ON THE STATUS OF RESEARCH LEADING TOWARD VOLCANO ENERGY UTILIZATION*,**

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I. INTRODUCTION

As the world demand for energy increases yearly and the global supply of fossil fuels diminishes at a fearful pace, the search for alternate sources of energy has become imperative. One alternate source frequently mentioned is geothermal energy. This is a generic term; in a broad sense, it is defined as heat from the interior of the earth. It occurs in several forms, such as hot intrusive rocks, volcanoes, hydrothermal reservoirs, and geopressured rocks; of these, only a few hydrothermal reservoirs have thus far been harnessed for electrical power generation. Although the popular concept of geothermal energy is an erupting volcano, productive geothermal fields are usually located tens of kilometers away from active volcanoes. So far, volcanoes have eluded the efforts of man to harness them.

For generating electrical power with present-day technology, a geothermal source should be in the form of a vapor-dominated or hot-water hydrothermal reservoir, rather rare geological formations. Throughout the world today, there may be as many as a dozen or so productive geothermal fields with a total global power output of 1000 to 1500 MW. Considering that a single American nuclear power plant can produce 1100 MW, the present global output of geothermal energy is dishearteningly small. This small output is not because finances are lacking (geothermal electricity in terms of cents per kilowatt hour is much cheaper than petroleum-fired electricity even when research and development costs are included), but the simple fact is that geothermal fields of usable hydrothermal aquifers are rare.

On the other hand, there are 800 volcanoes in the world that have been recorded as active during historical times.[1] Obviously, a vast resource is still untapped. In this paper we shall discuss the problems involved in utilizing this resource. As background to the subject, we shall touch on the various forms of geothermal energy and present a resume of volcano research up to 1973. The main body of this paper will consist of examples of recent accomplishments in volcano research, and the conclusion will present a discussion of the prospects of practicable utilization of volcano energy.

The authors apologize for the fact that their

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**The hypotheses and inferences in this article are as of June 15, 1975. They are subject to change with new data and information.

discussions are limited to geology and geophysics of volcano energy utilization. They leave discussions on turbines, heat converters, transducers, plumbing, and other engineering aspects to more competent persons.

II. DIFFERENT FORMS OF GEOTHERMAL ENERGY

The various known forms of geothermal energy may be enumerated as follows: (1) hydrothermal aquifer, (2) hot intrusive rock, (3) magma reservoir, (4) lava lake, and (5) geopressured rock. The hydrothermal aquifer can be divided into two different systems, vapor dominated and hot water.[2] The hot-water aquifer in turn is subdivided into high- and low-temperature types. Of all these different forms, the ones successfully harnessed for electrical power generation are the vapor-dominated hydrothermal aquifer and the high-temperature hot-water aquifer. The forms usually associated with volcanoes are hot-water hydrothermal aquifers, hot intrusive rock, and magma.

Vapor-dominated and high-temperature hot-water systems are usually found as confined hydrothermal systems. In this structural arrangement, a layer of permeable rock saturated with water is heated from below by hot intrusives and is overlain by a relatively impermeable cap rock. In effect, the aquifer is a natural steam boiler or pressure cooker, and a borehole drilled into the pressurized aquifer will release the steam or superheated water. To be economically utilizable with available technology, the temperature in the aquifer should be at least 180°C; a more desirable temperature is about 250°C.

A hot-water unconfined hydrothermal aquifer can become utilizable under certain conditions. How such a system works can be explained by using the schematic illustration shown in Figure 1.[3] A partly cased borehole is drilled, to a depth H, into a hydrothermal aquifer which becomes hotter with depth. The aquifer need not have a cap rock. For the sake of discussion, the lower part of the aquifer is considered to have a uniform base temperature, T_3. After the hole has been completed and cased part way into the temperature T_3 region, the water in the bottom of the hole is disturbed by injecting compressed air into the bottom, and the pressure P_4 at depth H is reduced. The resulting buoyancy pushes the hot water to a level Z*, at which point the hot water flashes to steam at saturated vapor pressure (SVP). The steam will shoot out of the well with a well head pressure (WHP). In a flashing condition, the pressure P_4 at depth H will be

$$P_4 = SVP + \rho_3 g(H - Z^*) \quad (1)$$

where

ρ_3 = the density of water at temperature T_3;
g = acceleration due to gravity.

The system will continue to flash if the pressure in the aquifer, P_3, remains sufficiently greater than the pressure in the borehole, P_4, so as to overcome WHP and the hydrodynamic resistance along the borehole.

The question is, how will P_3 be greater than P_4. If the mathematical reasoning of Elder[3] is followed, one must conclude that the rock formation contributes to P_3 by overburden pressure. This means that the rock formation is deformable and it follows that, if hot water is continually removed from the aquifer without recharge naturally or artificially, there will be ground subsidence around the borehole. Sometimes the subsidence can assume alarming proportions, as a few examples from the Wairakei geothermal field in New Zealand show. On the other hand, if the rock matrix of the aquifer is relatively rigid, such as is the case of basaltic flows, the system as shown in Figure 1 will not continue to flash.

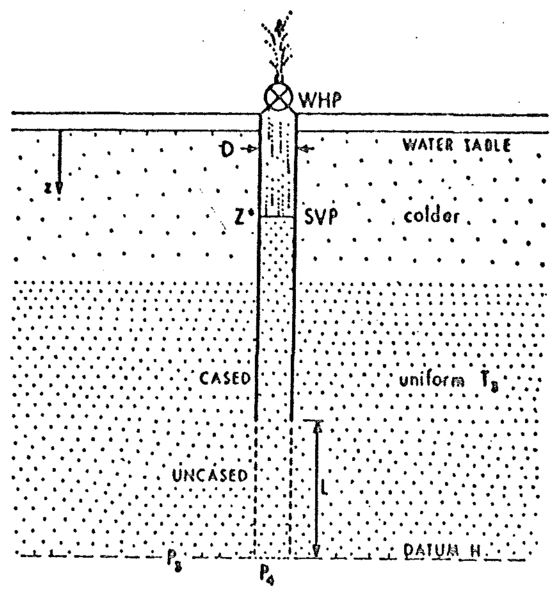

FIGURE 1. Diagram of a borehole drilled into an unconfined aquifer in a deformable rock formation: (WHP) well head pressure; (SVP) saturation vapor pressure; (D) diameter of borehole; (L) length of uncased part; (P_3) pressure in aquifer; (P_4) pressure in borehole at datum plane H; (T_3) base temperature of aquifer. (Courtesy of the American Geophysical Union.)

Recently, Nathensen[4] has shown that if flashing can be induced at a lower level so that it occurs within the region of base temperature T_3, the system will continue to flash even if the rock burden is rigid and does not contribute to P_3. The calculations were done for base temperatures of 200 and 250°C.

Of the above mentioned forms of utilizable geothermal reservoirs, vapor-dominated systems are usually found tens of kilometers away from active volcanoes or near ancient volcanoes that ceased activity in past geological ages. High-temperature hot-water systems of New Zealand are also quite removed from volcanoes. In Iceland, high-temperature hot-water systems are found in the volcanic zone but have not been harnessed for power generation. On the whole, thermal sources of volcanoes, in whatever form, have not been utilizable with present-day technology.

III. VOLCANO RESEARCH UP TO 1973

Volcanoes have been studied for decades from the academician's viewpoint, namely because volcanoes are fascinating phenomena. Along the way scientists began to give serious thought to defining the role that volcanoes play in geological processes. With the advent of plate tectonics theory, the amount of money and effort expended in volcano research increased significantly. As most of these research efforts were directed toward understanding basic geological processes, they were not geared to obtaining those parameters that would be useful in energy application. Nevertheless, a tremendous amount of information on volcanoes has become available in scattered places.

To ascertain the present-day level of volcano knowledge and to assess how far we have to go before volcano energy utilization becomes a reality, a U.S.-Japan Cooperative Science Seminar on Volcano Energy Utilization convened in Hilo, Hawaii for 1 week in February 1974, under the auspices of the U.S. National Science Foundation and the Japan Society for the Promotion of Science. In addition to Japanese and American participants, there were observers from the Philippines and Spain. The group represented a broad spectrum of interests, including geophysicists, geologists, engineers, economists, lawyers, and businessmen. Although the conclusions of the seminar have been published[5] and the papers and associated discussions have been edited and published,[6] the highlights of the seminar will be repeated here for the convenience of the reader.

The seminar provided an overall view of the status of volcano research in 1973. The participants were actively engaged in research in Japan, the Philippines, Papua New Guinea, New Zealand, Hawaii, the continental U.S., Alaska, and the Canary Islands; each was tackling problems peculiar to the volcanoes of his region. The seminar provided a forum where volcano researchers could obtain an overview of the present status of volcanology.

Some papers dealing with regional geology of volcanoes showed that heat flow through volcanoes accounts for only a small percentage of regional heat flow. Although not specifically expressed, these papers implied that for the purposes of volcano energy utilization, a volcanic zone, rather than particular volcanoes, should be studied. Volcanoes are, of course, surface indicators of sources of thermal energy.

One of the strong opinions expressed was that surface methods of exploration, i.e., geological, geophysical, and geochemical, have been used to their limit, and volcanology must now go into a new phase of extensive drilling programs if it is to advance significantly. Without probing into the interior of volcanoes, volcanologists have no check on evaluating the validity of their conclusions inferred from surface data. Some conclusions reached at the final discussion session of the seminar were that theoretical models of the relationship of volcanism-to-plate tectonics are insufficient and the heat transfer mechanism of the magma-hydrothermal system is not well understood.[7]

At the seminar Nakamura[8] proposed a classification of volcanoes according to global tectonic setting. Although we shall follow his line of thought, we have changed the nomenclature and list the types as follows.

1. Spreading zone volcanoes.
2. Subduction zone volcanoes.
3. Intraplate volcanoes, oceanic type.
4. Intraplate volcanoes, continental type.

The association of volcanoes with the processes of plate tectonics can be briefly explained with the assistance of Figure 2. Volcanoes of fissure-type eruptions producing basaltic flows occur along oceanic spreading centers, where mantle material wells up to form new plates. In subduction zones compressive forces cause rocks to melt, and the molten rocks find their way to the surface to form volcanoes. The mechanism of melting is a point of debate among geochemists. Erupted rocks along subduction zones are andesite, dacite, and related types. Volcanoes often appear in the middle of a plate, whether the plate is oceanic or continental. Both the hot spot theory[9] and the progressive crack theory[10] have been advanced to explain these volcanoes. In oceanic plates the rocks are usually shield basalts; in continental plates the rocks may vary from flood basalts to rhyolitic flows. Figure 3 shows the locations of recently active volcanoes with reference to such obvious tectonic features as oceanic ridges and trenches. It can be quickly seen that most of the volcanoes are associated with subduction zones. Table 1 gives the rate of production of volcanic material from different types of volcanoes, as enumerated by Nakamura.[8] Spreading zones apparently eject more material than subduction zones, but ejection takes place so quietly and smoothly that the activity is not recognized as an eruption.

In subsequent sections of this paper, we shall discuss research of volcano energy utilization in the four types of volcanoes. Although the seminar was held in February 1974, the amount of publication that has come to light since then is significant enough to justify devoting the body of this paper to the most recent accomplishments. Those who are interested in previous work should consult the proceedings of the seminar[6] and a recent monograph on physical volcanology.[11]

IV. SPREADING ZONE VOLCANOES: ICELAND

The active volcanoes of Iceland are situated in the spreading zones of the mid-Atlantic Ridge. As volcanism occurs along fissures of a spreading zone, geothermal specialists of Iceland tend to study the characteristics of the volcanic zone rather than the individual volcanoes. Because of ample ground water fed by high rainfall, unconfined hydrothermal systems are found along volcanic zones. To date, thermal waters from these hydrothermal systems have been used mainly for space heating.

Bodvarsson[12] has grouped the geothermal regions of Iceland into high-temperature and low-temperature areas. Of the approximately 250 geothermal areas, 13 are high temperature. These areas are characterized by aquifer temperatures of

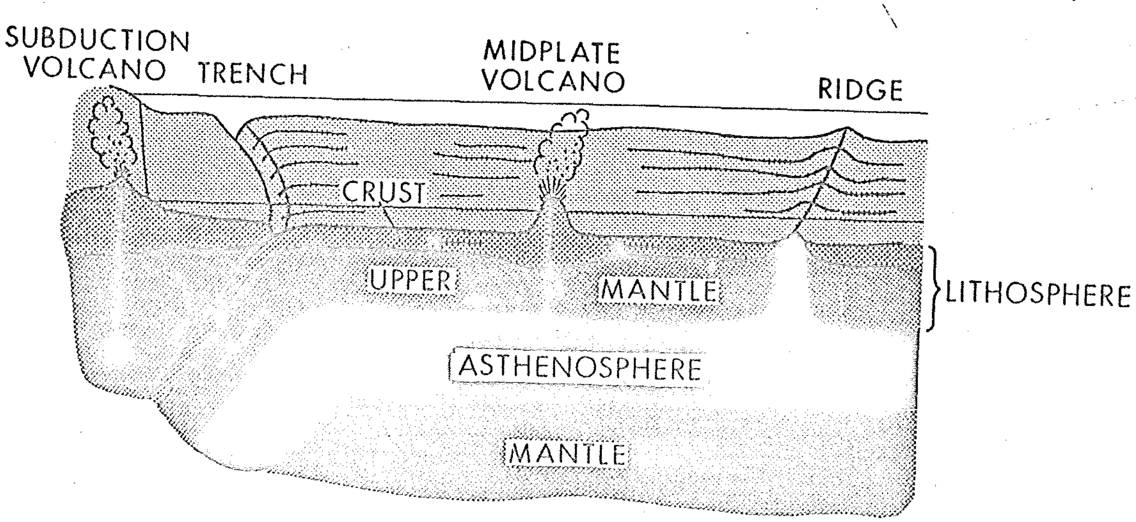

FIGURE 2. Relationship of volcanoes with tectonic processes.

