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THE UTILIZATION
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Geophysical Exploration on the Structure of Volcanoes: Two Case Histories

by

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ABSTRACT

Geophysical methods of exploration were used to determine the internal structure of Koolau Volcano in Hawaii and of Rabaul Volcano in New Guinea. By use of gravity and seismic data the central vent or plug of Koolau Volcano was outlined. Magnetic data seem to indicate that the central plug is still above the Curie Point. If so, the amount of heat energy available is tremendous. As for Rabaul Volcano, it is located in a region characterized by numerous block faulting. The volcano is only a part of a large block that has subsided. Possible geothermal areas exist near the volcano but better potential areas may exist away from the volcano.

INTRODUCTION

Over the past decade, I have been involved in geophysical exploration to determine the internal structure of two volcanoes: one a basaltic volcano called Koolau Volcano located on the island of Oahu in the Hawaiian Archipelago and the other an andesitic one called Rabaul Volcano in the island of New Britain in the new nation of Papua-New Guinea. These projects involved all geophysical techniques that were relevant: gravity, magnetic, seismic refraction, seismic reflection, monitoring of microearthquakes. This meant the cooperation of numerous specialists from various disciplines. In particular, the investigation of Rabaul Volcano involved many institutions from Australia, Papua-New Guinea and Hawaii.

Most of the results of the studies have already been published in journals, hence, in this paper a summary of the work will be presented to give a coherent picture of the investigations, and to compare a basaltic volcano to an andesitic volcano, as seen by geophysicists. First we shall treat the Koolau Volcano, as this study was completed before Rabaul Volcano was attempted.

KOOLAU VOLCANO

Koolau Volcano is an extinct volcano on the northeastern coast of the island of Oahu in the Hawaiian Archipelago. Roughly the remnants of the caldera include the areas marked off as Kaneohe, Kailua and Kaelepulu Pond in the lower map of Figure 1. Probably the central vent of the volcano was located under Kawainui Swamp, which is the swampy area beneath the label Kailua in Figure 1. The last eruption, a flank eruption, occurred many tens of thousands of years ago and erosion has removed most of the original shape and size of the volcano. Studying an extinct volcano is useful, just as an anatomy student can learn much by dissecting corpses. Besides, the proximity of the volcano to Hawaii Institute of Geophysics, University of Hawaii, provided a most convenient testing ground for exploratory instruments and techniques.

DISCLAIMER

The exploration project started out conventionally with gravity surveys. As Oahu is a densely populated island with excellent network of roads, there was no difficulty in making hundreds of readings. The resulting Bouguer anomaly map is shown in Figure 2 and an analysis attempted by Strange, et al. (1965) is shown in Figure 3.

During the years 1964 to 1966 a series of aeromagnetic surveys were carried out over the Hawaiian Islands (Malahoff and Woollard, 1966). The results showed that extinct volcanoes had a high degree of magnetization over the central vents while active volcanoes were much less magnetized. An exception was Koolau Volcano which showed a lower magnetization than surrounding rocks (Figures 4 and 5). This property of lower magnetization is a pivotal point of this paper and will be taken up later.

Seismic refraction and reflection surveys lasted several years from 1964 to 1969 because these surveys required a lot of men in coordinated team work. Usually explosives were set off at sea as close to shore as safety and environmental protection allowed, and seismic arrivals from these shots were recorded by parties on land and at sea on small ships. Small shots were sometimes fired in creeks and swamps in the caldera area (Figure 6). At other times, to study the crust offshore from the island, the two ship marine seismic refraction method was used. The results were published in several papers: Adams and Furumoto, (1965); Furumoto, Thompson and Woollard, (1965); Furumoto, Woollard, Campbell and Hussong, (1968); Furumoto, Campbell and Hussong, (1971). In the caldera area seismic reflection surveys were carried out to determine depth to reflecting boundaries that could be interpreted as high velocity material or residual high temperature. The shot locations and geophone spreads are shown in Figure 6. The depths to various layers as interpreted from seismograms are given in Figure 7. The reflection data have been published here for the first time.

The results of the various surveys using seismic refraction techniques can be compiled in a form as shown in Figure 8. The crust on the northeastern side of the island of Oahu is thinner by 6 km than the southwestern side. The difference in crustal structure is given further evidence by ocean bottom topography, as a trench or deep exists on the northern side of the islands but not on the southern side, except for a section around the southern tip of the island of Hawaii. This difference in crustal structure is significant in trying to understand the fundamental volcanic processes of the Hawaiian Islands. Ryall and Bennett (1968) have also posited a crustal mismatch across Mauna Loa volcano on the island of Hawaii. It may be that volcanoes have erupted through faults or cracks in the crust and mantle that extend very deep.

Let us now discuss the caldera and the central plug. Malahoff's magnetic surveys revealed that the magnetic intensity over the plug was low. There are three possible explanations: first that the plug is reversely polarized; second, the plug is hot enough to be above the Curie Point; and third, that the material is diamagnetic.

The third possible reason should be discarded. The other volcanic plugs in the Hawaiian Chain are magnetic, and Koolau hardly seems unique from other properties. The rocks on the flanks of Koolau are magnetic; it is hardly possible that the plug which is the source of the rocks on the flanks is diamagnetic.

The first explanation does not seem to be a good one either. The last epoch of reversed polarity of the earth's magnetic field occurred during what is known as the Blake Event (Strangway, 1970) about 100,000 years ago. Meanwhile, eruptions from Koolau Volcano occurred as late as 31,000 years ago, and the Honolulu Series of volcanics, which poured out from the southwestern side of the caldera, has been dated at 66±3 thousands of years old (Gramlich, Lewis and Naughton, 1971). As the remnant plug structure has been estimated to have a radius of about 8 km, the Honolulu Volcanic Series erupted above the plug structure, and the lavas could very well come from the plug itself. Hence there is much weight of argument that the Koolau plug did not cool below the Curie Point during the Blake Event but that the plug is still above the Curie Point. The Curie Point for rocks in Hawaii have been determined to be 325°±10°C (Belshe, 1965). This temperature is far below observed lava temperatures which ranges from 900°C to 1150°C.

This leaves the second explanation as the most plausible; that the plug at present has a temperature above the Curie Point.

