 5 kilometers using the Vibroseis reflection seismic method and an ultra-deep penetration electromagnetic sounding method.

Knowledge of the mechanism of heat transfer from a molten intrusive to overlying rocks is of great importance to the developing technology of exploration for and exploitation of geothermal energy.

It should no longer be necessary to document the need for investigating alternate sources of energy. Geothermal energy is merely one alternate source which must be considered, because it may be available to us at low costs, both in capital investment and environmental impact, in comparison with other alternate energy sources being considered. However, before geothermal energy can be shown to be more than a technological curiosity, it will be necessary to solve a series of problems related to its occurrence, its conversion to a useful energy form, and its environmental impact. We address ourselves here to the problem of understanding the geologic controls over hyperthermal systems intimately associated with igneous intrusions and volcanism. We recognize that other types of geothermal system also exist, in which there may be no igneous activity associated with the heat accumulation, but are not concerned with these in this proposed research.

The features of an intrusive-generated geothermal system are indicated on Figure 1, though it must be admitted that the model is speculative. In the Hawaii setting, one might expect an upper magma chamber to be formed just above "basement" the level of transition from high-density intrusive volcanic rocks to lower-density subaerial flows with vesicular porosity or submarine flows with extensive columnar jointing. It is likely that this storage reservoir is not a large cavity filled with molten rock, but rather, that it is a sequence of dike-like openings in which the molten rock is stored (Fiske and Kinoshita, 1969). Injection of molten rock into a water-laden section can lead to several significant processes, including conversion of ground water to steam, and assimilation of water into the molten rock. This latter mechanism can be used to explain why molten rock can exist in a plexus in melting-freezing equilibrium with the solid rocks forming the skeleton of the plexus. Assimilation of water will lower the freezing point of the melt beneath the melting point of the solid skeleton, so that over the range of temperatures between these two points, there will be no tendency for the magma to freeze or the wallrock to melt, when both are at the same temperature.

A second, and possibly more important process which may take place is the deposition of the original salt content of the ground water when it is converted to steam. Salt deposition can build up an impermeable barrier around the magma chamber, with water leaking through only occasionally when seismic activity opens joints (Kennedy, 1974). If the steam is heated to a sufficiently high temperature at the margins of magma chamber, it may dissolve a significant amount of silica, which is subsequently deposited above the magma chamber when the steam cools to temperatures of 300° to 400°C (Facca and Tonani, 1967). Depending on the relative rates of leakage of water into the magma chamber from the sides and escape of steam from the cap, the region within these permeability barriers may be at either an abnormally high or an abnormally low pressure. However, there is a reasonable possibility that the sealed region contains water vapor at super-critical temperatures -- above 372°C --, and thus be an attractive target for geothermal development. So far, no drill holes have penetrated into such a supercritical temperature regime, so its existence has yet to be verified.

Above the caprock, one might expect conductive transfer of heat, convective transfer, or both, depending on permeabilities. At Kilauea, where the existing drill hole has penetrated a convection system, both mechanisms are present. In this region, one might expect to produce either steam or hot water from a well, depending on the relationship between pressure and temperature in the rock (see White, 1973, for a detailed discussion of phenomena which probably take place in this region). All geothermal wells drilled to date have been drilled into these lower-temperature parts of geothermal systems.

The deeper parts of the geothermal system, including the caprock and lateral permeability barriers, the supercritical region, and the magma chamber itself, all should be characterized by suites of physical properties which are highly diagnostic. The problem is to make use of geophysical probing techniques which have the capability to reach to the depth of the magma chamber with sufficient resolution to recognize these characteristic physical properties. We propose using the reflection seismic technique and the time-domain electromagnetic induction technique to accomplish this. Details of the plans are described in the following two sections.

A similar proposal is being prepared by the Institute of Geophysics, University of Hawaii. Whereas the objectives of the work we propose are scientific, and the research will be carried out almost entirely within the Hawaii Volcanoes National Park, the objective of the University of Hawaii program is to demonstrate the economic viability of geothermal energy in Hawaii. Accordingly, their program will consist of surveys carried on outside of Hawaii Volcanoes National Park.

REFLECTION SEISMIC SURVEY

The reflection seismic survey is proposed for a summit area of Kilauea Volcano, along the profile lines indicated on Figure 2. We will use a vibrator source, rather than an explosive source, both because the vibrator source is more acceptable environmentally than the explosive source, and because the vibrator source provides more flexibility in experimental design than does the use of explosives. The Department of Geophysics at the Colorado School of Mines now has a 15 ton vibrator. The field technique to be employed would be 12-fold common depth point stacking (Mayne, 1962), with digital recording and processing.

No great amount of use of reflection techniques has been made of reflection seismic techniques in basaltic terraine. However, one might expect coherent reflections to be recognized from such acoustic wavespeed boundaries as the water table, tabular ponded lava flows, thick flow units, the geothermal caprock, dikes and basement. We are fortunate in having considerable information from well logs run in the Kilauea test hole including an acoustic log over a portion of the hole (see Figure 3). As is usually the case when acoustic logs are run above the water table, it is not possible to determine the acoustic wave speed at every depth because of problems associated with transmission of acoustic waves through undersaturated rocks. However, in order to obtain a better understanding of acoustic wavespeeds in intervals where acoustic logs could not be obtained, we found it possible to use a correlation between wavespeed and porosity (Figure 4) to convert the sidewall neutron porosity log (shown in the report on drilling at Kilauea Volcano included as an appendix) to an equivalent acoustic wavespeed vs depth profile. This profile was then used to generate a synthetic seismogram, including multiples, as shown in Figure 5. It may be seen that the section from the test hole is capable of giving rise to mappable seismic reflection events, providing these features have a reasonable lateral extent.