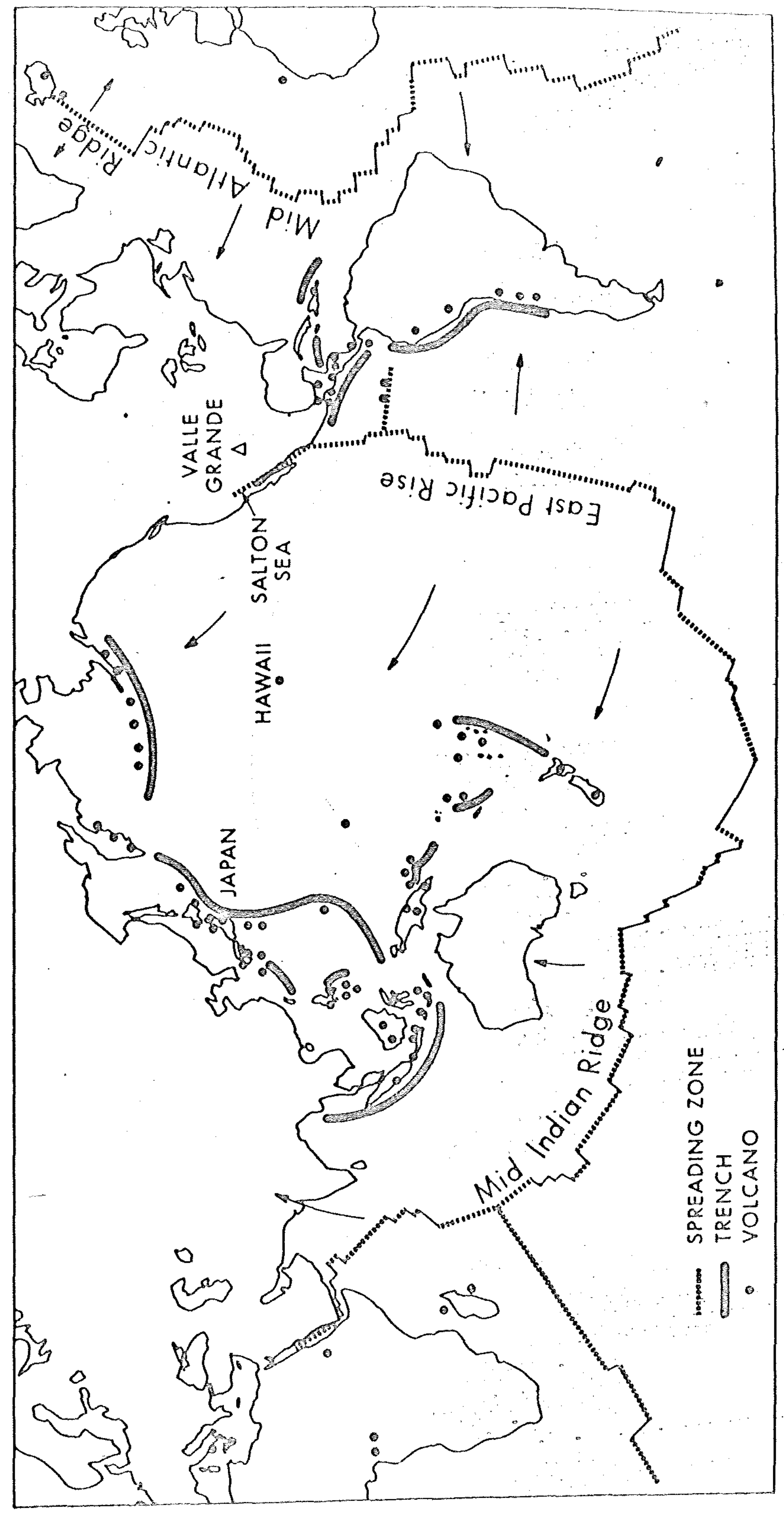

FIGURE 3. Global map showing tectonic features and volcanoes active during 1968 to 1974. The information on volcanoes (shown by solid circles) was compiled by the Center for Short Lived Phenomena, Smithsonian Institution.

TABLE 1

Volcanic Material Production Rate

		Annual production rate[7] of volcanic material in km³ [a]
Spreading zone volcanoes	Oceanic ridge-axis volcanoes	4 ~ 6
Subduction zone volcanoes	Island arc volcanoes	~0.75
Intraplate oceanic volcanoes	Volcanic islands seamounts, guyots	~1
Intraplate continental volcanoes	Flood basalts, cryptovolcanics	~0.1
Total		6 ~ 8

[a]Equivalent to 1 ~ 3 × 10^{26} erg/yr.

about 250°C (see Figure 4). The four high-temperature areas in Reykjanes Peninsula appear to lie on a plate boundary, i.e., a spreading zone, where an en-echelon fault swarm crosses the plate boundary.[13] Low-temperature areas are characterized by aquifer temperatures of around 100°C and are commonly about 10 km from the axis of the plate boundary.

A. High-temperature Areas

The high-temperature area of Krisuvik (see Figure 4) in the Reykjanes Peninsula has been studied systematically.[14] The area is characterized by two parallel hyaloclastite (volcanic ash) ridges which seem to indicate the location of subsurface maximum tectonic activity: in this case, plate accretion and spreading. Geophysical surveys carried out over the area reveal a rather consistent picture of crustal structure (Figure 5). A crustal layer with a P-wave velocity of 6.5 km/sec is encountered at a depth of 3 km. This layer is also the location of a concentration of microearthquakes and is characterized by low electrical resistivity. Icelandic geophysicists refer to this as Layer 3 and consider it to be the source of thermal energy for the hydrothermal aquifer riding on it. Electrical surveys showed another layer of low resistivity about 120 to 200 m below the surface, but borehole data from the area show that maximum temperatures exist to depths of 400 m (see Figure 6) followed by a temperature inversion at greater depths.

To account for the geophysical data and the temperature inversion at depth, Arnorsson et al.[14] have proposed two separate models. In the first model (Figure 7A) they assume that Layer 3 represents upwelling material in the tectonic spreading process and that heat is continually supplied through Layer 3. In the model, then, the aquifer will be in rapid convective motion with rising plumes of hot water (Figure 7A). In the second model (Figure 7B) Layer 3 is assumed to be an intrusive sill with a residual, diminishing source of heat. Convective motion in the aquifer will then be a more leisurely rising column of water. Both the geophysical data and the mineral content of water from the aquifer tend to favor the second model.

According to Arnorsson et al.,[14] if the first model and hypothesis are correct, then water at 260°C can be recovered for electrical power production. Conversely, if the second model and hypothesis are correct, only insignificant amounts of water about 230°C will be recovered and electrical power production is not feasible. However, the hot water could be used for space heating. To test which model is correct, Arnorsson et al. propose that a borehole be drilled to a depth of 2000 m.

B. Low-temperature Areas

The low-temperature geothermal areas of Reykjavik and Reykir, which have been described in detail by Tomasson et al.,[15] occur adjacent to the volcanic zone and not too far from the high-temperature field of Krisuvik (Figure 8). Both the Reykjavik and Reykir fields are comprised of quaternary volcanic rocks.

The ground water cycle of the low-temperature fields has been explained by Tomasson et al. as

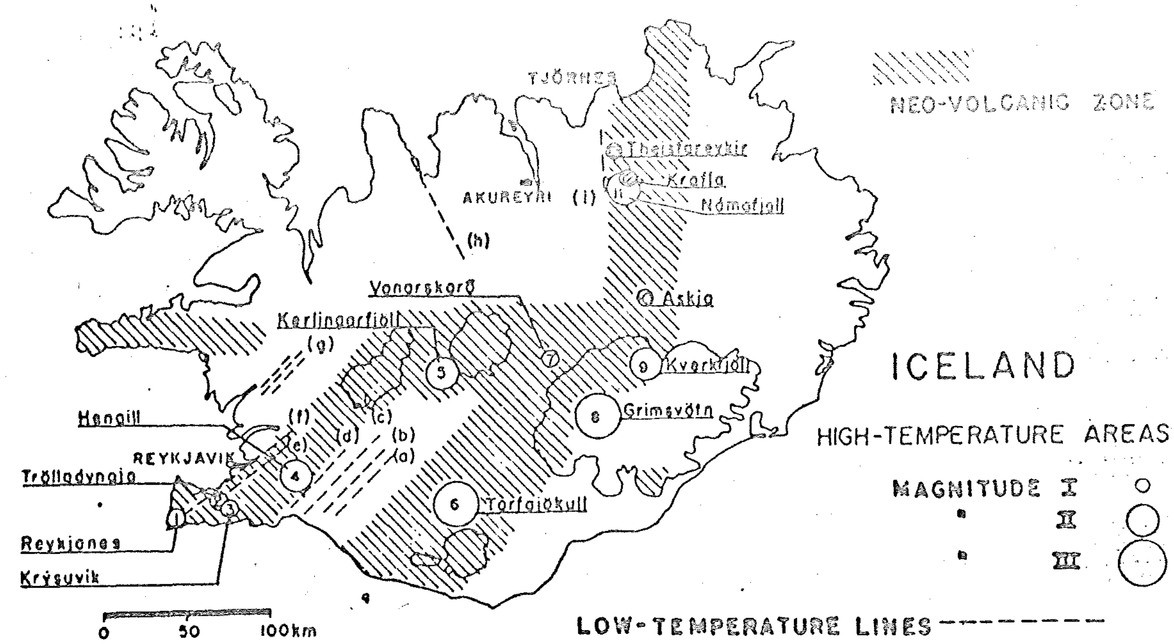

FIGURE 4. Volcanic zones of Iceland (shaded areas), high-temperature areas (circles), and low-temperature areas (broken lines). Magnitudes of thermal areas were defined in terms of total heat output: (I) 5 to 25 × 10^6 cal/sec; (II) 25 to 125 × 10^6 cal/sec; (III) 125-to 750 × 10^6 cal/sec. (from Bodvarsson, G., *New Sources of Energy, Proceedings of United Nations Conference,* Vol. 2, 1961, 82. With permission.)

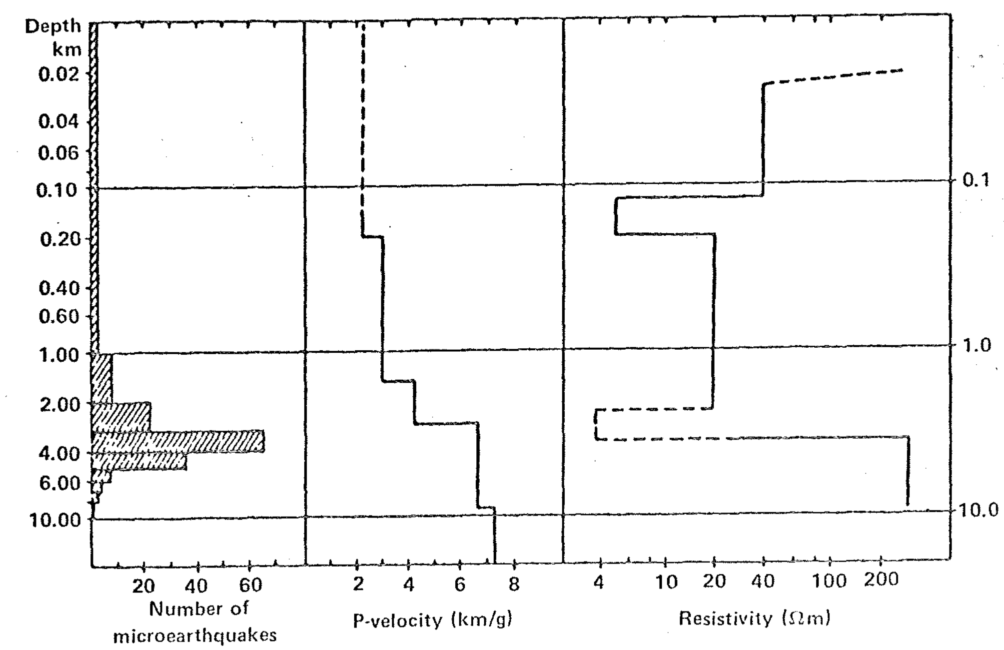

FIGURE 5. Crustal section of Krisuvik area, showing microearthquake distribution, P-wave velocity profile, and electrical resistivity profile. (From Arnorsson, S., Bjornsson, A., and Gislason, G., in Proc. 2nd United Nations Symp. on the Development and Use of Geothermal Resources, San Francisco, 1975.)

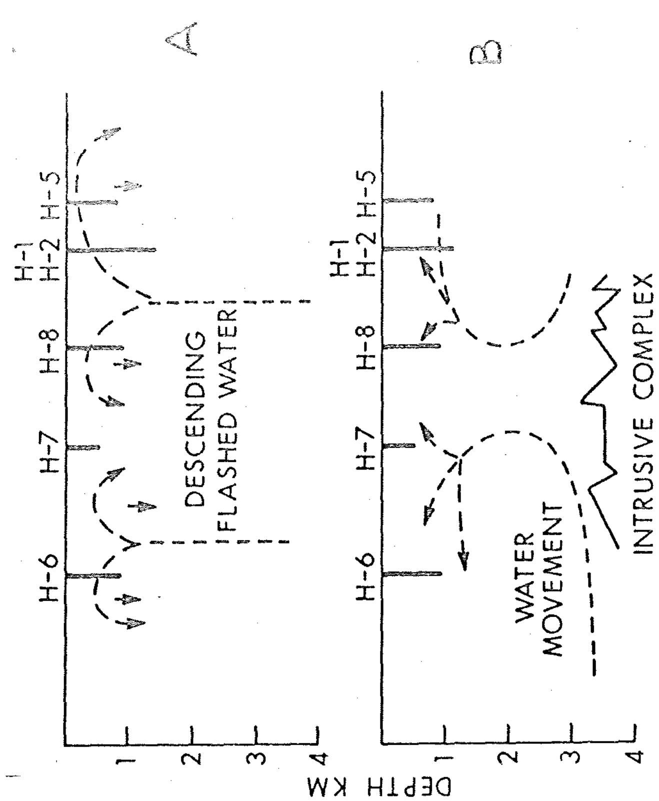

FIGURE 7. Convecting models for high-temperature hydrothermal system of Krisuvik. Model A assumes that the system overlies a spreading zone; model B assumes that the hot source is an intrusive with residual heat. (From Arnorsson, S., Bjornsson, A., and Gislason, G., in Proc. 2nd United Nations Symp. on the Development and Use of Geothermal Resources, San Francisco, 1975.)