Assuming that the plug is above the Curie Point, an attempt was made to calculate the amount of heat energy available. The size of the plug can be estimated from Strange's analysis: a cylindrical shape with density 3.2 g/cm^3, 8 km in diameter, extending from a depth of 2 km to the Moho discontinuity at 12 km. We assumed that temperatures in the Hawaiian area outside of volcanoes at the Moho discontinuity was 300°C and that ground surface temperature was on the average 30°. It is assumed that the energy will be used up when the plug has a temperature distribution same as the surrounding rock. The specific heat of the plug material was taken at .2 cal/g°C. With these parameters, it was found that the heat available in the plug amounted to 2 x 10^7 megawatt years.

The conclusions is that, if technology for hot rock development comes into existence, on the assumption of 1% efficiency, there is ample energy in the Koolau Plug to supply the present city of Honolulu for 100 years.

RABAUL VOLCANO

The exploration program over Rabaul Volcano was an extensive project that involved many institutions for several years. Gravity, magnetics, geologic and seismic refraction surveys were carried out. In particular the seismic refraction surveys of 1967 and 1969 involved scores of men in the field. For most of the work the coordinating agency was the Bureau of Mineral Resources of Australia, while the 1970 marine seismic survey was coordinated by the Hawaii Institute of

Geophysics. The University of Queensland participated in all of the projects while the following institutions participated at various times: Australian National University, University of New England, Department of Lands, Surveys and Mines of Papua-New Guinea, Papua-New Guinea Geological Survey.

As the paper by Wiebenga and Furumoto (1974) in this set of proceedings provide the details of the exploration, the discussion here will refer to the figures and results given in that paper.

The results of seismic refraction surveys are given in the form of an east-west profile across the northern tip of New Britain and an northwest-woutheast profile across the same island (Figures 3 and 4, Wiebenga and Furumoto). The profiles show that the structure in that region is in the form of crustal blocks and these blocks are reflected in the depths to the mantle. Whether these blocks are differentiated even in the mantle, we have no way of saying at the present time.

Upon examining the east-west crustal profile (Figure 3, Wiebenga and Furumoto) one notices that Rabaul Volcano, by its size, is only a small feature in a crustal block that is 50 km wide in the east-west direction. Thickness of the block is 33 km. The volcano sits in the middle of the crustal block.

The crustal blocks immediately to the west of the Rabaul crustal block are about the same thickness as Rabaul, but the crustal block under the Bismarck Sea abruptly thins to 20 km. To the east, the crustal block under St. George's Channel is no thicker than 15 km. From one crustal block to another, the change is rapid. The inference is that in this region fracturing of the crust and upper mantle by tectonic forces is the characteristic feature.

The crustal block in which Rabaul Volcano is located is a sunken block, with crustal material extending to a depth of 33 km. It might be surmised that because of extrusions from Rabaul Volcano the whole block submerged to replace the void. However there is no calculation of the volume extruded from Rabaul Volcano to check whether such a hypothesis can be substantiated.

The caldera of Rabaul Volcano is very small compared to the crustal block. Furthermore, whether by gravity data or seismic refraction data, the caldera does not have a characteristic expression. That is, there is nothing in the gravity maps or seismic refraction results to show that the caldera area is different from the rest of the crustal block.

Robin J. S. Cooke of Rabaul Volcano Observatory has been monitoring earthquakes in Rabaul Caldera for the past several years (Cooke, 1974). Seven seismographs are deployed around Rabaul Caldera with on line data telemetered to the central station at the volcanological observatory (Fig. 9). The epicenters of the earthquakes are rapidly determined by time difference methods. Calibration explosions had been set off in Rabaul Harbor a few years ago to develop tables for this rapid method of epicenter determination. Depth of foci, however, are not well determined. The results showed that earthquakes occur in rather limited areas in the caldera, marked of as A and B C D in

Figure 9. The area B C D is along the southeastern rim of the caldera and the earthquakes here may represent a continual subsidence of the caldera. The earthquakes in area A may represent intrusive making its way to the surface. In area A, especially in the northern section, can be found fumaroles and hot springs

The purpose of investigating Rabaul Volcano was to determine its internal structure so that eruptive activity could be predicted to save lives and property. The sum results of the investigations were that the internal structure remained elusive as ever, that Rabaul Volcano is only a part of a large crustal block, that the region is an area of tectonic activity characterized by conspicuous block faulting. Volcanoes are only a part of these tectonic activities. Attempts at labeling the region as an area of subduction do not harmonize with an abundance of grabens, horsts and normal faulting.

The existence of normal faults point to areas where there may be geothermal resources. Especially the Keravat and Baining Faults (Figure 5, Wiebenga and Furumoto) seem the likely area. The area there is mantled by tertiary limestones, which can form cap rocks. The fumaroles and hot springs in Rabaul Caldera itself indicate thermal sources, but these are exposed to the rather temperamental behavior of nearby volcanoes, which have been in explosive eruptive activity in historic times.

CONCLUSIONS

For the investigation of Koolau Volcano, which is quite typical of Hawaiian volcanoes, a straightforward application of geophysical techniques resulted in outlining the internal structure. The difficulty resided in organizing teams to carry out the field surveys and to master the obstacles of logistics. Proper interpretation of geophysical data delineated the central vent or plug.

With the model for Koolau Volcano as a prototype, the structure of other Hawaiian volcanoes can be readily inferred. With gravity data the dimensions of the central vents of other volcanoes can be determined, by using the density parameters obtained from Koolau Volcano.

In regards to Rabaul Volcano, geophysical methods failed to outline vents or plugs. However the relation of regional structure to volcanoes became clear. Although the internal structure of Rabaul Volcano remains elusive, possible geothermal sources became apparent, a benefit which Koolau Volcano did not provide.