ULTRA-DEEP ELECTROMAGNETIC SOUNDING

Although electromagnetic sounding methods have not been used to the extent that seismic reflection methods have, they offer a second approach to studying structure and physical properties at depths of 2 to 5 kilometers in Kilauea Volcano. The method we propose using is the time-domain wire-loop method in which a magnetic field is generated by passing a step current through a length of grounded wire, with the transient magnetic field caused by this step current being recorded at sites where soundings are to be made. Interpretation of such transients in terms of the electrical conductivity structure to depths comparable to about a third the distance from source to receiver is a simple matter (Daniels, 1974).

Extensive electromagnetic sounding surveys have already been carried out over Kilauea Volcano, some of which have been reported in the literature (Jackson and Keller, 1973). All of these previous soundings were carried out using separations between source and receiver of less than 7 kilometers, providing information on the subsurface conductivity to depths of 1 to 2 kilometers, at most. In order to make measurements at greater distance from the source, and thus provide the capacity for measuring conductivity to greater depths, it is necessary to provide a greater source moment, which is defined as the product of current intensity and line length. The time derivative of the magnetic field detected with a magnetometer is given by the formula (Keller, 1967):

$$\frac{dH_z}{dt} = \frac{3IL\rho\sin\theta}{2\pi\mu R^4}$$

where A is the area of the receiving loop,

I is the amplitude of the current step,

L is the length of the grounded wire,

θ is the angle between the line connecting the receiver to the midpoint of the source, and the axis of the source,

R is the distance from the source to the receiver, and

ρ is the apparent resistivity.

Previous surveys (Jackson and Keller, 1973; Keller, 1973) indicate that over the summit of Kilauea Volcano, the resistivity above the water table is very great, being many thousands of ohm-meters; this decreases to values of several tens of ohm-meters immediately below the water table (491 meters below the surface) and then appears to further decrease to values of 3 to 6 ohm-meters at depths of 2 kilometers. Apparent resistivity values measured from a dipole source located about 6 kilometers away from Kilauea Crater are shown as an apparent resistivity contour map in Figure 6, and as a dipole sounding curve in Figure 7. It would be expected that if molten rock is present in large volumes in a magma chamber at still greater depths, this region would also have a resistivity of the order of 1 to 10 ohm-meters.

Arbitrarily assigning a value of 5 ohm-meters as the resistivity likely to be detected with an ultra-deep electromagnetic sounding survey, we can calculate the signal strength that should be measured at various distances from the source. The other parameters that need to be specified are the current (300 amperes) and the source length (1000 meters). With these specifications, the relationship between $\partial H_z/\partial t$ and distance is

$$\frac{\partial H_z}{\partial t} = \frac{5.70 \times 10^{11}}{R^4}$$

or at $R = 10$ km, $\partial H_z/\partial t = 5.70 \times 10^{-5}$ amp/m-sec
at $R = 12$ km, $\partial H_z/\partial t = 2.75 \times 10^{-5}$ amp/m-sec
at $R = 15$ km, $\partial H_z/\partial t = 1.12 \times 10^{-5}$ amp/m-sec.

Experience has shown that received signals with an amplitude of 1.0×10^{-5} amp/m-sec can be recorded with good accuracy, particularly if the signals are stacked to improve the ratio of signal to noise. Therefore, we propose to install a dipole source in the vicinity of the 27-mile milepost on the Hilo-Volcano Highway (see location on Figure 8), so that most of the summit area of Kilauea Volcano will lie at a distance of 12 to 15 kilometers. In order to obtain source currents of 300 amperes, it will be necessary to drill shallow holes, probably to a depth of approximately 100 meters, so that electrode contacts can be installed below the high resistivity fresh flows at the surface.

Much of the summit area is accessible only on foot, inasmuch as it lies within Hawaii Volcanoes National Park. A Josephson-effect magnetometer will be used as an electromagnetic field detector, because it is highly portable, and extremely sensitive. The magnetometer now owned by the Colorado School of Mines, and which was purchased with another NSF grant, has three orthogonal magnetometer elements, with sensitivities of approximately 10^{-8} amp/m. The major expense in operating this magnetometer is in supplying liquid helium; approximately one liter per day is required.

PROPOSED SCHEDULE OF OPERATIONS

Mobilization of the vehicular equipment, which consists of one 15-ton vibrator truck, a digital recording truck, and a cable-laying truck, will take several months, inasmuch as they must be transported to the West Coast, and then loaded aboard a ship bound for Hilo. Moreover, the shallow holes must be drilled for electrodes before the electromagnetic program can be undertaken. Approximately 6 months will be required for this mobilization, so we urge that funding be approved by October 1, 1974, permitting field operations to be undertaken about April 1, 1975. The field surveys would proceed intermittently over a period of three months, until approximately July 1. A relatively slow pace for field operations will allow the later part of the surveys to be based on results obtained during the early stages. Inasmuch as extensive computer-based data processing procedures will have to be carried out before a full interpretation of the data can be made, a period of six months, from July 1, 1975, to January 1, 1976, will be provided for this phase of the study.

Figure 1. Hypothetical cross section of Kilauea Volcano indicating phenomena related to heat flow.

Figure 2. Proposed locations for seismic reflection profiles crossing the summit of Kilauea Volcano.

Figure 3. Acoustic log of the interval from 1000 to 3064 feet in the Kilauea geothermal research hole.

Figure 4. Correlation between acoustic wavespeed and porosity used in compiling a synthetic seismogram for intervals in which no acoustic log was obtained.

Figure 5. Synthetic seismogram, with multiples, computed from 4100 feet of log, with an additional 3000 feet of similar section added beneath the borehole.

Figure 6. Contour map of apparent resistivity values measured from a bipole source located 7 kilometers west of Kilauea Caldera.