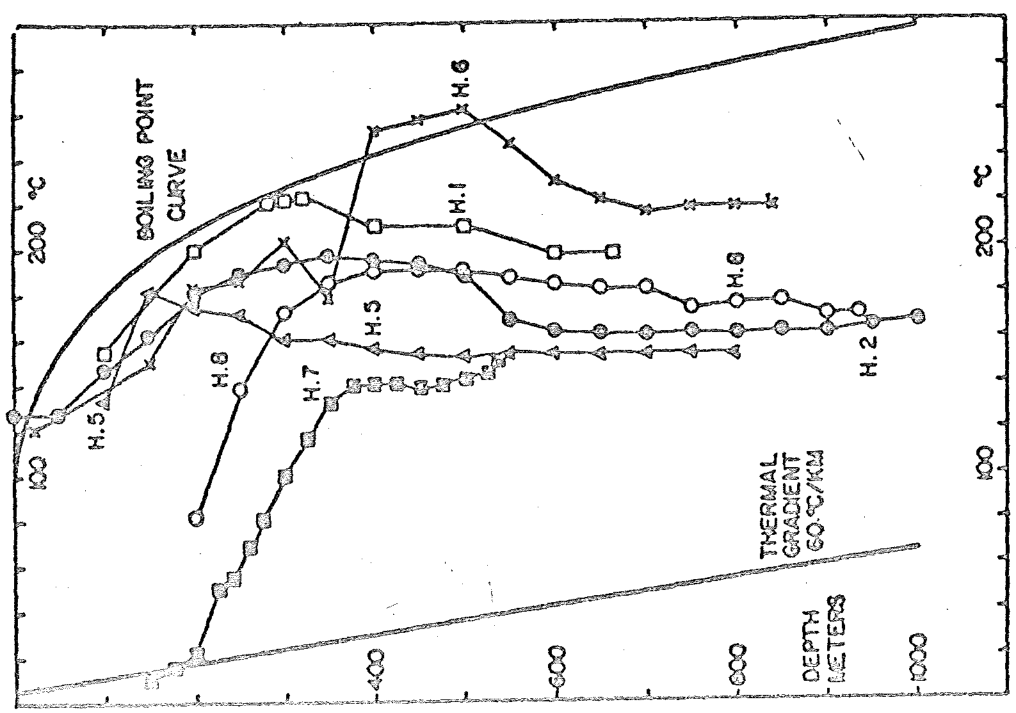

FIGURE 6. Temperature profiles of boreholes in Krisuvik thermal area. (From Arnorsson, S., Bjornsson, A., and Gislason, G., in Proc. 2nd United Nations Symp. on the Development and Use of Geothermal Resources, San Francisco, 1975.)

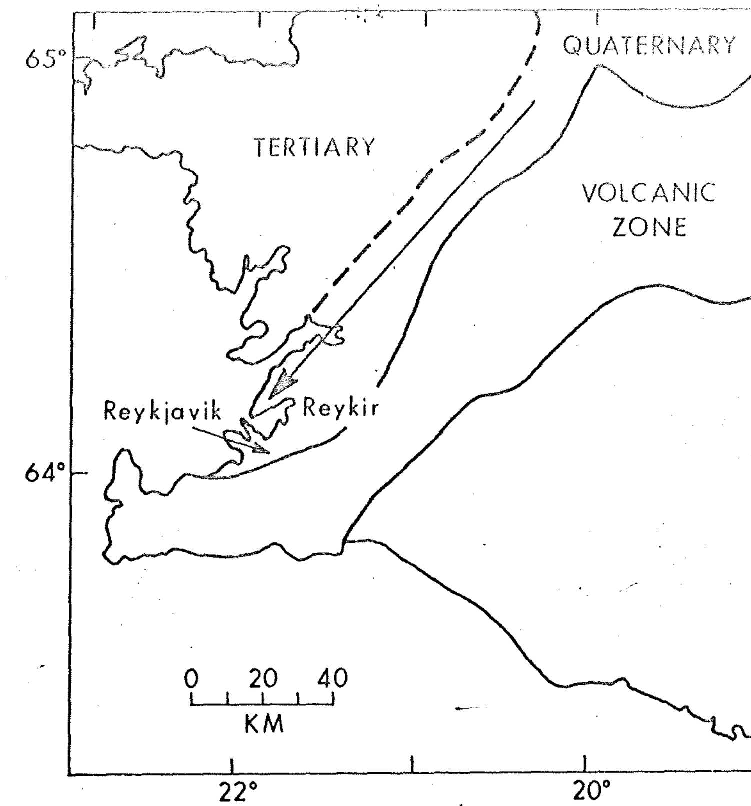

FIGURE 8. Locations of low-temperature fields of Reykjavik and Reykir and their relation to the volcanic zone, quarternary and tertiary volcanoes. The arrow shows the general direction of ground water flow. (From Tomasson, J., Frioleifsson, I. B., and Stefansson, V., in Proc. 2nd United Nations Symp. on the Development and Use of Geothermal Resources, San Francisco, 1975.)

follows. Rain water from the highlands seeps through the ground, moving toward the ocean following geological trends. As the volcanic zone in the Reykjanes Peninsula is a linear feature trending northeast-southwest, the dike zones in the quaternary rock zone parallel the volcanic zone, since the quaternary rocks originally formed at the spreading centers and moved westward along with the Atlantic plate movement. Ground water then percolates seaward through porous sections between dike complexes in the general direction indicated by the arrow in Figure 8. Figure 9 illustrates how the three thermal fields (Seltjarnarnes, Laugarnes, and Ellioaar), which occur within the Reykjavik low-temperature area, are separated by dike complexes. Ground water flows between the dike complexes is similar to channel flow. However, heat from Layer 3 warms the moving water and forms a convective pattern, as shown in the Ellioaar field to the right.

By deuterium studies, Tomasson et al.[15] concluded that the ground water is of meteoric origin, that there is little mixing between channels, and that hot water from the volcanic zone does not penetrate the low-temperature areas.

The Ellioaar field which is closest to the volcanic zone has the lowest temperature of the three fields. This inverse property is explained by the higher porosity of the Ellioaar field, through which the ground water moves more rapidly than through the other two fields.

The temperature in these three fields ranges from 70° to 145°C, making the resource impracticable for electrical power generation with present-day technology. However, the hot water from the fields is used extensively for space heating. As a result, today Reykjavik is a smokeless city in the severest winter, with such luxuries as swimming in heated pools all year round. By means of hothouse agriculture, the anomalous

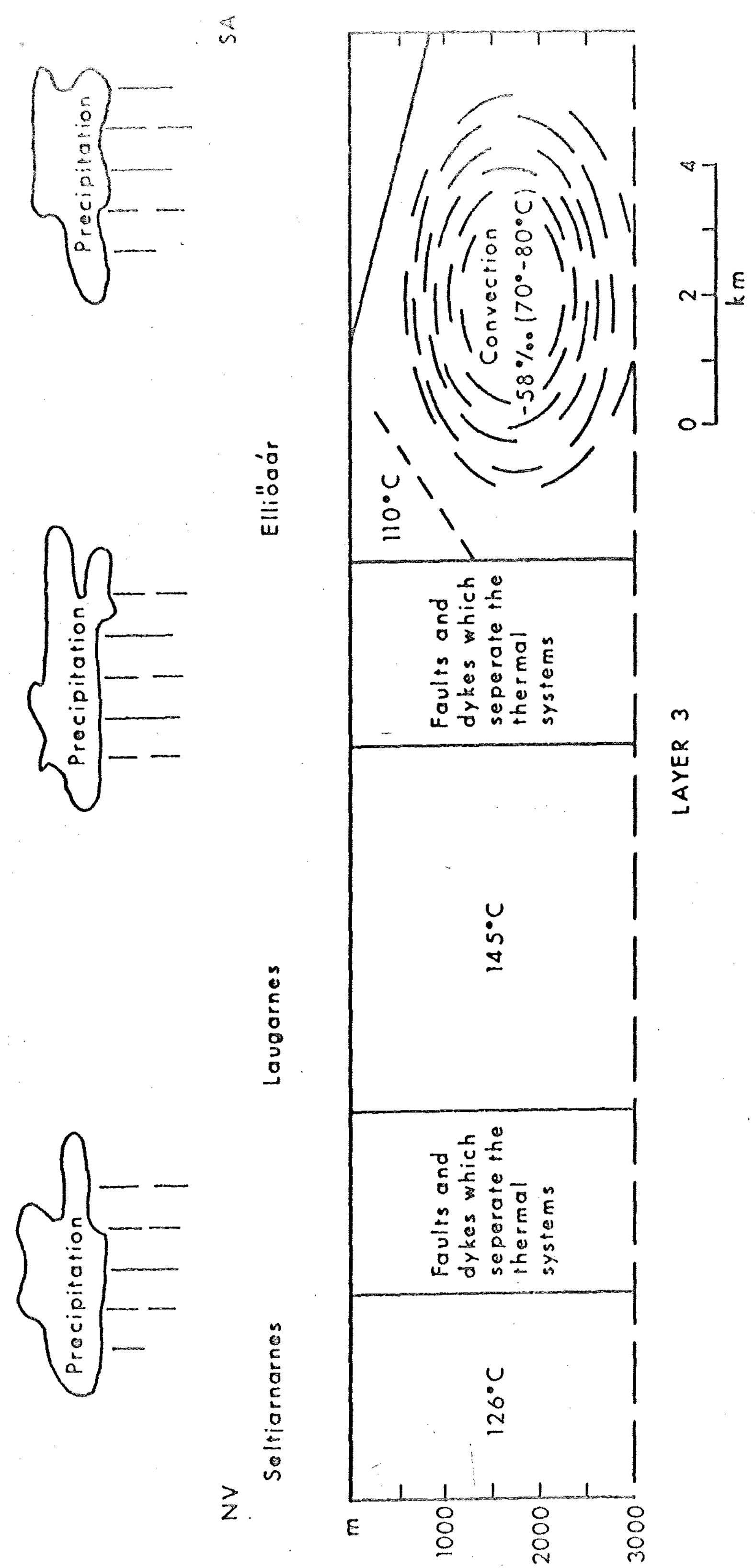

FIGURE 9. Convection models for Reykjavik low-temperature area. The names are local areas; NV is northwest and SA is southeast. (From Tomasson, J., Frioleifsson, I. B., and Stefansson, V., in Proc. 2nd United Nations Symp. on the Development and Use of Geothermal Resources, San Francisco, 1975.)

phenomenon of a small banana industry in Iceland has become a reality.

V. SPREADING ZONE OVERLAIN BY A CONTINENTAL PLATE: SALTON TROUGH, U.S.

On its northern end the spreading zone for the Pacific Ocean plate (the East Pacific Rise) enters the Gulf of California and plunges under the North American continental plate. The tectonic activity of the spreading zone has given rise to the Salton Trough, which includes the Imperial Valley and Salton Sea of California and the Mexicali Valley of Mexico. An excellent summary of structural geology and tectonic processes of the Salton Trough region is given by Elders et al.[16] In fact, we shall use their pictorial representation of tectonic history (Figure 10).

According to Elders et al.,[16] a two-layered

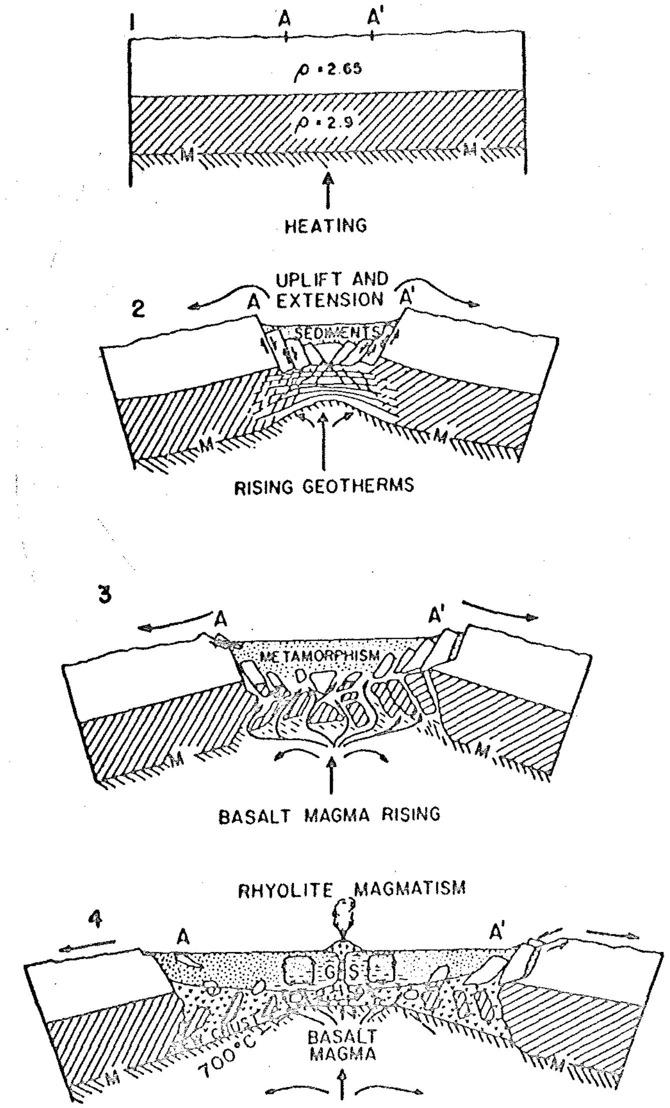

FIGURE 10. Tectonic history of the Salton Trough, case of a continental plate overlying a spreading zone. For explanations of various stages, see text. (From Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., *Science*, 178, 15, 1972. With permission.)

continental crust begins to be disrupted by rising hot material from the deep mantle (Figure 10, Stage 1). Due to spreading action, a trough is formed, which becomes partly filled by sediments (Stage 2). The widening trough is invaded by basaltic magma, and metamorphism of the sediment takes place (Stage 3). This is followed by the melting of the basement and extrusion of rhyolitic magma. Ascending hot brines then form a hydrothermal system in the sediment.