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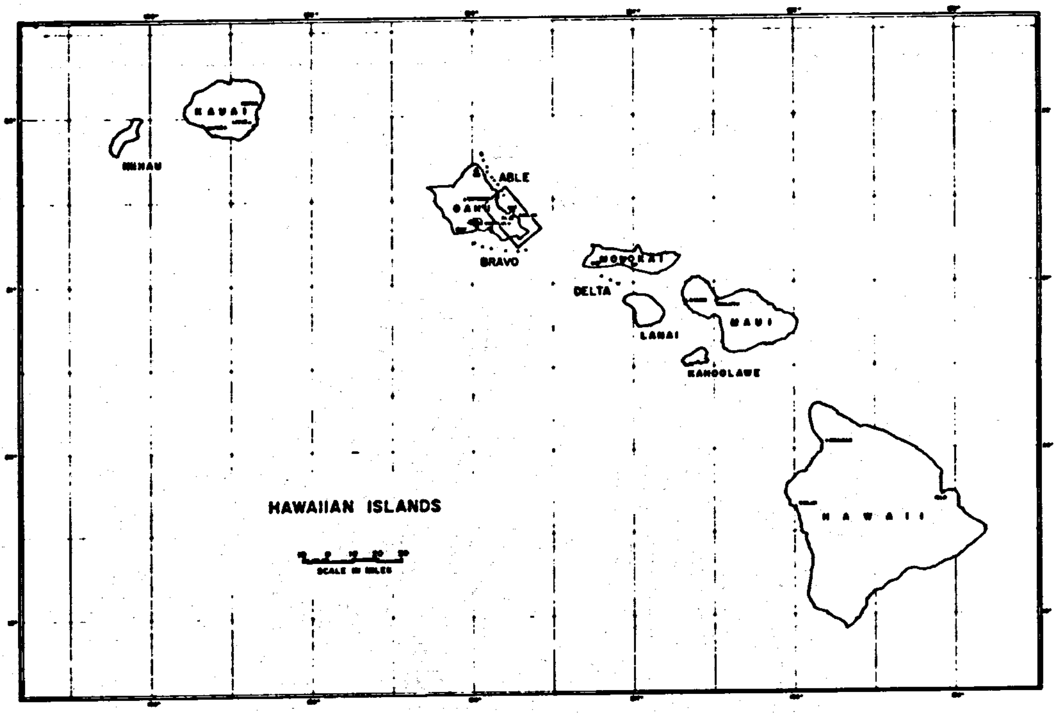
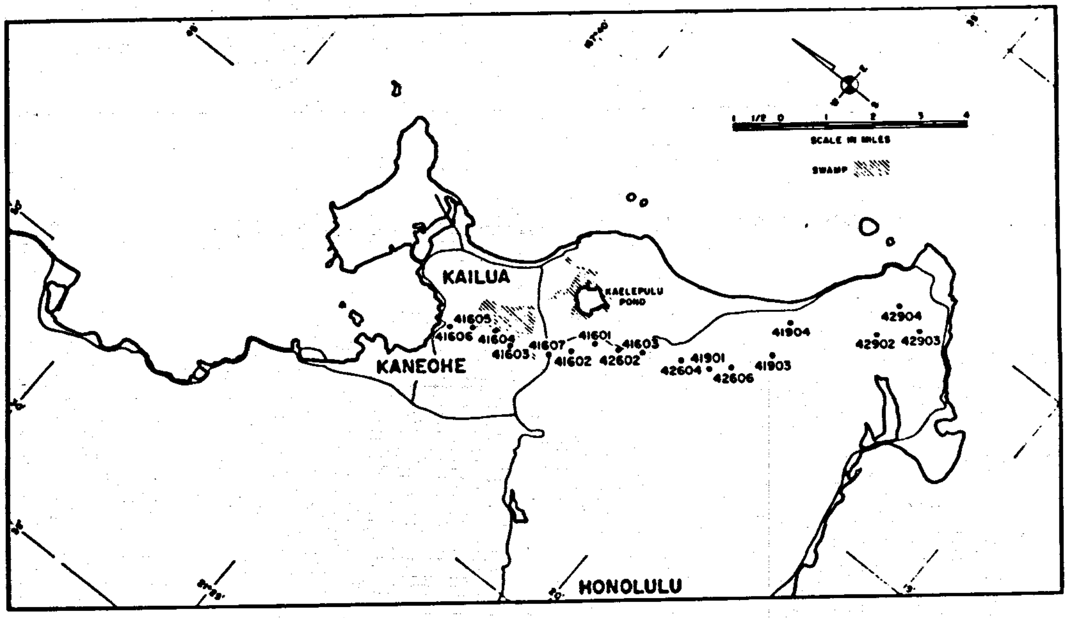


Location map of the seismic field program.



Location map of the field stations in the vicinity of Koolau caldera.

Figure 1. Hawaiian Islands with location map of seismic field program

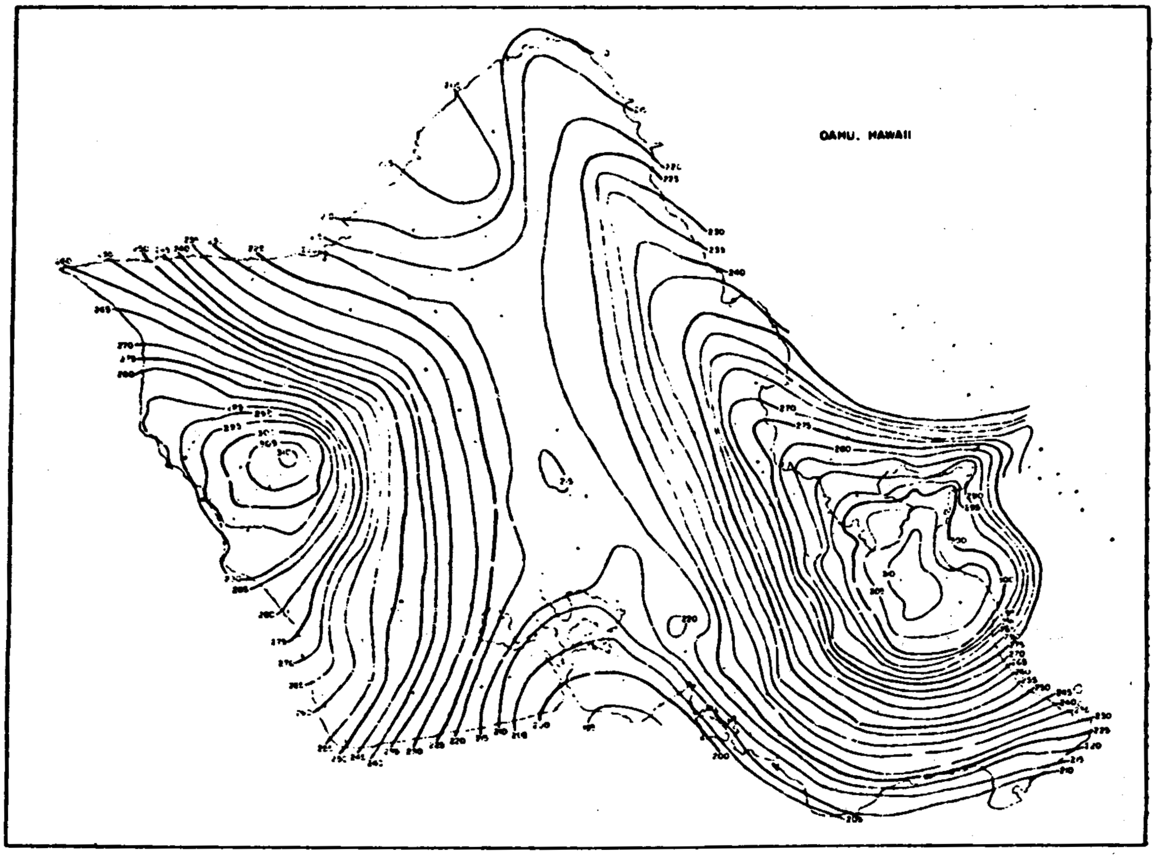


Figure 2. Bouguer anomaly map of island of Oahu (Strange, 1965)