Figure 7. Dipole sounding curve recorded over the summit of Kilauea Volcano.

Figure 8. Area proposed to be covered in the ultra-deep electromagnetic sounding study.

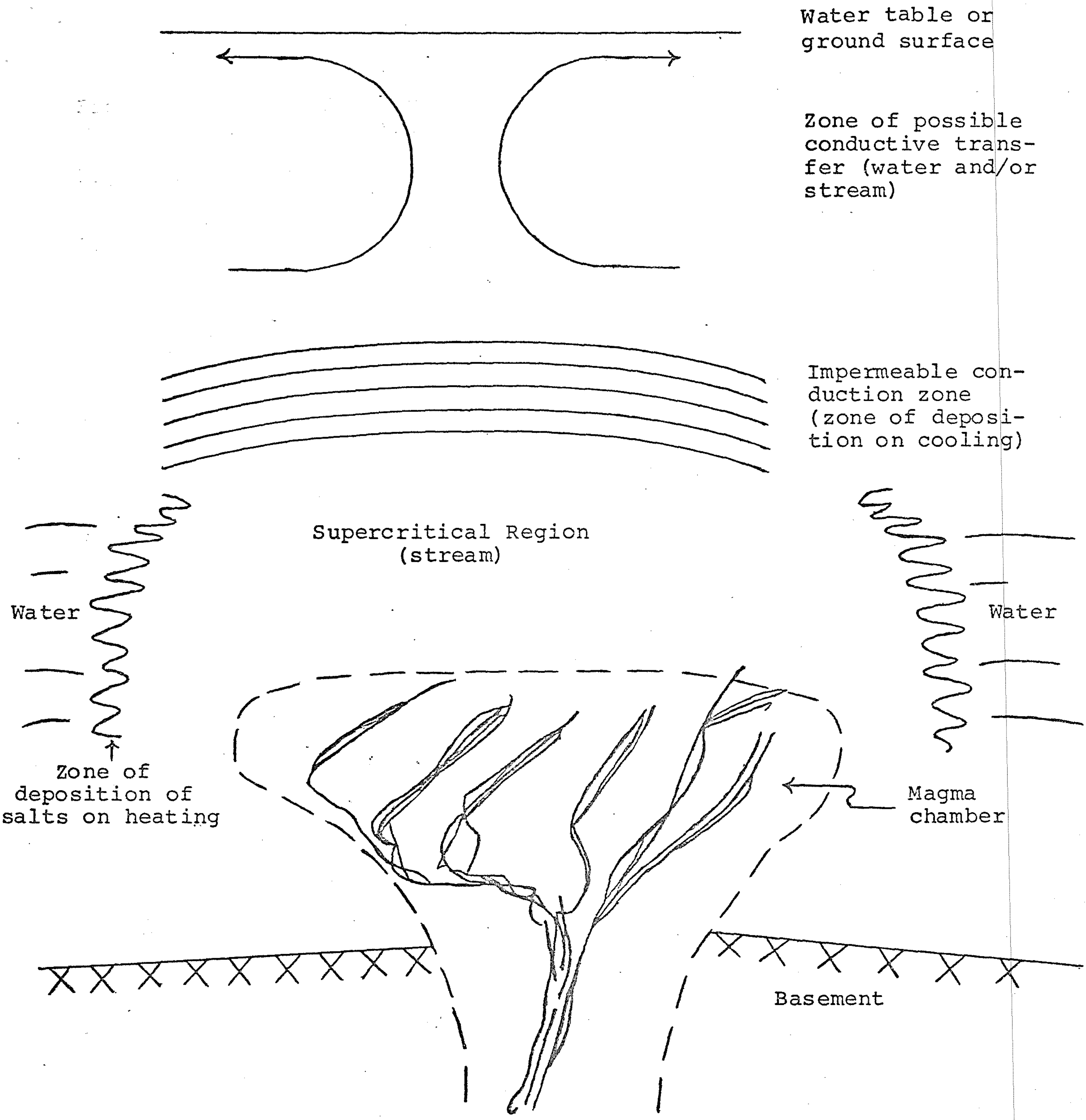

Figure 1. Hypothetical cross section of Kilauea Volcano indicating phenomena related to heat flow.