The geothermal fields of the Salton Trough contain unconfined hydrothermal systems in sedimentary layers, a utilizable form of geothermal energy. At the present time, at 37-MW geothermal power plant is in operation at Cerro Prieto in the Mexicali Valley. In the Imperial Valley on the American side, no electrical power plants are now in operation, but plans for large-scale exploitation have been laid. A pilot plant for desalinization of water using energy from hot brine is in operation at East Mesa in Imperial Valley.[17]

Exploitation of the thermal fields of the Salton Trough has been delayed because of the extremely high salinity of the thermal waters. Solutions to the problem are being developed. One proposed method for utilizing the hot brine is the total flow concept.[18] In this method hot pressurized brine is allowed to flash at the well head to drive a hydraulic impulse turbine. The great advantage of this system is that corrosion-erosion resistant material can be used in the fabrication of the turbines and accessories. Since the literature on the geothermal fields of the Salton Trough is abundant (e.g., Palmer et al.,[19] Rex et al.[20]), we will end our discussion here.

VI. SUBDUCTION ZONE VOLCANO: EXPERIMENTS ON SATSUMA-IWO JIMA VOLCANO, JAPAN

As previously pointed out, by far the largest number of active volcanoes occur along subduction zones. Volcanism results from partial melting of rocks as they are compressed by tectonic forces. There are several theories to explain the paradox of how a downgoing lithospheric slab, which is relatively cold, can contribute to melting; they all seem to agree that water (which is present in the sediments and crustal portion of the lithosphere), by lowering the melting point of rocks, is the active ingredient. The molten rock or magma undergoes differentiation, and the less dense portions migrate upward to erupt on the earth's surface as andesitic or dacitic lava.

Along the subduction zones conventional geothermal reservoirs may be found, but, as previously mentioned, volcanoes are much more numerous than geothermal fields. Thus far, conventional geothermal fields have been found separated from active volcanoes, usually occurring in regions of ancient volcanism. Many a covetous eye has been cast on the volcanoes to harness them for electrical power generation, just as has been the case with conventional geothermal fields.

In Japan (as part of a national effort called the Sunshine Project, to exploit various domestic sources of energy) the volcanic island Satsuma-Iwo Jima (off the southern coast of Kyushu) was selected as the site of a test project to utilize volcano energy. This is the only project known to date where a case study has been initiated specifically for volcano energy utilization. As this case study is intended to be as comprehensive as possible, it includes all conceivable stages from exploration to development to power generation, and even to the study of the impact on the environment, economy, and social structure of the local community. At the present writing, the project is at an advanced stage of exploration. Table 2 shows a rough outline of the plan up to 1976.

Satsuma-Iwo Jima is an island located at 30°47′N, 130°17′E on the north end of the Ryukyu Archipelago. It is 6 km long in the east-west direction and 3 km in the north-south direction, encompassing an area of 8.25 km^2. Together with its small neighbor to the east (Takeshima), Satsuma-Iwo Jima is part of the northern section of the outer rim of a large caldera called Kikai Caldera.

The island is made up of four topographical and geological features, which will be explained with the use of the map in Figure 11. The first feature is Yahazudake Peak which is part of the second feature, a ridge running from the northern end (Heikenojo) to the western end (Jonohara). The third feature includes the two cones, Iwodake and Inamuradake. The fourth feature is the plateau surrounded by the peaks, ridge, and cones. Yahazudake is an old volcano, while Heikenojo and Jonohara are ridges formed by lava and ash flows. The southern part of Yahazudake and the ridge are cut by a steep cliff, which in effect is the northwest wall of the large Kikai Caldera. Iwodake

TABLE 2

Research Program for Satsuma-Iwo Jima

Program	Content	Schedule
Meteorology, climatology, hydrology	Weather conditions, rainfall, ground water survey; automatic recorders	1974–1976
Seismicity	Tripartite array, continuous surveillance	1974–1976
Fumarole and hot spring survey	Measurements of volume, temperature, chemical composition; time variation	1974–1976
Heat flow	Heat flow measurements, ground water movements, infrared photography of hot areas	1974–1975
Subsurface structure	Geophysical and geochemical surveys	1975–1976
Geological structure	Geological survey and borehole survey	1975–1976
Environment and ecology	Base line data on environment and society	1974–1976
Feasibility study of power generation	Investigation of power generation potential	1976

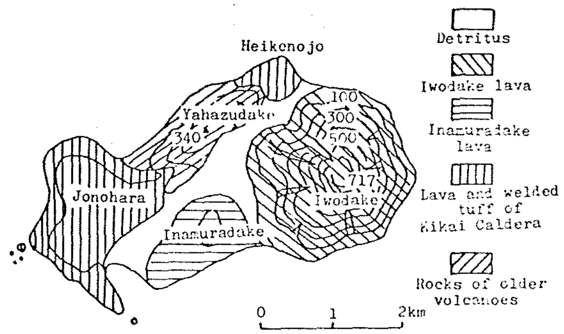

FIGURE 11. Map of Satsuma-Iwo Jima Island with its four geological divisions.

and Inamuradake are stratovolcanoes or cones inside Kikai Caldera.

The last eruption occurred in 1934 to 1935. During that eruption, a new island, Shin-Iwo Jima, appeared at 30°48′N, 130°20′35″E (2 km east of Satsuma-Iwo Jima) as a result of submarine eruption. At the present time the new island is 500 m long in the east-west direction, 300 m wide in the north-south direction, and 26 m high.

There are many fumaroles and hot springs on the island of Satsuma-Iwo Jima. Most of them are located near the crater of Iwodake (Figure 12). As seen from Table 3, there is spatial and temporal variation in the temperatures of the fumaroles. Table 4 shows the chemical composition of the fumaroles. Most of the hot springs are located along the seashore, where interaction of the thermal waters with sea water discolors the sea by producing milky white or reddish precipitates. The analysis of the thermal waters is given in Table 5. Because of the steep cliffs and dangerous choppy conditions of the sea, temperature measurements and water sampling were done by a remotely controlled unmanned boat (190 cm long and 67 cm wide) filled with equipment. The occurrence of high temperatures over a large area indicates that a large volume of hot water is entering the sea.

The best way to keep tabs on subsurface volcanism is by monitoring the microearthquakes associated with a volcano. As silica content of the lava here is known to be about 65%, which means that the magma has a high viscosity, subsurface movement of the magma will be accompanied by detectable earthquakes.

Three seismic stations were established in the central area of the flat section of the island. These stations (shown as A, B, and C in Figure 13) telemetered their signals by hard wire to a central recording unit. Station A had three-component

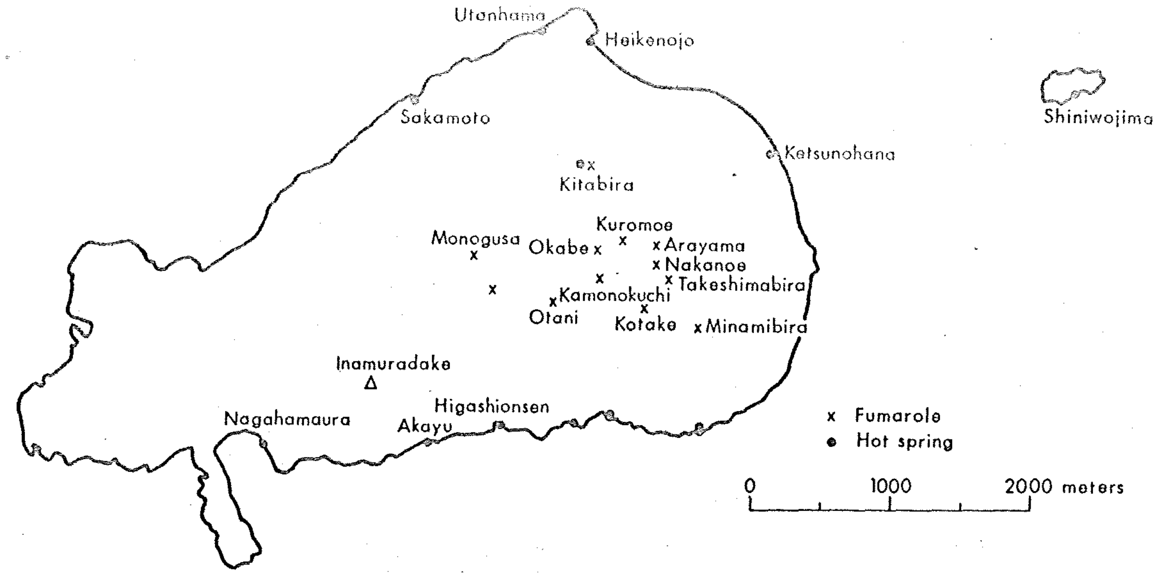

FIGURE 12. Locations of fumaroles and hot springs on Satsuma-Iwo Jima Island.

TABLE 3

Variation of Temperatures of Fumaroles at Summit of Iwodake Volcano

Name of solfataric field	Maximum temperature, °C 1961	1962	1973	1974
Arayama	102	106		850
Kamanokuchi	745	740	235	97
Kitabira	98			
Kotake	98		97	
Kuromoe	460	585	710	890
Monogusa		98	99	
Nakanoe			835	700
Okabe	106	200	224	105
Otani		205		
Takeshimabira	570	575		

seismometers, while stations B and C had only vertical components. The seismic array was an unmanned system, including protection against corrosive vapors and an independent power supply.

The tabulation of microearthquakes of magnitude less than 0.6 and of S-P travel time of less than 5 sec during the period from June to December 1975 is shown in Figure 14. These earthquakes also have the following characteristics:

$$\frac{\text{Maximum Amplitude at B}}{\text{Maximum Amplitude at C}} = 0.2 \sim 1.0, \qquad (2)$$

$$\frac{\text{Maximum Amplitude at A}}{\text{Maximum Amplitude at C}} = 0.1 \sim 0.7. \qquad (3)$$

Earthquakes fulfilling all of the above conditions would then have epicenters in the area bounded by shaded borders in Figure 15. Epicenters of the more prominent earthquakes are also shown.

Originally it was thought that there was very little ground water on Satsuma-Iwo Jima, but since

TABLE 4

Chemical Components of Fumaroles at Summit of Iwodake

Name of solfataric field	Date	Temp., °C	H_2O, %	Gas component HF	HCl	SO_2	H_2S	CO_2	H_2
Arayama	July 30, 1962	106	96.8	1.2	47.6	32.6	7.6	10.6	0.4
Kamanokuchi	July 25, 1962	740	97.8	2.2	5.0	44.3	3.4	25.5	18.0
Kitabira	May 27, 1958	98	99.2	0.004	0.1	63.7	1.3	34.4	0.5
Kotake	July 30, 1962	98	98.8	0.2	0.5	57.5	3.3	38.0	0.5
Kuromoe	July 26, 1962	575	97.9	2.8	31.0	37.5	3.4	22.0	2.6
Okabe	July 28, 1962	200	97.1	9.0	44.2	28.7	3.9	12.7	0.4
Otani	August 4, 1962	205	97.2	8.6	36.6	32.5	9.3	12.6	0.4
Takeshimabira	August 3, 1961	570	98.3	2.4	38.0	33.9	6.8	14.5	4.4

TABLE 5

Chemical Components of Hot Springs of Satsuma-Iwo Jima

Name of hot spring	Temp., °C	pH	Chemical component, mg/l Na^+	K^+	Mg^+	Ca^+	Mn^+	Fe^{2+}	Fe^{3+}	Al^+	Cl^-	SO_4^{2-}	CO_2	H_2SiO_3
Heikenojo	70.0	1.3	545	240	115	222	20.9	240	–	1,250	2,450	9,216	149	330
Higashionsen	73.3	1.6	555	140	91.5	193	17.3	3.4	13.6	771	1,390	6,000	–	306
Kitabira	79.2	1.1	800	202	175	680	16.6	620	29	1,220	1,156	14,250	–	396
Nagahamaura	46.2	4.6	3,085	205	348	326	31.8	151	33	–	4,875	2,544	–	198
Sakamoto	49.5	6.3	4,180	171	602	272	–	0.79	–	–	8,040	1,220	129	119
Shin-Iwojima	55	5.4	10,200	510	1,240	396	8,611	–	–	40	17,250	2,736	387	119
Utanhama	64.9	2.1	–	–	–	–	–	–	–	–	8,187	2,352	–	–

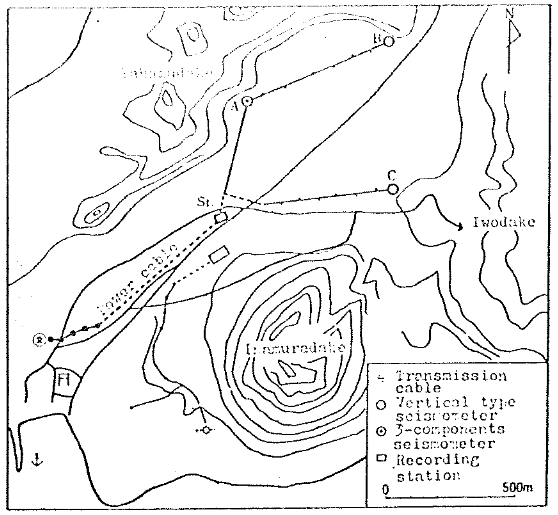

FIGURE 13. Seismic array established on Satsuma-Iwo Jima.