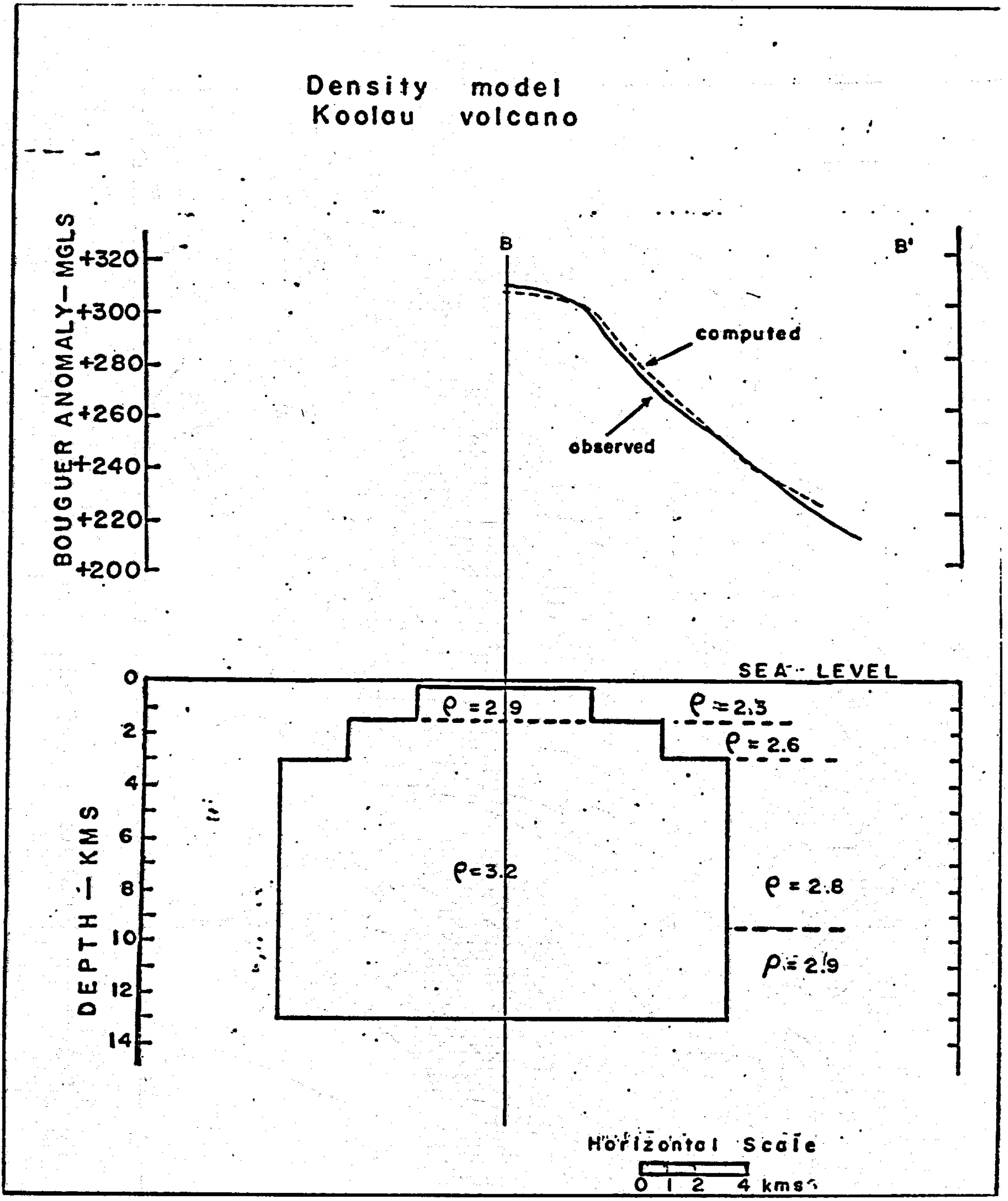


Figure 3. Density model of Koolau volcano (Strange, 1965)