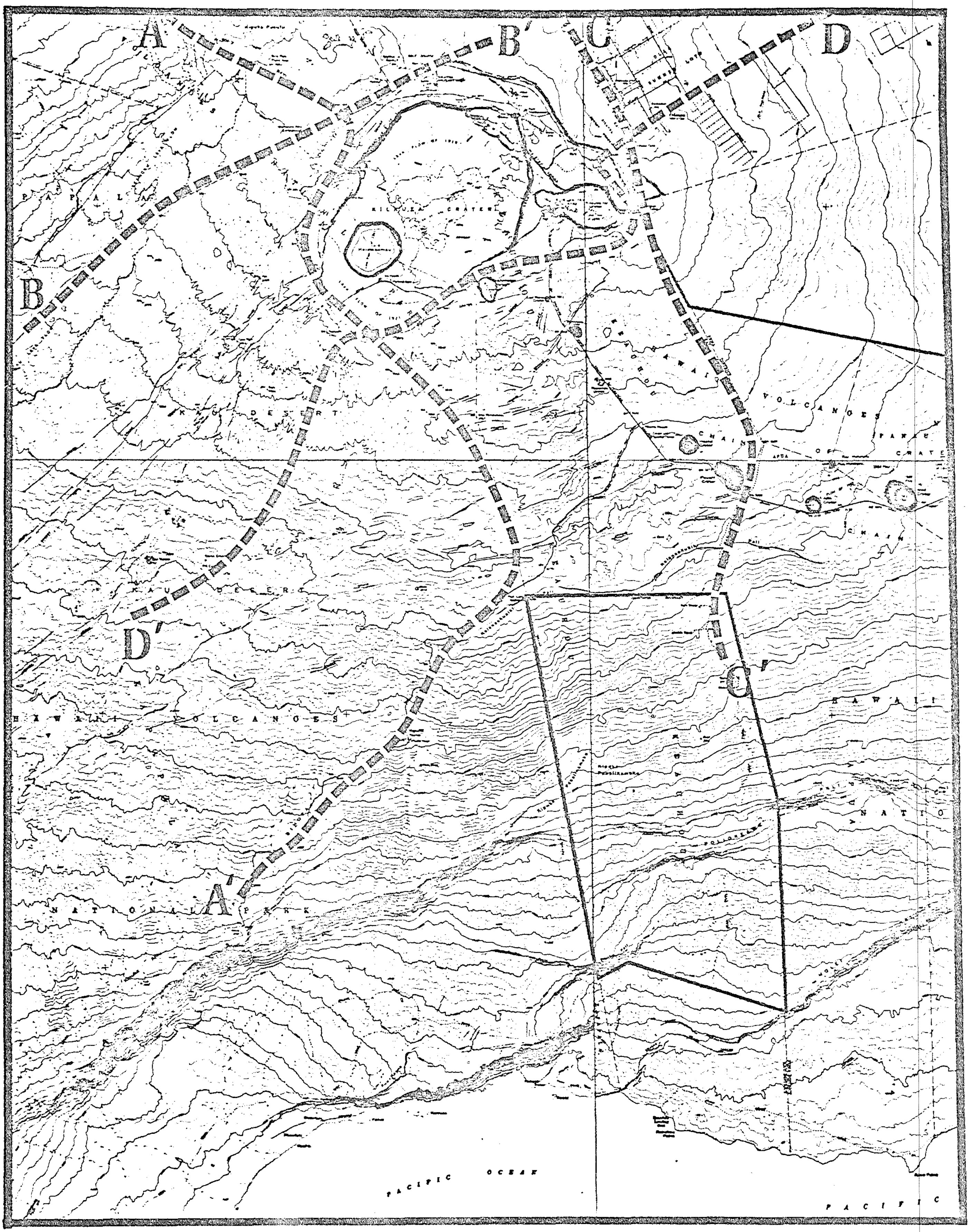

Figure 2. Proposed locations for seismic reflection profiles crossing the summit of Kilauea Volcano.

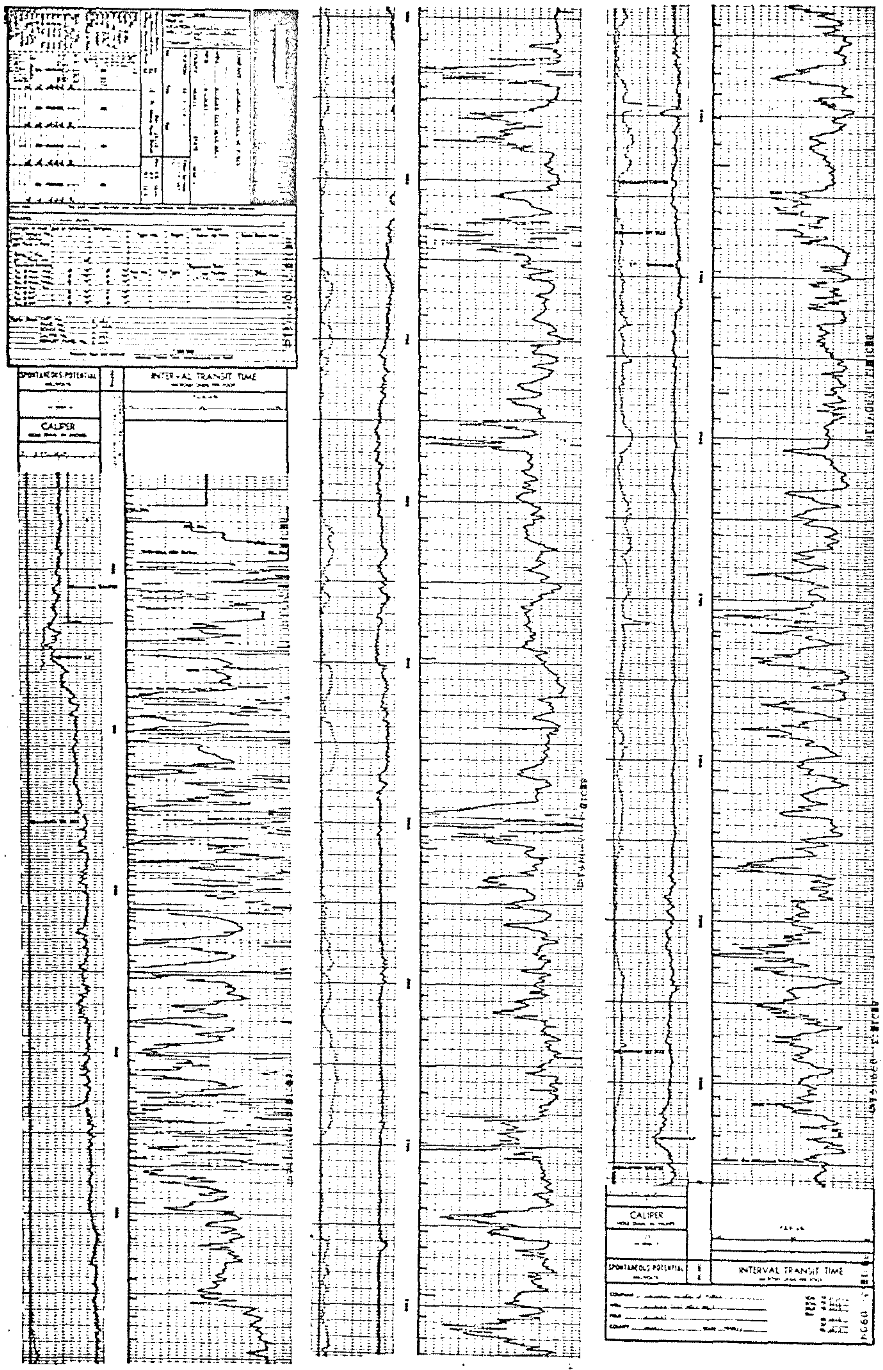

Figure 3. Acoustic log of the interval from from 1000 to 3064 feet in the Kilauea geothermal research hole.