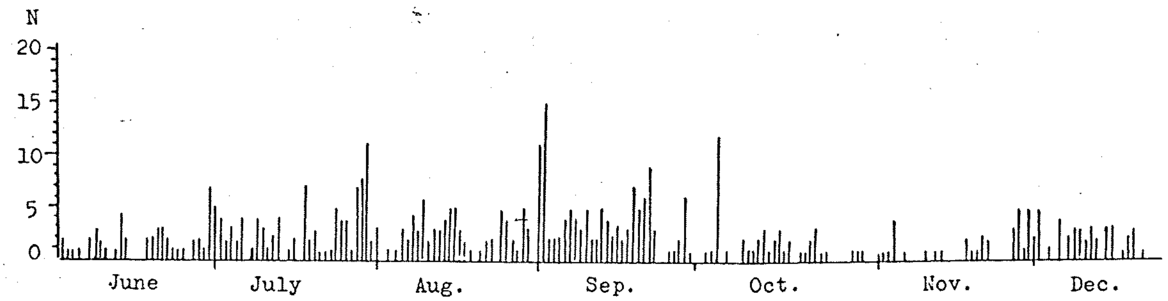

FIGURE 14. Number of earthquakes recorded per day in 1975.

the measured average annual rainfall for 30 years from 1941 to 1970 amounted to 2087 mm or about 3.2 X 10^7 tons, even allowing generously for evaporation and runoff, there should be a tremendous amount of water seeping into the ground. As Iwodake is a stratovolcano, the rain falling on the cone should drain downhill through and between the inclined layers of ash, and lava flows to the foot of the cone to form aquifers. Following this line of thought, if we could trace the movement of ground water, we could then infer the internal structure of the volcano from the movement. With this idea in mind, a series of nine wells was drilled in 1974 to 1975 (Figure 16). Every well had a hydrostatic head except for well No. 6; the heads became higher as one went farther inland (Table 6). It seems that a Ghyben-Herzberg lens exists under the island. Except for wells No. 2 and No. 4, high temperatures were recorded in the wells, indicating that most were affected by volcanic activity of Iwodake.

From the well data, the following hydrological interpretation can be inferred. Part of the ground water on Iwodake is heated by conduction or fumarolic action. The heated water drains downhill through the more permeable layers of the stratovolcano to be collected along the lowlands to form a lens-shaped aquifer. Permeable layers are found on the northern and southern slopes of the volcano, and high-temperature ground water is found on these slopes. Where the slopes meet the sea, hot springs appear. The low temperatures of wells No. 2 and No. 4 indicate that hot ground water does not flow westward toward them.

An electric survey using the Schlumberger galvanic method was carried out to further probe the subsurface structure of the island. Figure 6 shows the two electrical traverses; traverse A was

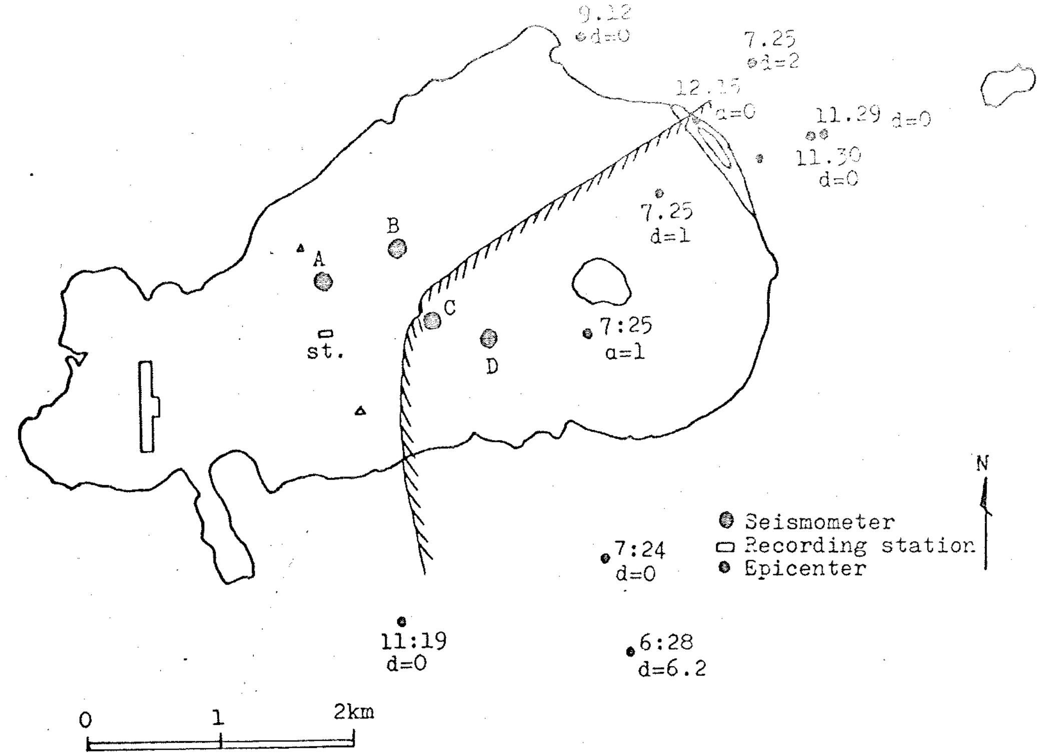

FIGURE 15. Map showing locations of seismometers, epicenters of prominent earthquakes, and the area (shaded) of frequent occurrence of earthquakes.

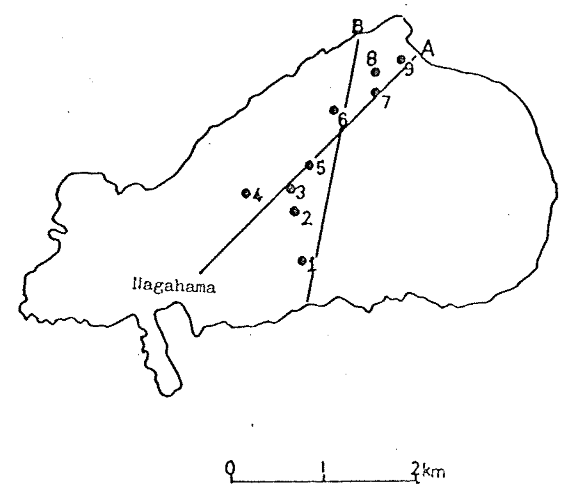

FIGURE 16. Locations of boreholes drilled to map ground water and of the two electrical resistivity traverses, A and B.

TABLE 6

Temperature of Water Found in the Borehole

Number of well	Altitude m	Depth m	Depth of water level, m	pH of water	Temperature of water, °C	Depth °C
1	74	150	63.4	5	95 (77 m)	108 (150 m)
2	108	120	50.1	5	29 (60 m)	30 (120 m)
3	76	100	50.7	5	42 (55 m)	54 (100 m)
4	67	134	77.1	6	21 (80 m)	22 (100 m)
						23 (134 m)
5	115	150	104.1	7	97 (108 m)	138 (150 m)
6	94	120	94.2	7	96 (100 m)	117 (120 m)
7	95	150	72.4	1	77 (75 m)	79 (109 m)
8	74	100	56.7	5	29 (58 m)	101 (100 m)
9	55	80	51.9	4	51 (53 m)	85 (80 m)

TABLE 7

Analytical Results of Galvanic Sounding

	Traverse A		Traverse B	
Layer	Resistivity, Ω-m	Thickness, m	Resistivity, Ω-m	Thickness, m
1	180–450	3.5–9.0	250–600	4–6
2	500–2,500	35–55	540–1,900	7–45
3	60–200	20–40	40–550	50–160
4	1.4–2.5	1,000+	2–4	1,500+
5	5–20		6–10	

3200 m long, and traverse B was 260 m long. The resistivity-depth profile resulting from the survey (Table 7) shows a low-resistivity layer of 1.5 to 4 Ω-m beginning at shallow depths of 100 to 200 m. It is not yet certain which part of this low-resistivity layer is due to themal waters and which is due to invading sea water.

Core samples from the wells and surface rocks from Iwodake were examined by X-ray refraction methods to determine the degree of hydrothermal alteration. In general, rocks below the water table were altered significantly, while those above the water table were only slightly altered. The core samples from the nine wells can be classified according to the alteration products found.

1. Those characterized by alunites.
2. Those characterized by montmorillonite.
3. Those including both alunite and montmorillonite.

Of these, group 1 is found at about midpoint between Iwodake and Inomuradake and at the north-northwest side of Iwodake, while groups 2 and 3 are found between these two locations. Considering these facts and the distribution of the hot springs, it is apparent that geothermal activity occurs roughly along two orthogonal lines, one extending from Inamuradake to Iwodake to Shin-Iwo Jima and the other from Minamibira to Kitabira to Utanhama (see Figure 12 for location).

Future plans call for the drilling of a 500-m borehole into the flanks of Iwadake to explore the interior of the volcanic edifice. The goal is to ascertain whether there is a geothermal reservoir, an intrusive hot rock, or a self-sealing aquifer.

VII. MIDPLATE OCEANIC VOLCANO: HAWAII

As shown in Figure 2, volcanoes sometimes appear in the middle of an oceanic plate, for example, the Hawaiian volcanoes. From earthquake data, Eaton and Murata[21] inferred that magma originated from depths of 40 to 60 km. Two of the theories that have been advanced for the origin of magma are the hot plume theory[9] and the progressive crack theory.[10] Leaving aside the problem of origin of magma as an academic conundrum, let us consider the shallower structure of a volcano for the purpose of possible energy utilization. For our example we shall consider Kilauea Volcano, where a tremendous amount of work has been done.

Kilauea Volcano is the youngest of the five volcanoes that make up the island of Hawaii (Figure 17). It is located on the southeastern side of the island. It has two well-defined rift zones: the southwest rift zone and the east rift zone. The east rift zone, the more important of the two as more study has been done on it, passes through what is geographically known as the Puna District and enters the sea at Kapoho (Figure 17).

The shallower structure of Kilauea Volcano may be represented schematically as shown in Figure 18. The magma rising from great depths may be stored for a while in the magma chamber or reservoir under the summit caldera. Assuming that earthquakes will not occur in a very hot region of rocks but will occur on the outer boundaries of the hot region, Minakami[22] inferred that high-temperature material, if not molten material, occupies the space in a span from a depth of 1 to 10 km below the caldera floor. From data on ground deformation accompanying eruptions, Mogi[23] and Fiske and Kinoshita[24] proposed several different centers for the magma reservoir; however, they all fall within the interval of 2 to 4 km depth. From these evidences it can be concluded that the upper part of the Kilauea reservoir chamber is at a very shallow depth, about a kilometer or so below ground surface.

Topographically, the summit caldera of Kilauea is well defined, with steep caldera walls exposed through breccia and volcanic ash, except for a small section in the southwestern section. After carrying out electrical surveys[25] and evaluating seismic and ground deformation data, Keller[26] carried out a drilling project to study the thermal profile of the summit area. The location of the

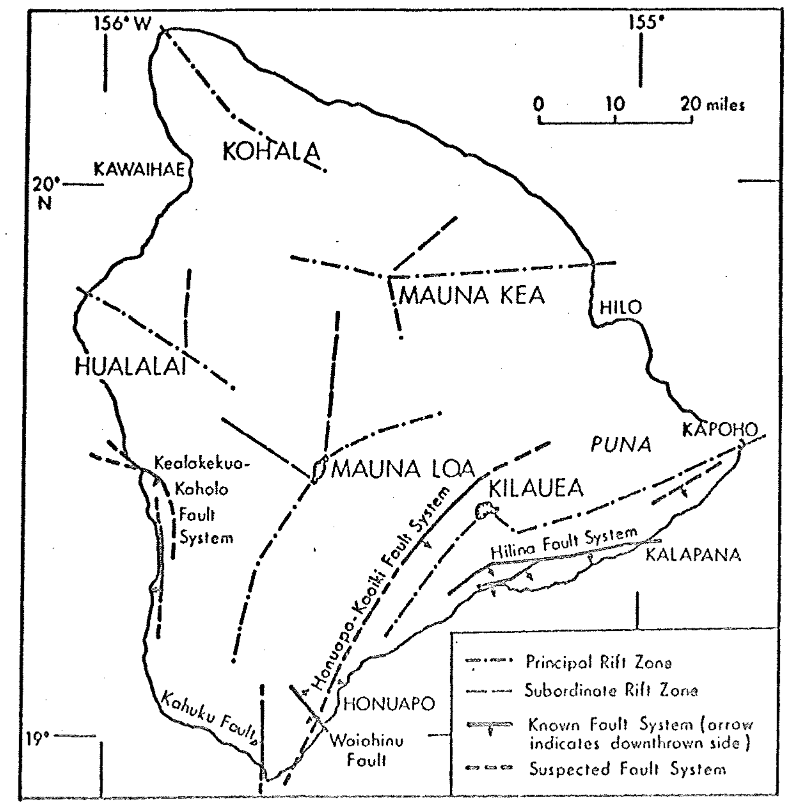

FIGURE 17. Map of the island of Hawaii showing five volcanoes and their associated rift zones. Faults with surface manifestations are also shown.

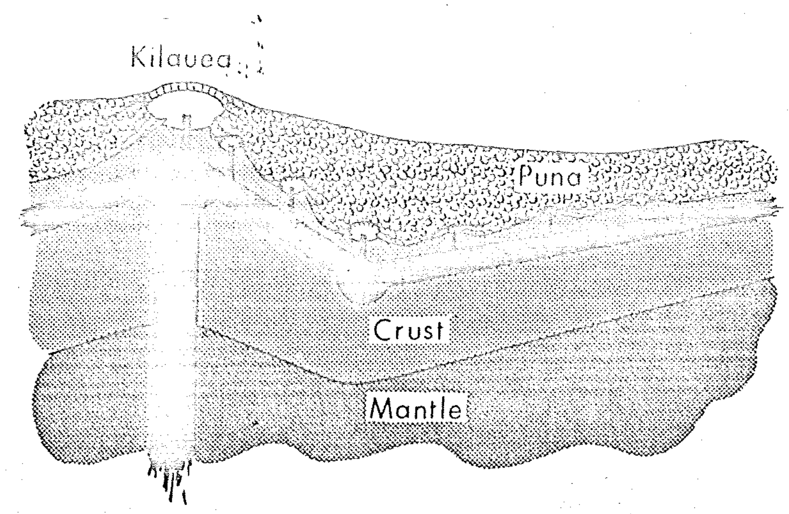

FIGURE 18. Shallow structure of Kilauea Volcano, showing magma reservoir, caldera, and the east rift extending into the Puna District.

drill hole is shown in Figure 19 and the temperature profiles of the hole in Figure 20. Other data, such as electrical resistivity, density, and permeability, were logged for the hole.[27] The drilling ended at a depth of 1250 m, as funds ran out.