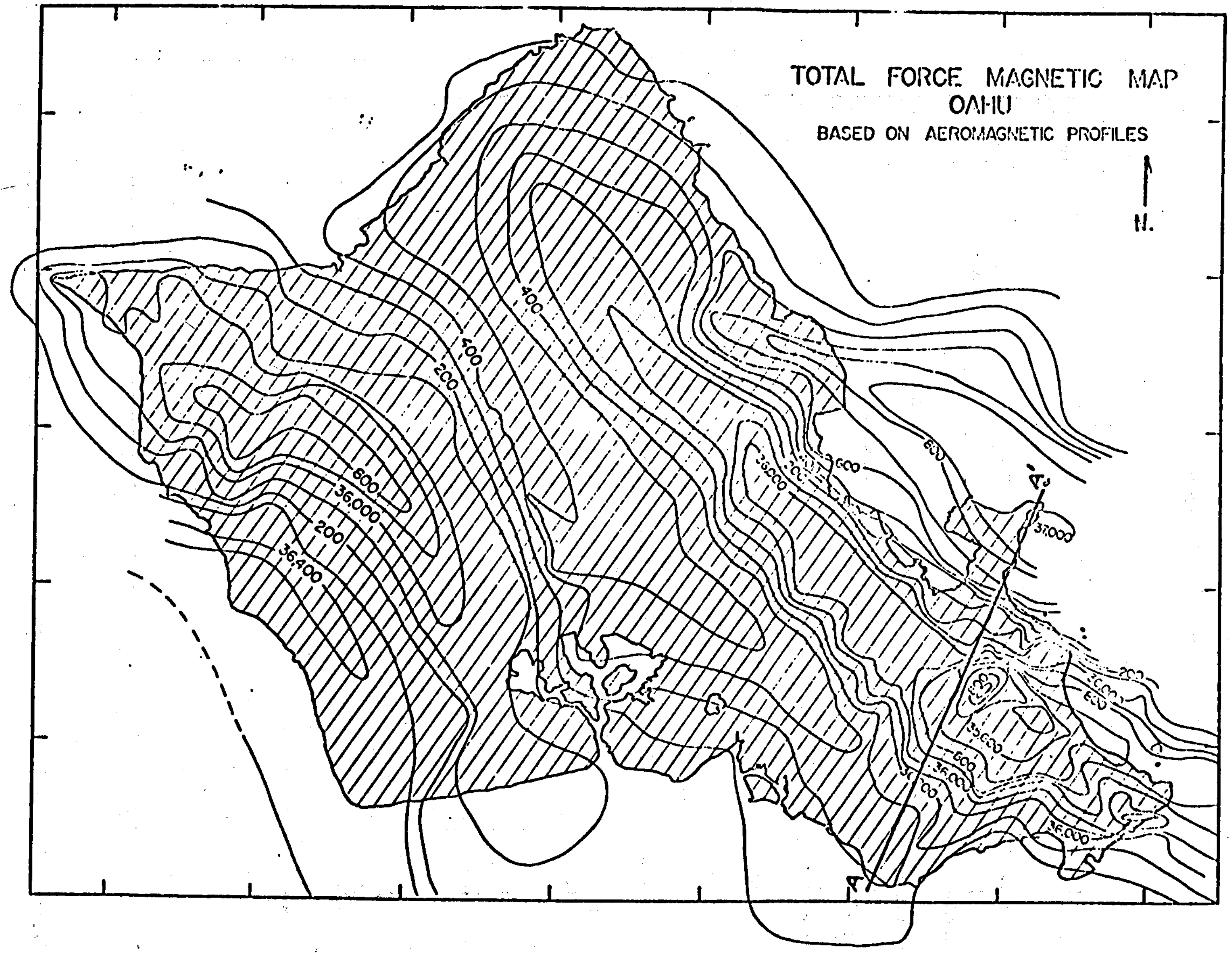


Figure 4. Total force magnetic map (malahoff, 1965)

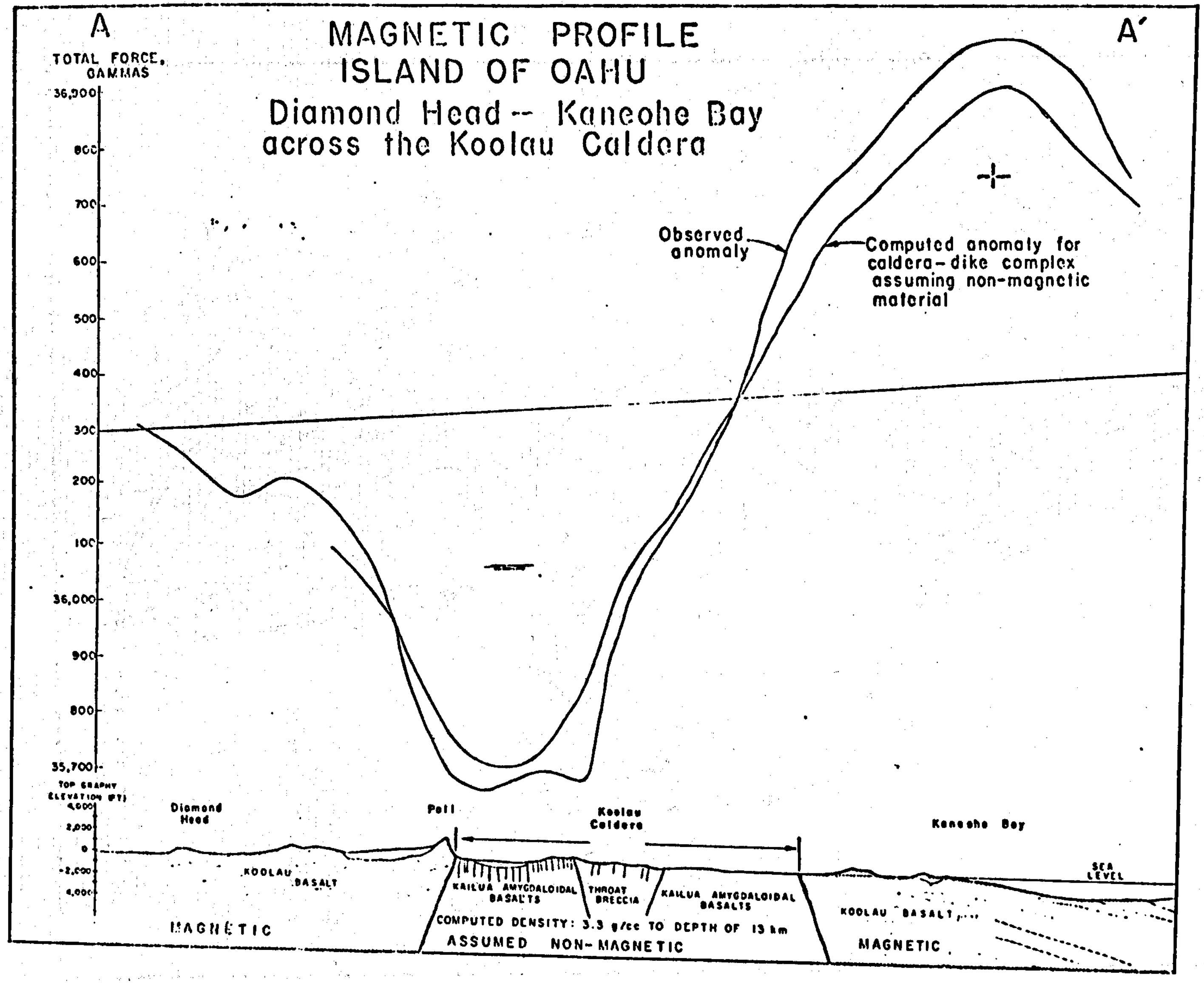


Figure 5. Magnetic profile of Oahu (Malahoff, 1965)