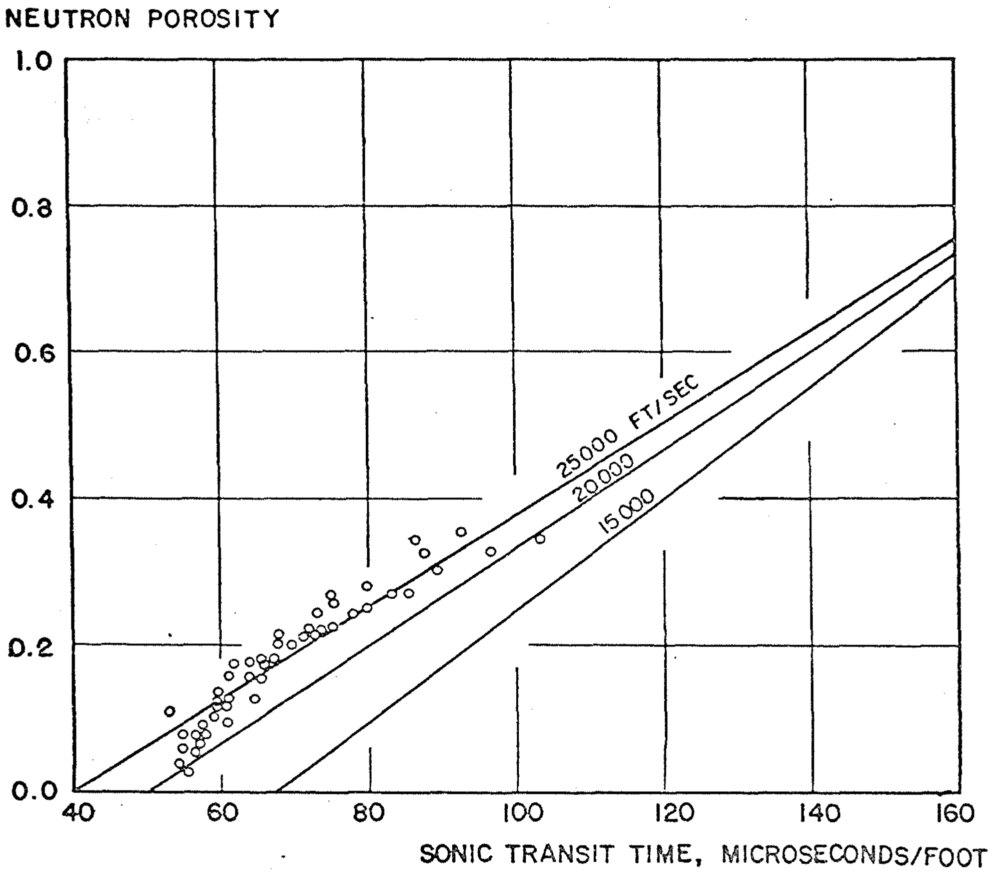

Figure 4. Correlation between acoustic wavespeed and porosity used in compiling a synthetic seismogram for intervals in which no acoustic log was obtained.

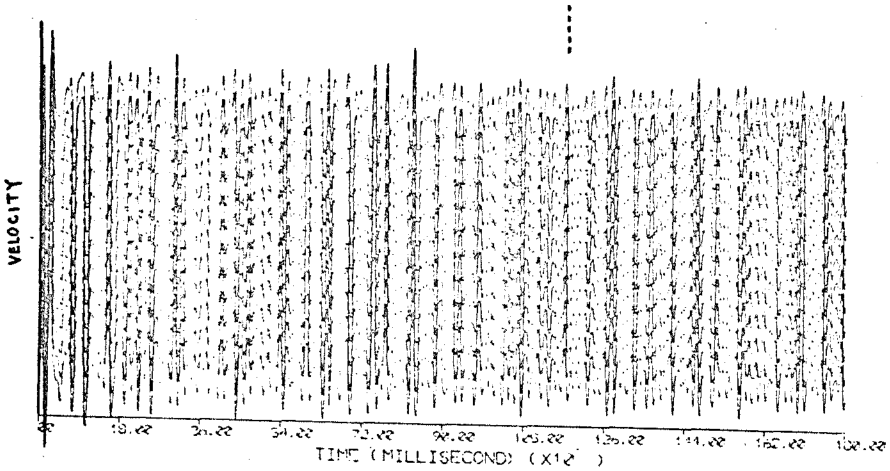

Figure 5. Synthetic seismogram, with multiples, computed from 4100 feet of log, with an additional 3000 feet of similar section added beneath the borehole.