Murray[28] has interpreted the data from the drill hole in terms of an unconfined hydrothermal system, as illustrated in Figure 21. In essence, a low-temperature field closely resembling the Icelandic type was found, with the maximum temperature of the aquifer at about 85°C. If the temperature gradient observed at the bottom of the hole were to be considered constant for the conductive regime of Murray's model, then temperatures equivalent to molten matter, 1100°C, would be encountered at a depth of 2.5 km from ground surface. This projection agrees with other geophysical data on depth to the top of the magma reservoir.

The eruptions since 1959 along the east rift of Kilauea have left lava pools in Kilauea Iki, Alae, and Makaopuhi craters (see Figure 19). After a short time a hard crust had formed over all the lava pools so that researchers could safely walk over them to investigate the properties of the crust and lava below. Small holes were drilled through the crust into the lava; the holes were logged for temperature, oxygen fugacity, and lava viscosity.[29] Core samples were taken for measurements of thermal conductivity, magnetic properties, and chemical analysis. The field work was curtailed by the Mauna Ulu (see Figure 19) eruptions of 1969 that overran Alae crater and partially buried Makaopuhi crater.

The thickening of the crust over the lava pools has been measured over a number of years (Figure 22). Peck[29] has reported that the rate of thickening is about the same for all pools, and the thickness of the crust increases with the square root of time. The thickening crust with time negated the usefulness of a lava pool as an energy source; even experiments of magma tap will be difficult to perform there because of the congealing lava.

After the drilling project in the summit caldera was completed, the east rift in the Puna District (see Figure 17) was examined for possible thermal sources.[30] Although a wide range of surveys (from infrared aerial scanning surveys to all sorts of geophysical and geochemical surveys) were carried out, we shall limit our discussion to those results that yielded information on the thermal profile along the east rift.

As it turns out, the magma of the Hawaiian volcanoes has a higher density than the country rock making up the volcanic edifice. Because of this fortunate circumstance, a gravity survey would reveal the location and dimension of a dike zone or magma conduit. With this in mind, a gravity survey was carried out on the eastern side of the Puna District, where the east rift shows surface expressions of fumaroles and sulfurous vents. The results of the survey, assuming surface density of 2.3 g/cm^3 for Bouguer corrections, are shown in Figure 23. The maximum value of the gravity data was arbitrarily set at zero.

An analysis of the gravity data along traverses AA′ and BB′ of Figure 23 projects an anomalous body at a depth of about 1 km, if a density contrast of 0.6 g/cm^3 is assumed (Figures 24 and

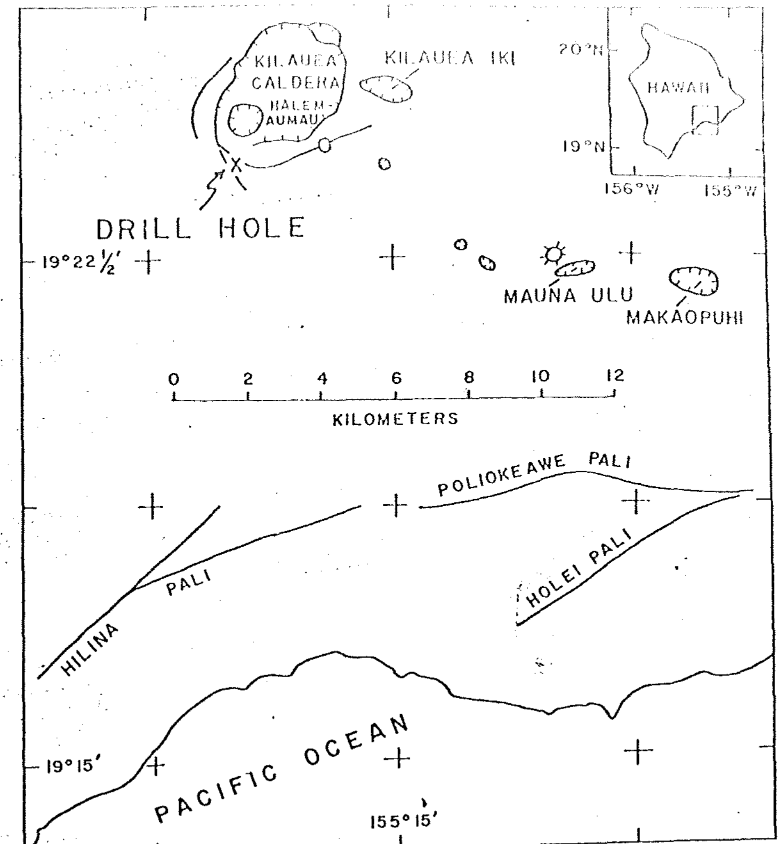

FIGURE 19. Map of Kilauea Caldera, craters, and drill hole site. (From Keller, G. V., *Drilling at the Summit of Kilauea Volcano*, Colorado School of Mines, Golden, 1974. With permission.)

25). Of all those attempted, this solution best fits the constraints of topography and geology: namely, the southern edge of the anomalous body coincides with what is suspected (from the line of vents and steep sides) to be the southern boundary of the dike complex of the east rift. A further inference from the analysis is that the anomalous body will have a density of 2.9 g/cm^3 and that since the particle density of basalt is 3.0 g/cm^3, it will have an overall porosity of less than 4%.

We shall identify the anomalous body as the dike complex through which the magma moved down from the summit magma reservoir to the east rift. The complex is made up of a series of thin vertical dikes, ranging in thickness from tens of centimeters to as much as a few meters, a phenomenon observed in eroded dike complexes of ancient volcanoes. We surmise that in any one eruption vertical cracks appeared through which the magma moved rapidly. When the eruption stopped due to some as yet undetermined mechanism, the magma in the cracks began to chill and gradually solidified into a dike. After hundreds or thousands of eruptive periods over the ages, the dike complex was formed. Monitoring of microearthquake activity over the Puna District also generally confirmed the locations and dimensions of the dike complex as obtained from gravity data.[31]

Electrical surveys were carried out to locate hydrothermal activity in the Puna District.[32,33] Five areas with low-resistivity anomalies of 2 to 5 Ω-m were detected, as shown in Figure 26. The smallest area of the anomalies (area A) included a drill hole site which was preselected to search for a geothermal reservoir. The results of the drilling will be discussed shortly.

A number of wells in the Puna District were drilled for irrigation purposes. Some of them were abandoned because they yielded thermal waters. The highest temperature encountered in the wells

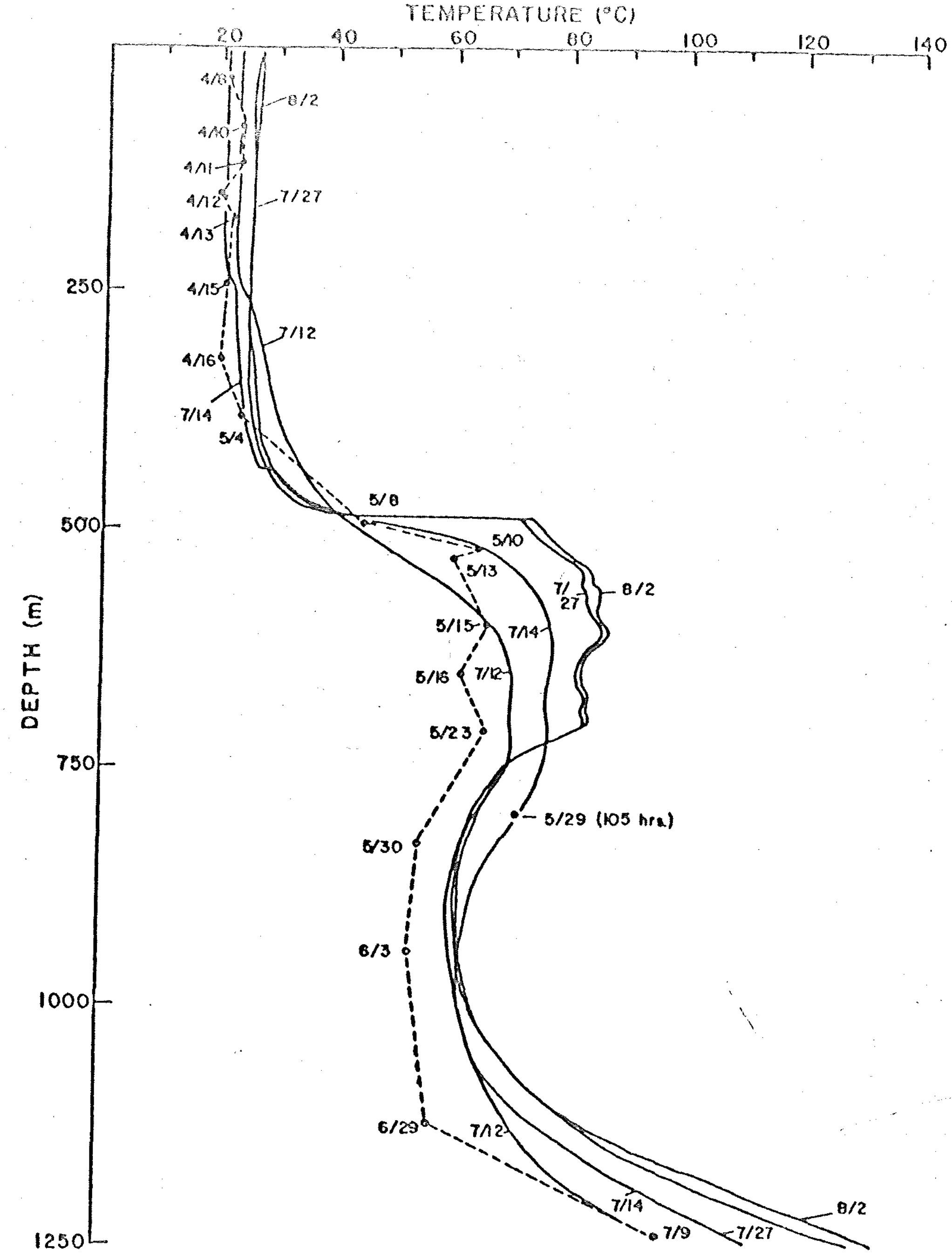

FIGURE 20. Thermal profile of drill hole in Kilauea Caldera. Numbers indicate the days in 1973 when measurements were taken. (From Keller, G. V., *Drilling at the Summit of Kilauea Volcano*, Colorado School of Mines, Golden, 1974. With permission.)

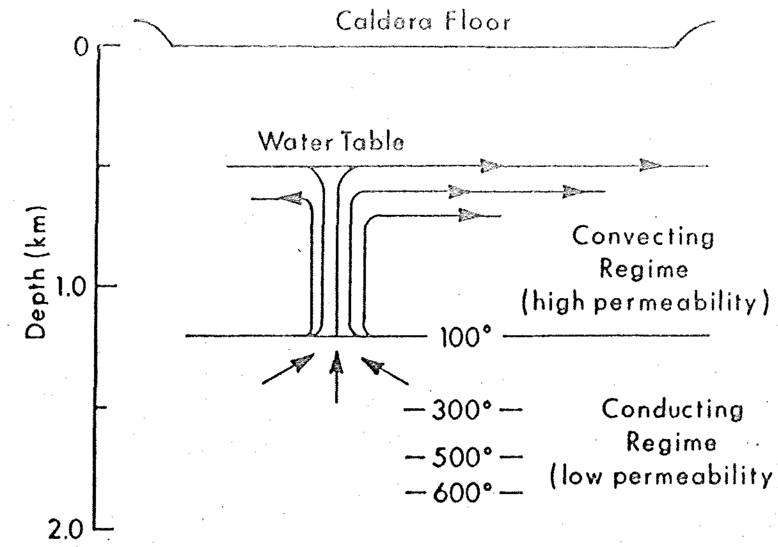

FIGURE 21. A model of the hydrothermal system in the caldera area of Kilauea as proposed by Murray.[28]

was 92°C. Chemical and isotope analyses of water samples from the wells were done. The conclusion was that the water samples were of meteoric origin and less than 3 years old.

In April 1976 the exploratory drilling into low-resistivity area A in Figure 26 was completed to a depth of 6445 feet (1964 m).[34] Temperature logs of the drill hole are shown in Figure 27. Upon completion of the hole, a temperature log probe (15 hr, curve of Figure 27) was able to penetrate to a depth of 6000 ft, but in a matter of days the hole became clogged with solidified drilling mud at a depth of 4400 ft (1340 m). In June 1976, the mud was flushed out from the hole and another temperature log was taken on June 15, 1976, all the way to the bottom. The June 15 temperature profile suggests that a region of convective motion with a base temperature of 300°C may exist from a depth of 4000 ft (1200 m) to 5700 ft (1700 m). In a 6-hr test on July 22, 1976, the hole flashed at a pressure of about 5 kg/cm^2. The hole has probably penetrated a geothermal reservoir of commercial quality.

An interpretation of the dikes and hydrothermal system of the east rift of Kilauea is shown in Figure 28. The hot section consists of the dike complex where residues from previous eruptive activity remain emplaced. The dike complex is about 6 km wide and 4 km in vertical height. The bottom at 5 km depth sits on what was the original oceanic crust before the volcano was formed; the top is at about 1 km depth from ground surface. Above the dike complex are numerous vents through which eruptions have occurred. The rocks around the dike complex are in layers whose P-wave velocity values have been determined by seismic refraction surveys.[35,36] The exploratory drill hole has penetrated about 1 km into the dike complex. In-between the series of vertical dikes of the complex are cracks formed by the contracting of rocks when the temperature of the dike became lower. Ground water has seeped into these cracks and become heated by the hotter parts of the dikes. The drill hole has probably penetrated one or more of these cracks and tapped the steam trapped in these cracks.