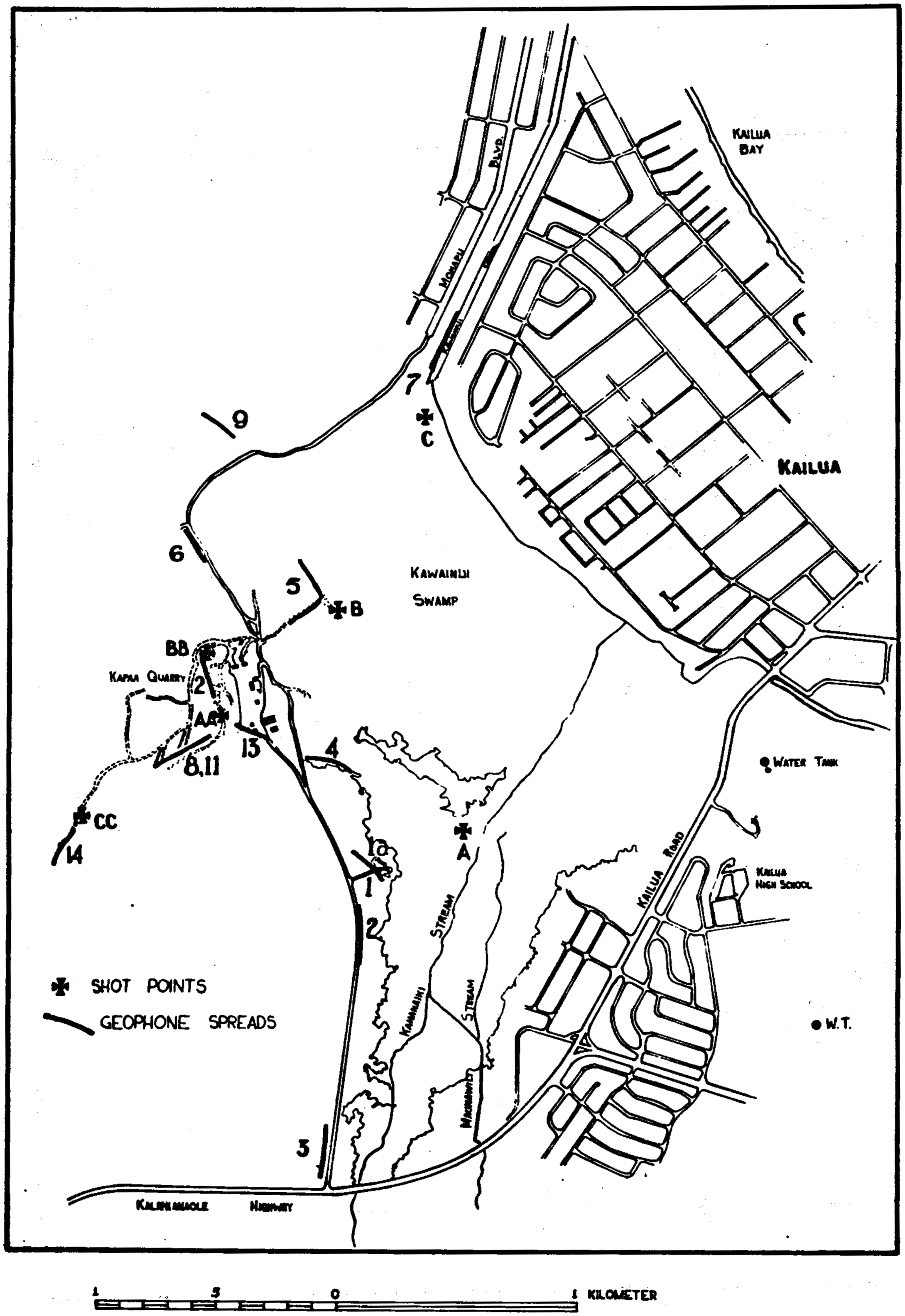


Figure 6. Location map of seismic reflection surveys over Koolau volcano

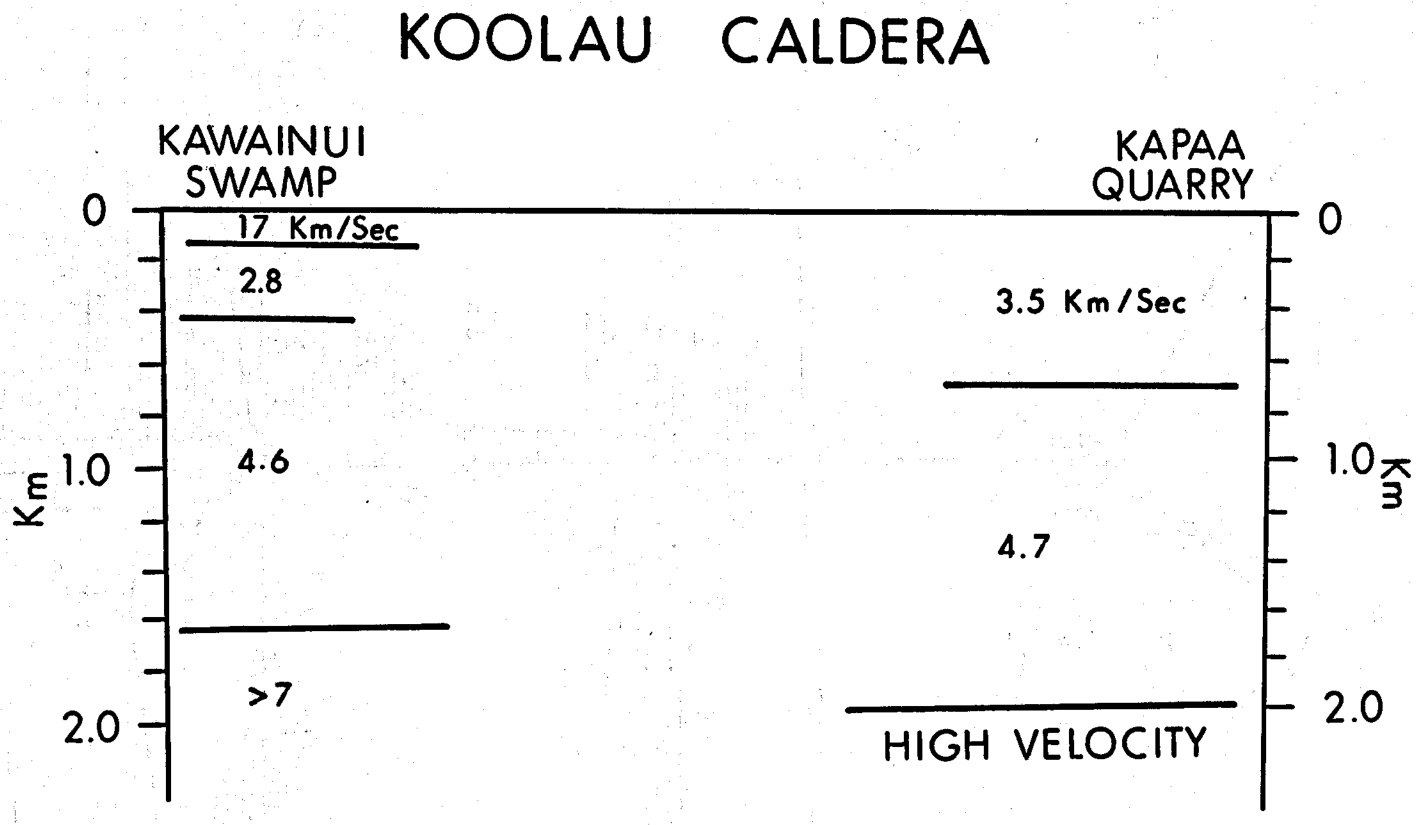


Figure 7. Results of seismic reflection surveys in caldera area

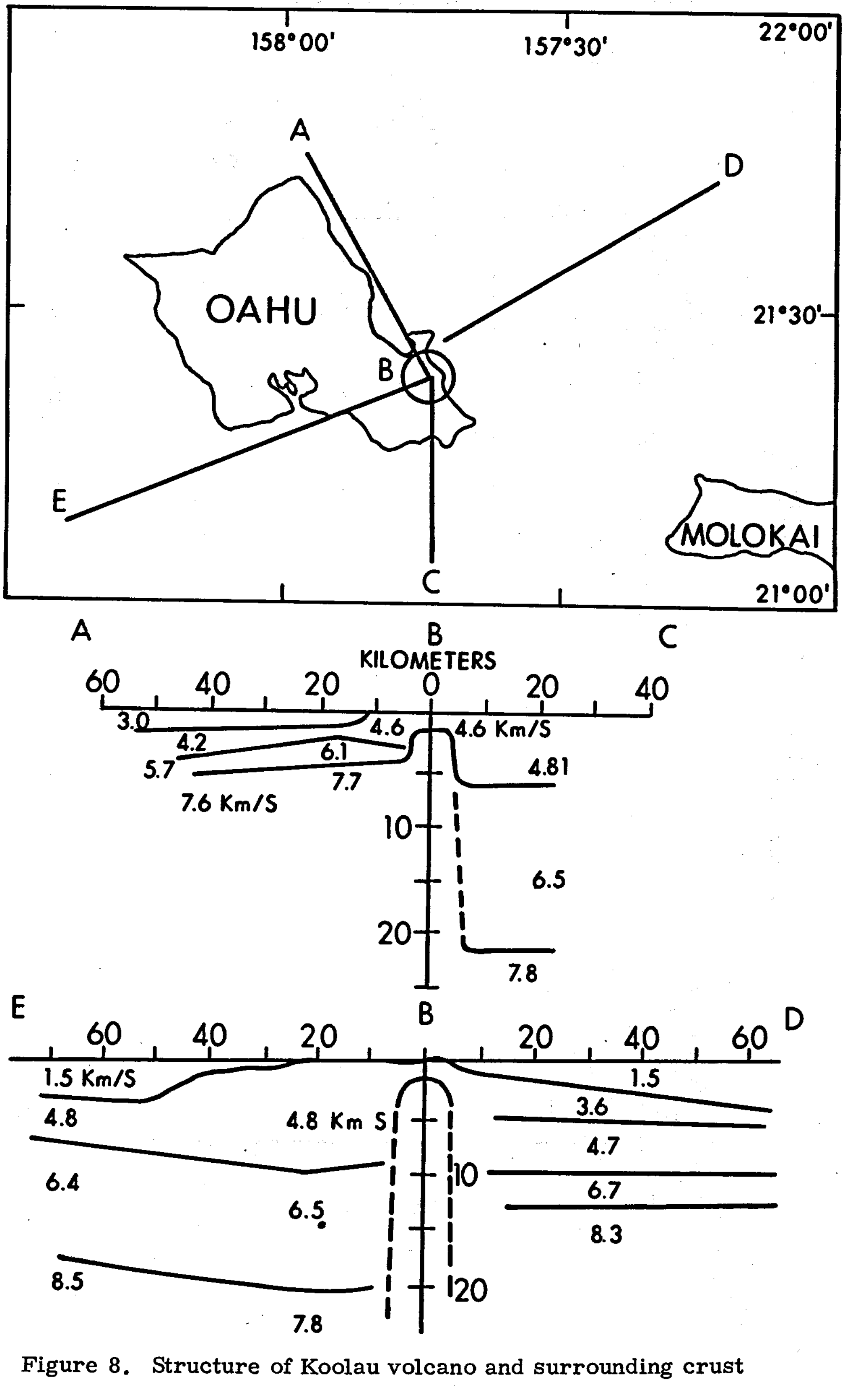


Figure 8. Structure of Koolau volcano and surrounding crust

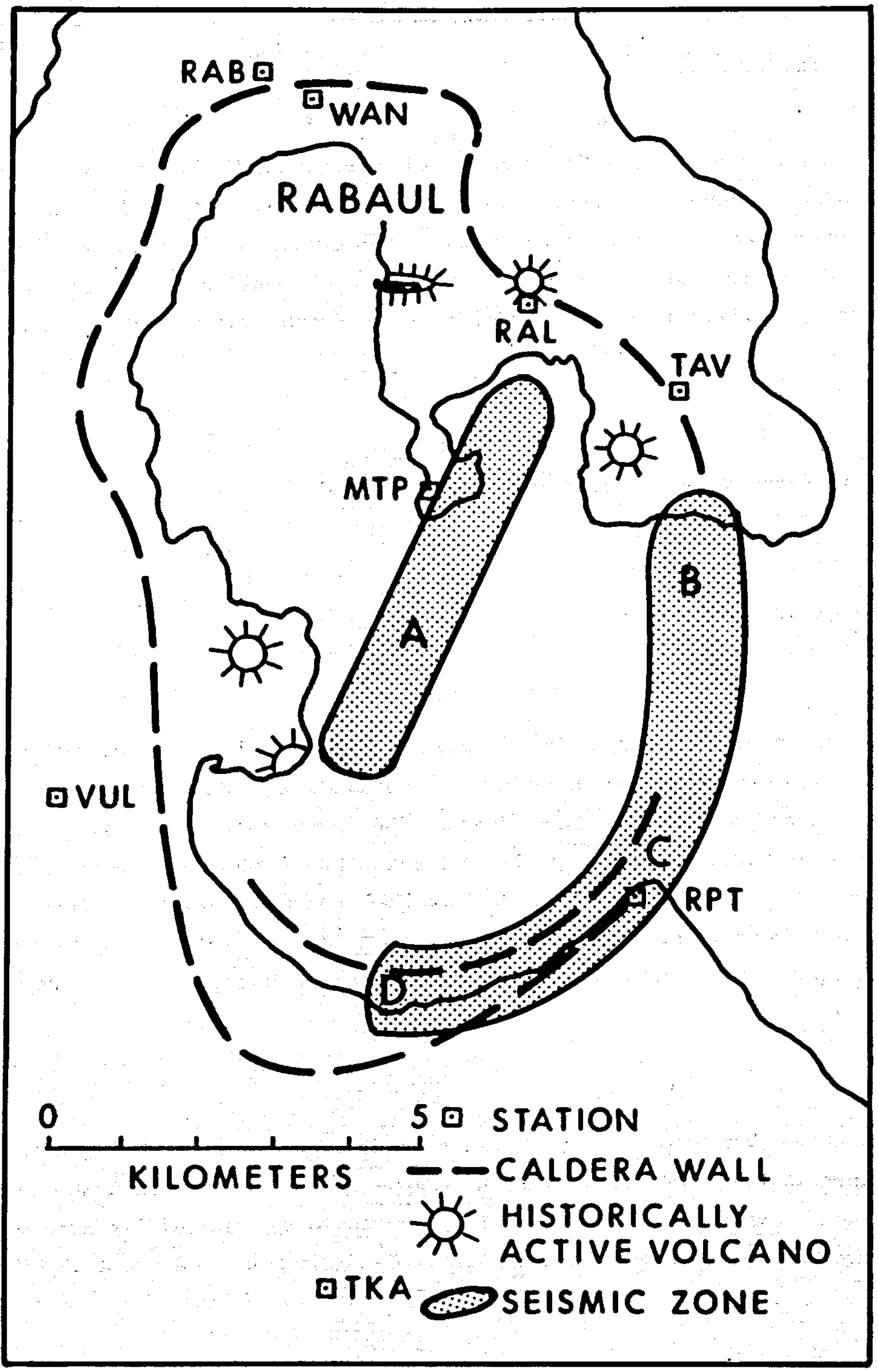


Figure 9. Epicenters of small earthquakes in Rabaul caldera (Cooke, 1974)

Discussion of Furumoto's Paper

Unidentified

Gus, just this one comment. I did the quartz alteration in the Koolau crater. The oxygen in that quartz, which came completely from the hydrothermal secondary quartz, looks like high-temperature silicate oxygen. In other words, it is not the ordinary shallow hydrothermal quartz which you would ordinarily expect. It looks like it's intensively equilibrated to very-high-temperature water. It's been swept out completely by the silicate oxygen equilibration at very high temperatures.

Furumoto

That means it favors the possibility of very hot material.

Unidentified

Yes, it supports your idea.

Peck

I have a question on the Koolau crater. That is the interpretation of the magnetic low. I've got two points I want to make. One question is whether it could be hydrothermal alteration of the plug area. As I remember, MacDonald describes a rather pervasive alteration that oxydized the magnetite. The second question is this. Although the very latest volcanism was quite young, as I remember from MacDougall's dates, the bulk of the Koolau was built several million years ago. I wonder whether that very late Koko Head-Diamond Head volcanism really is related at all to the upper part of that plug. So I wonder whether you can really, convincingly, say it is not magnetically reversed.