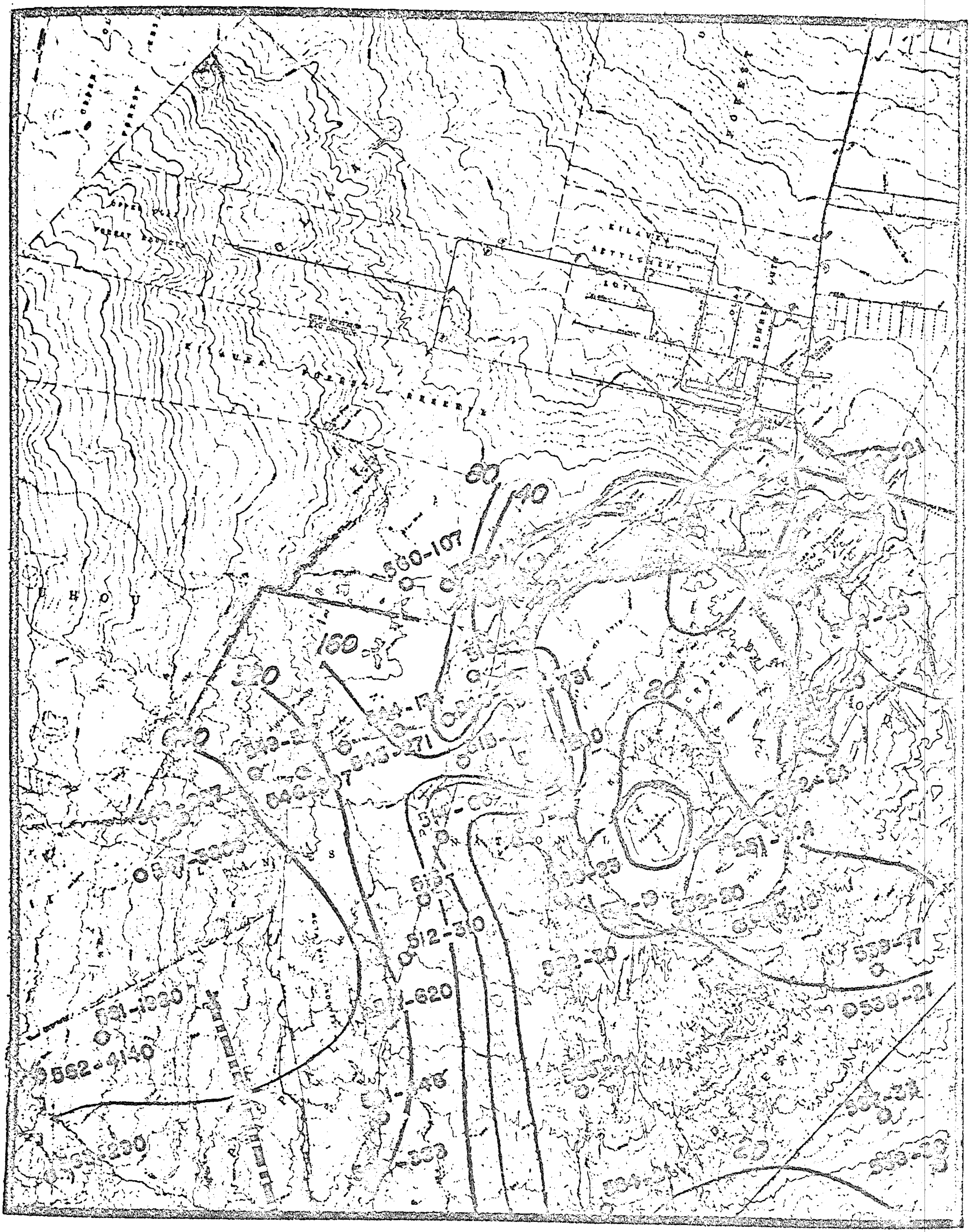

Figure 6. Contour map of apparent resistivity values measured from a bipole source located 7 kilometers west of Kilauea Caldera.