In addition to the trapped steam in cracks between dikes, it is suspected that another kind of hydrothermal reservoir exists. In various drilling, the rocks surrounding the dike complex have been found to be too permeable, so that at best only low-temperature systems have been found. However, between the extremely permeable neighboring rocks and the hot rocks of the dike complex should be a region of proper permeability where a high-temperature hydrothermal system can exist and where the recharge rate is sufficient to maintain a productive geothermal well. Such a section may be found in the 3.1 km/sec (of Figure 28) along the sides of the dike complex. In geographical terms, such a place may be found in the low-resistivity area B of Figure 26.

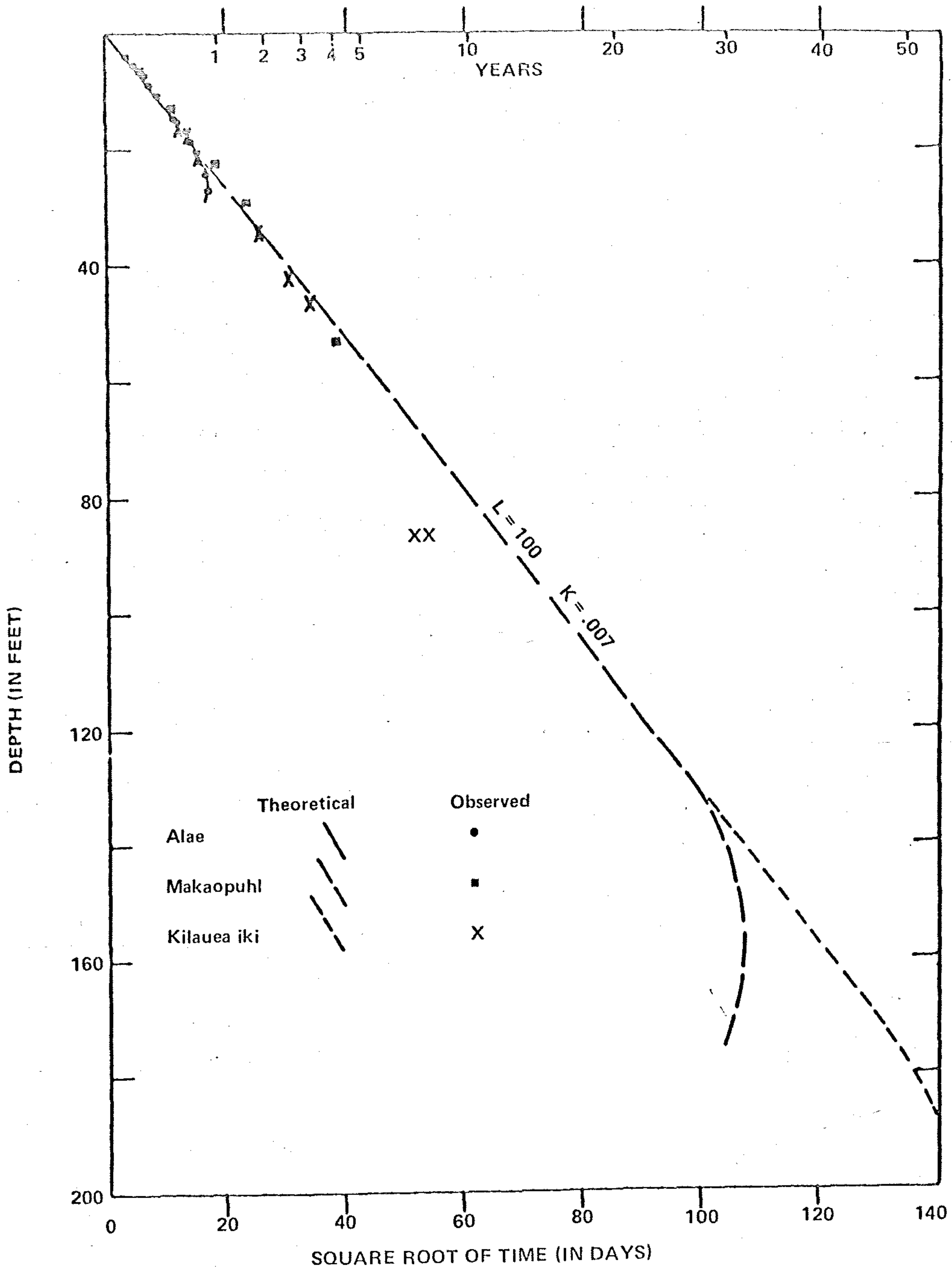

FIGURE 22. Chart showing growth of crust on lava pools. The broken line is the theoretical rate of cooling based on models developed by Peck. (From Peck, D., *Utilization of Volcano Energy, Proceedings of a Conference*, Sandia Laboratories, Albuquerque, N.M., 1974, 287. With permission.)

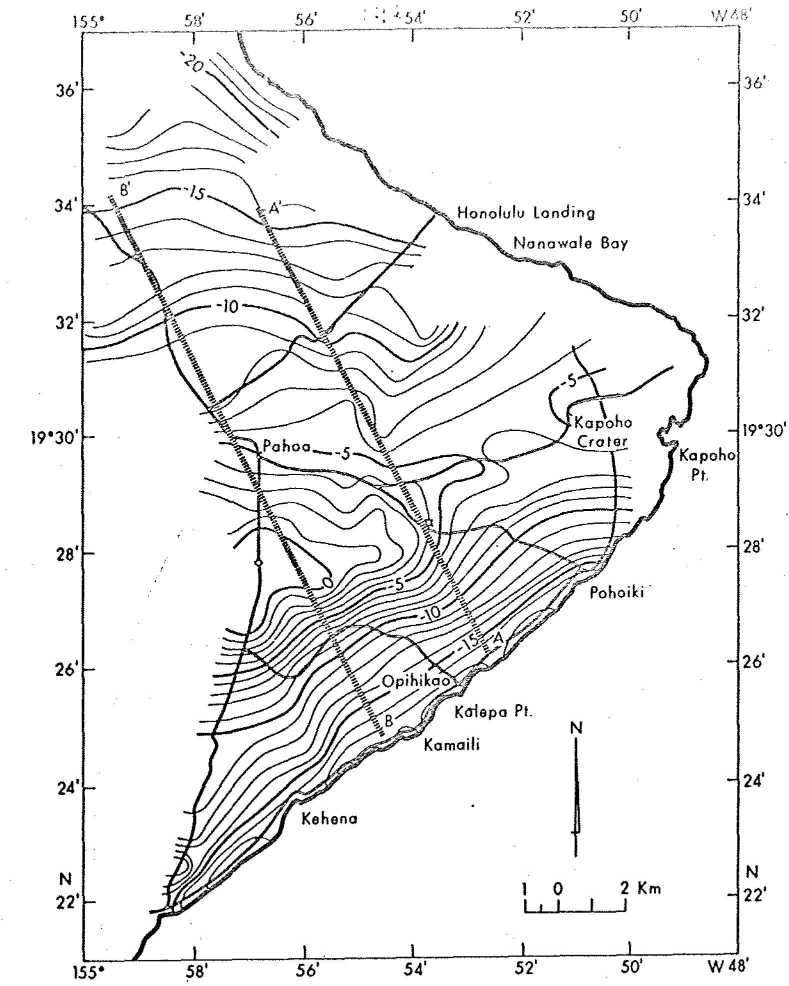

FIGURE 23. Bouguer gravity map of Puna District after a survey in 1975. The maximum value observed was arbitrarily set at 0.

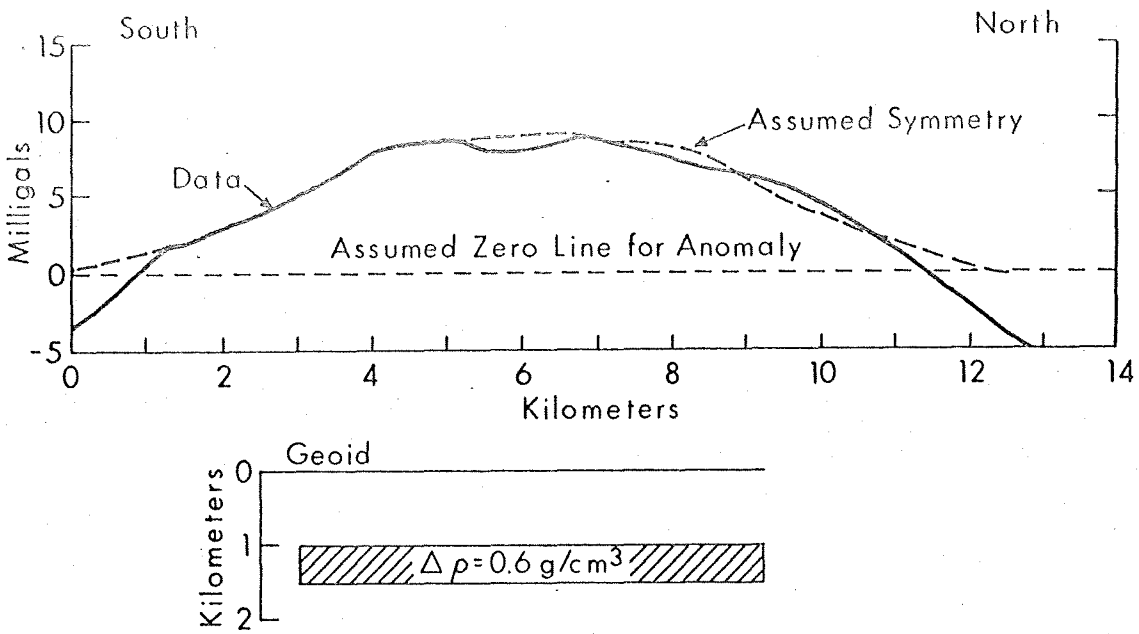

FIGURE 24. Gravity section along AA′ of Figure 22 and the high-density body to account for the gravity anomaly.

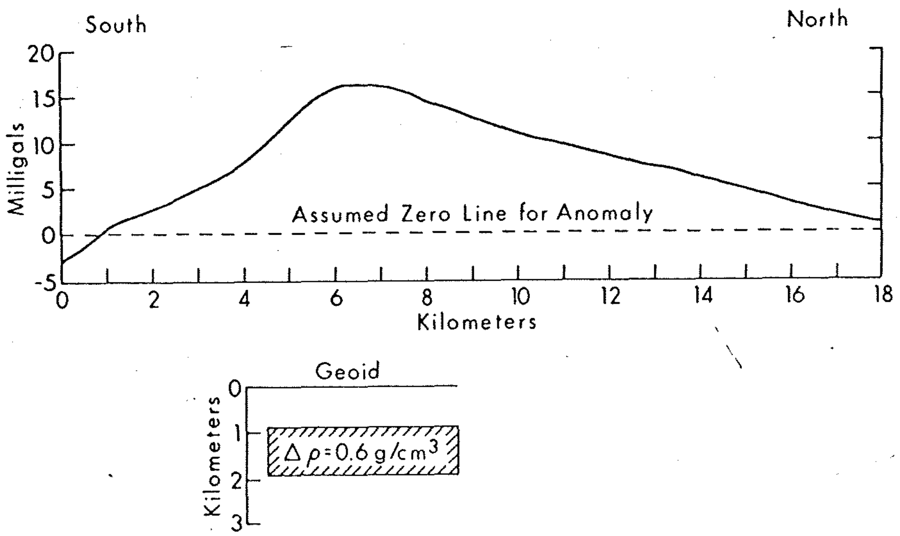

FIGURE 25. Gravity section along BB′ of Figure 23 and the high-density body to account for the gravity anomaly.

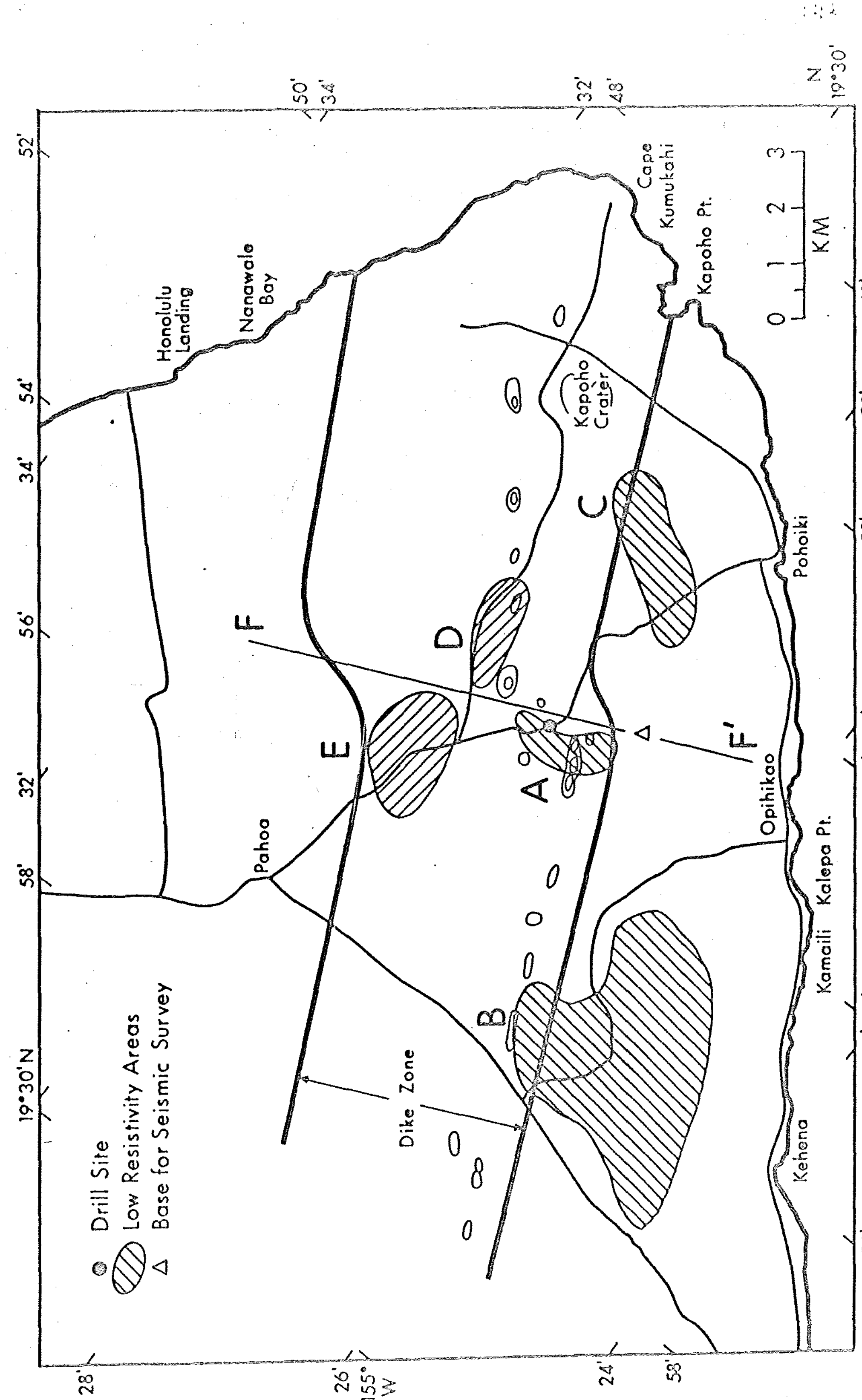

FIGURE 26. Low resistivity areas (shaded) uncovered by electrical surveys and the dike zone outlined by gravity.