Furumoto

The fact that it is 2 million years ago--did he have the plug material itself at that age? We do know, certainly, that the flank material is 2 million years old. Some of the flank material is 5 million years old. The Blake event occurred 100,000 years ago. Granted that there is not, necessarily, only the Diamond Head, there are also some closer flows to the plug than Diamond Head.

Peck

But there's that study by Jackson and Wright where they were looking for nodules, and I think there is some postulation that these were drilling up through the Koolau magma chamber and sampling it, and the magma underneath it, as it came blasting through. They were coming from a much deeper source than the shallow Koolau plug.

Furumoto

True. It could be reversely polarized, but I still maintain it's--from the point of view that these recent volcanics occur all around, not just on one side of the Koolau plug. It's a funny thing that we really don't have, once the volcano starts cooling down, more flank activity rather than central plug activity.

Peck

It's rather like Mauna Kea: after the central activity, you get the cinder cones all over the place. Blasting up, maybe, from a greater depth. As I remember, MacDonald hypothesized that, if there was a magma chamber, it was much deeper.

Unidentified

What is the Curie temperature of the rocks?

Furumoto

It's 325°. So it could have flowed 2 million years ago, but when you cool that thing down from 1000° to what's normal now, you should have, if it's reversely polarized, one which is much higher than this is.

Peck

Of course, it could be almost nonmagnetic because of alteration.

Rex

It still is a loss of magnetite, even in the altered material. When I did mineral fraction separations on it, there was still a substantial amount of magnetite that had survived the alteration.