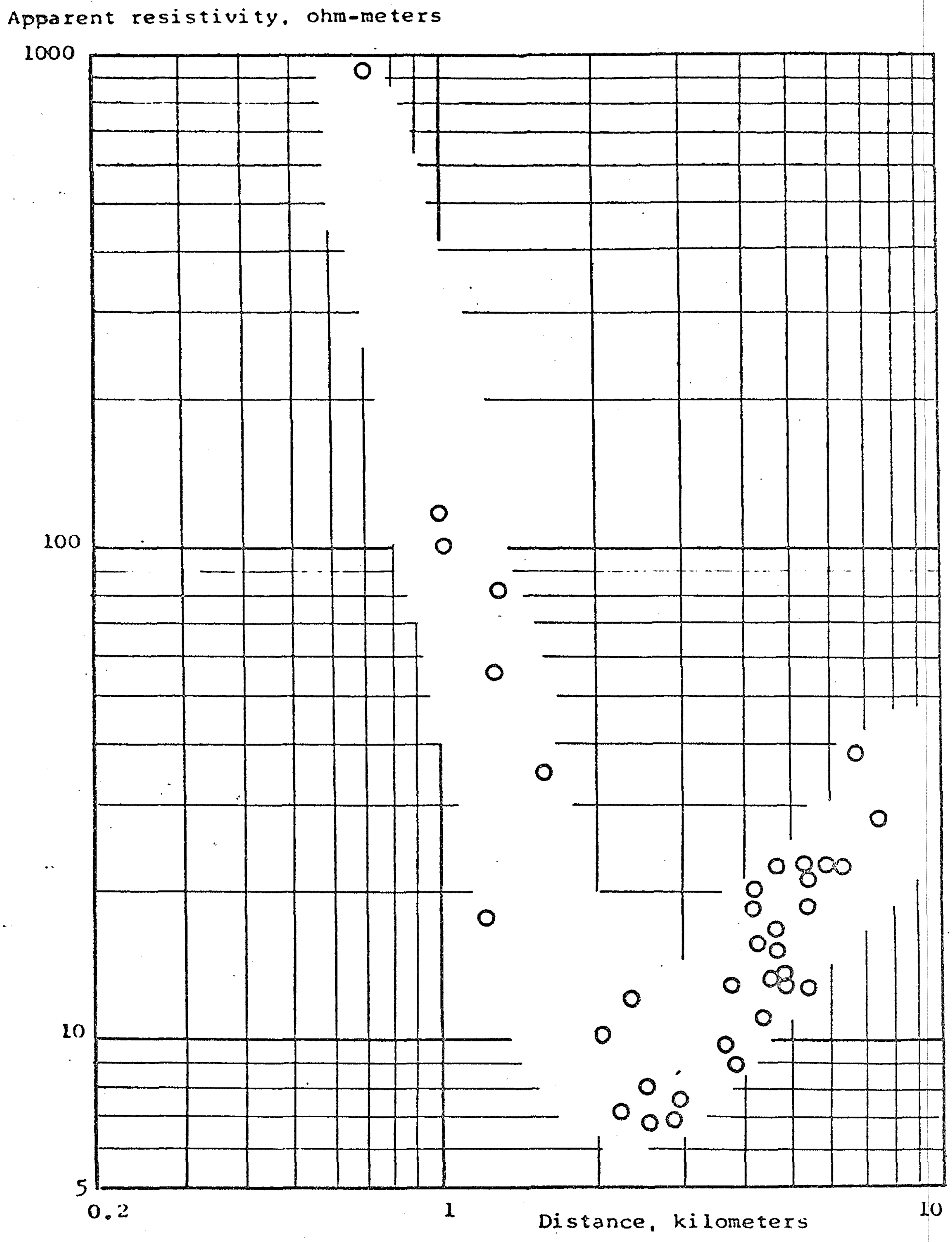

Figure 7. Dipole sounding curve recorded over the summit of Kilauea Volcano.

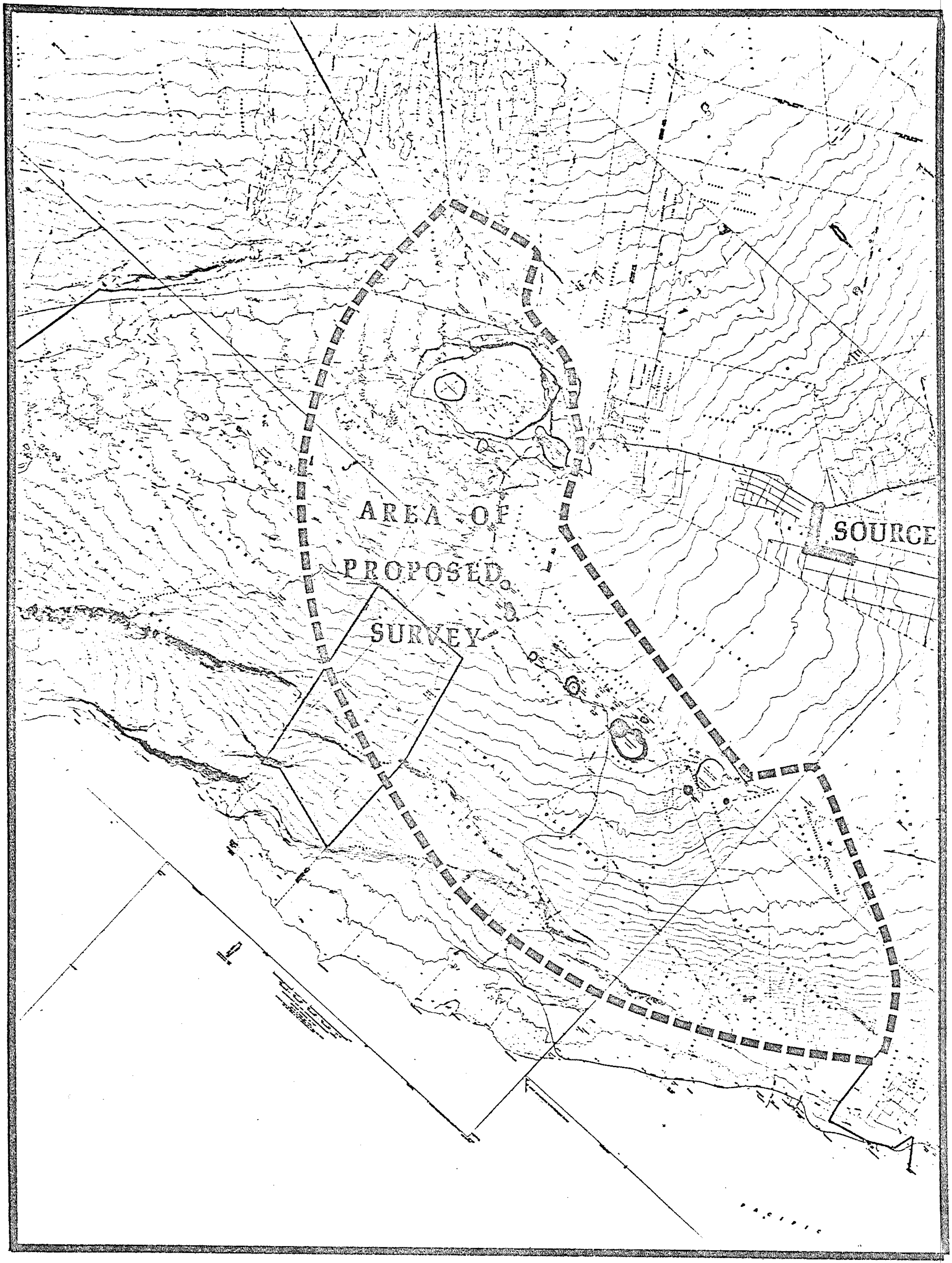

Figure 8. Area proposed to be covered in the ultra-deep electromagnetic sounding study.