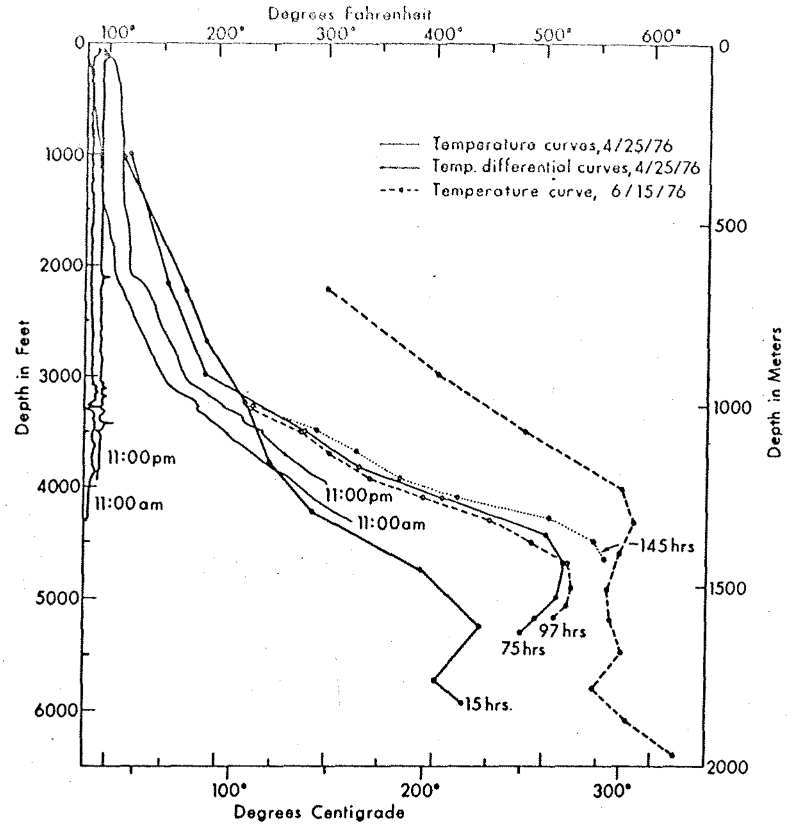

FIGURE 27. Temperature profiles of the drill hole at site shown in Figure 26. The different hours indicate profiles after 11:00 p.m. on April 25, 1976. The profile of June 15 was taken several days after the drilling mud was flushed out of the hole.

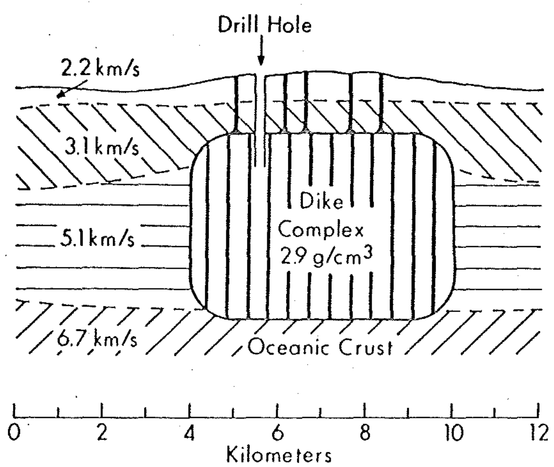

FIGURE 28. Structure of the dike complex of the east rift as inferred from various geophysical data. The crustal layers of 3.1, 5.1, and 6.7 km/sec were found by Hill;[35] the surficial layer velocity was determined by Suyenaga.[36]

VIII. MIDPLATE CONTINENTAL VOLCANO: VALLES GRANDE CALDERA EXPERIMENT

Volcanoes also appear inside a continental plate. Magma for these volcanoes originates at great depths, but interaction of the magma with the continental plate and differentiation of the mix can produce granitic intrusions and rhyolitic flows. For example, the Jemez Mountain volcano of New Mexico produced basaltic and rhyolitic flows. The process of formation of rhyolites is similar to that occurring in spreading zones beneath continental plates, as was explained for the Salton Trough.

As the last eruption of the Jemez Mountain volcanics occurred only 40,000 to 50,000 years ago,[37] Fenton Hill (which is located only a few kilometers west of the Valles Grande caldera in the Jemez Mountain complex) was selected by the Los Alamos Scientific Laboratory for a dry hot rock experiment.[38] The Valles Grande caldera itself contains commercial quality geothermal fields which are being developed by Union Oil Company. Proximity of the experiment site to the Los Alamos Laboratory is an advantage. Holes were drilled into the Precambrian granites underlying the Jemez Plateau,[39] where temperatures utilizable for geothermal power production were expected.

The purpose of the experiment was to produce an artificial geothermal reservoir by hydrofracturing. The first hole was drilled to a depth of 3 km into the Precambrian granite basement. After forming a near vertical fracture by means of hydrofracturing techniques familiar to the petroleum industry, a second hole was drilled to intersect the fracture. The operation was successful, and communication between the two holes was established.[40]

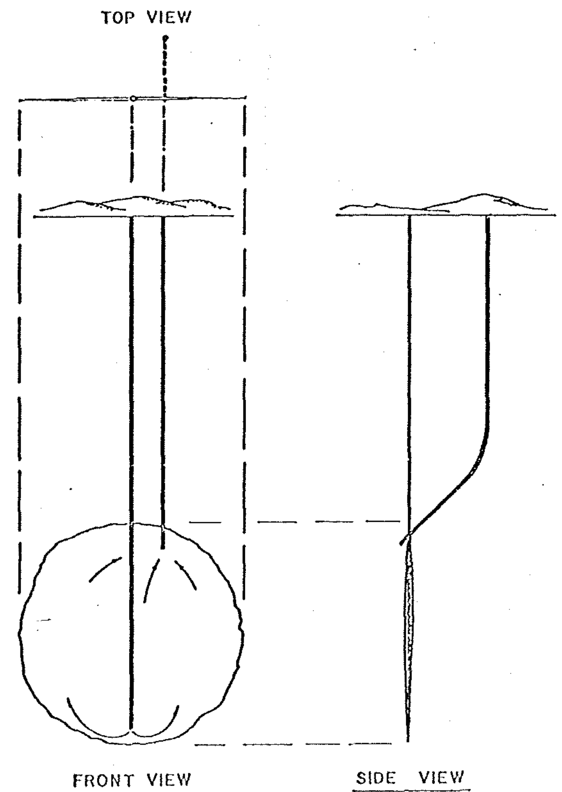

FIGURE 29. Method of circulating water through artificially induced cracks in rocks. (From Aamodt, R. L., in *The Utilization of Volcano Energy, Proc. of a Conference*, Clop, J. C. and Furumoto, A. S., Eds. Sandia Laboratories, Albuquerque, N.M., 1974, 415. With permission.)

A schematic diagram of how such a crack can be used for hot water production is shown in Figure 29.[41] Cool surface water is pumped down the deeper well and is allowed to percolate upward through the crack in the hot rock, to be collected at the top by the second well. The water when collected at the top should be hot enough for power generation. In the Fenton Hill site, the temperature at the bottom of the deeper well was 205.5°C and that for the second well was 197°C.[39]

This first field experiment at energy extraction from dry hot rock was successful as an experiment because a crack was produced and communication between the two holes was established. The amount of water circulated was too small to be of commercial value. This success augurs well for energy prospects of the U.S., as there are numerous, presumably hot, intrusive rocks in the western half of conterminous U.S. It has been estimated that the heat content of igneous-related systems in the conterminous U.S. is about 30 times the total estimated heat content of all tabulated hydrothermal systems.[42] On the global scale, intrusive bodies hidden in the 800 or so volcanoes of the world can be tapped, if the dimensions of the bodies can be delineated.

IX. SUMMARY AND CONCLUSIONS

Compared to the number of utilizable hydrothermal systems, whether vapor dominated or hot water, the number of volcanoes with potentially utilizable heat is far greater, by perhaps an order of magnitude, and represents a tremendous untapped natural energy resource.

Volcanoes can be classified according to their place in tectonic processes: spreading zone types, subduction zone types, and oceanic and continental midplate types. Whether by pure coincidence or design, active exploration and experiments for the purpose of energy utilization are being performed on each type.

The most common form of energy encountered in probing volcanoes is the unconfined hydrothermal system of the low-temperature type. Theoretically, even thermal waters from low-temperature areas can be used for power generation. The amount of energy extractable from a unit volume of thermal water at different temperatures has been worked out and tabulated by Bodvarsson.[43] The rest is a matter of economics. In Iceland low-temperature areas are disregarded for power generation because hydroelectric power is available and competitive. In Hawaii, where the source of electric power is almost entirely petroleum imported from overseas, low-temperature fields for electric power generation will be very attractive during the next petroleum squeeze.

The concept behind hot-rock technology is to exploit what is geologically a very simple thermal source, that is, a volume of rock that is hot. The most efficient approach seems to be to convert the hot rock into an artificial hydrothermal system. Direct conversion of heat to electricity by thermoelectric methods does not appear to be presently feasible, the main obstacle being the low thermal conductivity of rock itself. The process of making an artificial hydrothermal system includes fracturing the rock by one means or another to increase permeability and then injecting water into the fractured rock system to produce recoverable hot water or steam. Calculations on various aspects of hot-rock technology have been done,[44] and experiments at Los Alamos Scientific Laboratory have proved to be promising to date, as mentioned earlier.

If hot-rock technology proves to be successful, the amount of utilizable energy becomes tremendously large. It has been estimated that the amount of heat in hot dry rock less than 10 km deep within the confines of the U.S. amounts to 48,000 quadrillion Btu, while the consumption of energy in the U.S. in 1974 was just over 70 quadrillion Btu.[45] Even with a low efficiency of extraction and utilization, say 1%, this still represents a sizable amount of energy for quite some time.

In a dike zone in basaltic regions, such as Hawaii or Iceland, fracturing of the rock may not have to precede injection of water. After magma has solidified in the cracks to form dikes, small openings or cracks will appear between the country rock and dike due to thermal contraction. Nature has already provided cracks in the hot-rock system, so that fracturing by hydraulic means or chemical explosions can be eliminated. Holes can be drilled into the system so that one will intercept the cracks at depths and another will intercept the cracks at shallower places. Water can then be pumped into the deep hole and hot water extracted from the shallower hole.[46] This process is the same as that of hot-rock technology. The knowledge gained from and techniques developed in the Valles Grandes experiment are applicable.

A few words should be said about the proposal for a magma tap experiment. The idea is to use the heat contained in magma reservoirs by means of a yet-to-be-developed heat exchanger. The presumed advantage of this idea is that the convective motion of magma in the reservoir will continue to supply large amounts of heat. Many obstacles may be encountered in trying to realize this objective. First, a magma reservoir must be identified and delineated. Magma reservoirs are suspected to exist under Yellowstone and Kilauea volcano, but their vertical and horizontal dimensions, temperature profiles, and viscosities are not known. To obtain these parameters is no mean feat, even with today's geophysical tools. Second, the highly corrosive property of molten rock at 800 to 1000°C makes implanting of any equipment into molten magma a difficult project. Research in finding corrosion-resistant materials and in using cathodic protection is being conducted, but solutions have not been found. A third obstacle is the high viscosity of magma. Measured viscosities of basaltic lavas range from 10^3 to 10^4 cgs, which is relatively fluid; but measured viscosities of andesitic and dacitic lavas, which are usually found in continental or marginal regions, range from 10^8 to 10^{11} cgs.[47] With such viscosities, the velocity of convective motion will be very slow. Hardee and Larson[48] calculated that the velocity of convective motion of basalt of 4000 cgs viscosity in a 2.2-km radius magma chamber will be 5.75×10^{-4} cm/sec. With such slow motion, heat transfer by convection will be about the same order of magnitude as heat transfer by conduction. Under these conditions, the rate of heat extraction will be too small for power generation. The concept of magma tap has a long way to go before realization is effected.[49]

In conclusion, we note that progress toward volcano energy utilization is being made along various avenues. It is most heartening to know that actual exploration and field experiments are being carried out on all representative types of volcanoes: spreading zone, subduction zone, and midplate types. As progress has been rather rapid, we may actually see the realization of a volcano energy power plant in a few years.

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