Unidentified

It's still a low.

Rex

No, it's more than a low; this thing behaves like hole. You see, that's the point; the calculation makes it look like a magnetic hole, much more than a simple reversal, or an ordinary low.

Peck

I don't think you can rule out the reversed polarizing.

Furumoto

The only solution is to drill down there, so I'm proposing to drill down there. Now, based on the fact that this is still above the Curie point, and if we assume a reasonable temperature gradient from the flank rocks to the mantle, a simple calculation shows that there is heat in the amount of 2×10^7 megawatt-years. At an efficiency of 1 percent, this would support the city of Honolulu for 100 years, so we are just hoping that that's hot enough. Of course, we don't have the "hot rock" technology to exploit that yet, but when we finally do, I think we'll have a source for Honolulu right in its own backyard. I hope we get money to drill, as it's crucial that we drill at least to a 2 kilometers depth.

Peck

If nothing else, you'll have a reversely polarized hole in basalt.

Kienle

In your gravity model, the base of the plug was at what level? Was it a semi-infinite cylinder, as a gravity model?

Furumoto

It had a bottom to it at 12 kilometers depth.

Unintelligible Question

Furumoto

I can't answer that, as I haven't studied that problem.

Unintelligible Question

Furumoto

That's a big question in Hawaiian petrology. It's just that the gravity data is such that, when we try to put models there, we've got to come up with this high density to explain the gravity data. We'll leave it up to the petrologists to explain how we have this high-density material.