References

Daniels, J. J., 1974, Interpretation of electromagnetic soundings using a layered earth model; Colo. School of Mines Thesis T-1627, Golden, Co., 86 pp

Eaton, J. P., Koyanagi, R. Y., and Endo, E. T., 1971, Earthquakes and magma sources in the upper mantle beneath Hawaii: Am. Geophys. Union, Trans., 52, p 372

Facca, G. C., and Tonani, F., 1967, The self-sealing geothermal field: Bull Volcanolog., vol. 30, pp 271-273

Fiske, R. S., and Kinoshita, W. T., 1969, Inflation of Kilauea Volcano prior ot its 1967-1968 eruption; Science, vol. 165, pp 341-349

Jackson, D. B., and Keller, G. V., 1972, An electromagnetic sounding survey of the summit of Kilauea Volcano, Hawaii; J. Geophys. Res., vol. 77, no. 26, pp 4957-4965

Keller, G. V., 1973, An electrical resistivity survey of the Puna and Kau districts, Hawaii County, Hawaii; Report to the University of Hawaii, Honolulu, 101 pp

Keller, G. V., Murray, J. C., Zablocki, C. J., Tilling, R., Christiansen, R., and Peterson, D., 1974, A deep research drill hole at Kilauea Volcano, Hawaii: Progress Report; (submitted to Science)

Kennedy, G. C., 1974, Self sealing of geothermal reservoirs; Proceedings of the US-Japan seminar on extraction of Volcano Energy, Hilo, Hawaii, Feb. 3-7, 1974; Sandia Laboratory, Albuquerque, N. Mex.

Kinoshita, W. T., Swanson, D. A., and Jackson, D. B., 1974, The measurement of crustal deformation related to volcanic activity at Kilauea Volcano, Hawaii; in P. Gasporini, L. Civetta, A. Rapolla, and G. Juongo (Editors), Physical Volcanology, Elsevier, Amsterdam

Koyanagi, R. Y., and Endo, E. T., 1971, Hawaiian seismic events during 1969; U.S. Geol. Survey Prof. Paper 750-C, pp C158-C164

Macdonald, G. A., and Abbot, A. T., 1970, Volcanoes in the sea; Univ. Hawaii Press, Honolulu, 441 pp

Mayne, W. Harry, 1962, Common reflection point horizontal data stacking techniques; Geophysics, vol. 27, no. 6, pp 927-938

Murray, J. C., 1974, The geothermal system at Kilauea Volcano, Hawaii: Colo. School of Mines, Thesis T-1556, Golden, Co., 86 pp

Peterson, D. W., 1967, Geologic map of the Kilauea Crater quadrangle, Hawaii: USGS Geol. Map GQ 667

Stearns, H. T., 1966, Geology of the State of Hawaii; Pacific Books, Pub., Palo Alto, Calif, 266 pp

White, D. E., 1973, Characteristics of geothermal resources, <u>in</u> Kruger, Paul, and Otte, Carel, eds., Geothermal energy: Stanford Univ. Press, Palo Alto, Calif.

RESEARCH GRANT PROPOSAL BUDGET

Year Beginning October 1974

	NSF Funded Man-Months			
Budget Category	Cal.	Acad.	Sum.	Amount
A. SALARIES AND WAGES				
1. Senior Personnel				
a. Co-Principal Investigators				
George V. Keller	1.90	.90	1.00	$5,000
Phillip R. Romig	3.25	2.25	1.00	5,960
Sub-total				$10,960
2. Other Personnel (non-faculty)				
a. Technician	6.00	3.33	2.67	7,200
b. Research Assistants (2)	7.50	4.50	3.00	11,250
c. Field Assistants (UH-Hilo Students) 1600 hrs @ 3.25/hr	9.00	6.00	3.00	5,200
Total Salaries & Wages				$34,610
B. STAFF BENEFITS 13% of A.1 and 2.a				2,361
C. TOTAL SALARIES, WAGES & STAFF BENEFITS (A+B)				36,971
D. PERMANENT EQUIPMENT				
1. Sweep-frequency oscillator, required to provide driving signal for vibrators				6,000
2. Phase comparator to couple two vibrators				2,000
Total				8,000
E. EXPENDABLE SUPPLIES				
1. Liquid helium				1,500
2. Recording supplies, magnetic tape				3,500
3. Maintenance of Vibroseis equipment				10,000
F. TRAVEL AND TRANSPORTATION				
1. Freight charges to ship four heavy vehicles to Hilo and return to Denver				12,000
2. Common carrier travel, Denver/Hilo for 10 round trips				3,300
3. Other common-carrier and interisland travel				1,000
4. Vehicle rental, Hilo				4,500
5. Gasoline, oil and lubricants				2,000
6. Per diem expenses, 300 man/day				7,500
Total				$30,300
G. PUBLICATION COSTS Typing, drafting, & printing costs				3,500
H. COMPUTER COSTS 10 hrs @ 500/hr				5,000
I. OTHER COSTS				
1. Sub-contract for drilling 300 meters of shallow holes				30,000
2. Sub-contract for leasing a field processing system for 3 months				30,000
Total				$60,000

Budget Category		Amount
J.	TOTAL DIRECT COSTS (C through I)	$158,771
K.	INDIRECT COSTS	
	1. On-campus 54.30% of $17,244 All AY salaries except UH students	9,364
	2. Off-campus 19.89% of $17,366 All summer salaries + UH students	3,454
	Total Indirect Costs	$12,818
L.	TOTAL COSTS (J+K)	$171,589
M.	TOTAL CONTRIBUTIONS FROM OTHER SOURCES (CSM Cost Sharing)	(4,290)
N.	TOTAL ESTIMATED PROJECT COST	$167,299