AN OVERVIEW OF SOME GEOLOGIC AND ENVIRONMENTAL ASPECTS OF GEOTHERMAL DEVELOPMENT IN HAWAII

by

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CHAPTER I

THE NATURE AND OCCURRENCE OF GEOTHERMAL RESOURCES IN HAWAII

1.1 The History of Geothermal Exploration in Hawaii

The recognition and use of geothermal energy in Hawaii has been recorded well back into the history of the Hawaiian Islands. Early explorers identified fumaroles and thermal features on Kilauea and Mauna Loa volcanoes as early as 1827[1,2], and some of the Kilauea summit fumaroles have been used almost continuously for a variety of cooking and heating purposes from pre-contact times[1] to the present[3]. However, largely as a result of the relatively small number and low temperatures of the surface thermal features outside of the areas of active volcanism, very little serious geothermal exploration or research was conducted in Hawaii until the early 1960's.

During the two decades since 1960, however, eleven exploratory geothermal wells have been drilled by five different research or development organizations (Table 1.1). Although all of those wells have been drilled on the island of Hawaii, they are distributed among three prospective geothermal areas: Kilauea east rift, Kilauea summit and Hualalai northeast rift (Fig. 1.1). In 1961, four privately financed exploratory wells (Fig. 1.1, well nos. 2686-01, 2686-02, 2982-x, 3081-02) were drilled into the Kilauea east rift zone by Hawaii Thermal Power Company[4]. Although all of these wells encountered temperatures well above that expected for normal groundwater, they were all too shallow to provide sufficiently high temperatures to be economically exploitable and thus all were

Table 1.1 GEOTHERMAL EXPLORATION AND RESEARCH WELLS IN HAWAII

Drilled by	Year Drilled	Name	U.S.G.S. Well No.	Maximum Temp.(°C)	Depth/Elevation (meters)	Status	Data Source Reference #
Hawaii Thermal Power Co.	1961	GEOTHERMAL 1	2686-01	54°(129)	54.3/307.5 178/1009	abandoned capped	4
Hawaii Thermal Power Co.	1961	GEOTHERMAL 2	2686-02	102°(216) (97.1°)(207)	169.5/315.5 556/1035	abandoned capped	4 (5)
Hawaii Thermal Power Co.	1961	GEOTHERMAL 3	2982-01	93°(199) (92.5°)(198)	210.3/171.6 690/563	abandoned capped	4 (5)
Hawaii Thermal Power Co.	1961	GEOTHERMAL 4	3081-02	43°(109)	88.4/76.2 290/250	abandoned plugged	4
Colorado Schl. of Mines/GEDCO†	1973	NSF-KILAUEA	2317-01	137°(279)	1262.2/1102.2 4141/3616	abandoned plugged	6
Univ. of Hawaii /GEDCO†	1976	HGP-A	2883-01	358°(676)	1967.5/184.1 6455/604	producible	7
Puu Waawaa Steam Co./GEDCO†	1979	STEAMCO 1	4650-X		1889.8/777.2 6200/2550	abandoned capped	8
Puu Waawaa Steam Co./GEDCO†	1979	STEAMCO 2	4850-X		2072.6/725.4 6800/2400	abandoned capped	8
Barnwell Indus. /GEDCO†	1980	ASHIDA 1	2685-X	-*-	-*-/244.8 /803	-*-	8
Barnwell Indus. /GEDCO†	1981	LANIPUNA I	2883-X	-*-		-*-	8
Puna Geothermal Ventures	1981	KAPOHO STATE I	2883-X	-*-	-*-/260.	under test	

† GEDCO = Geothermal Energy Development
* Data is not publicly available.

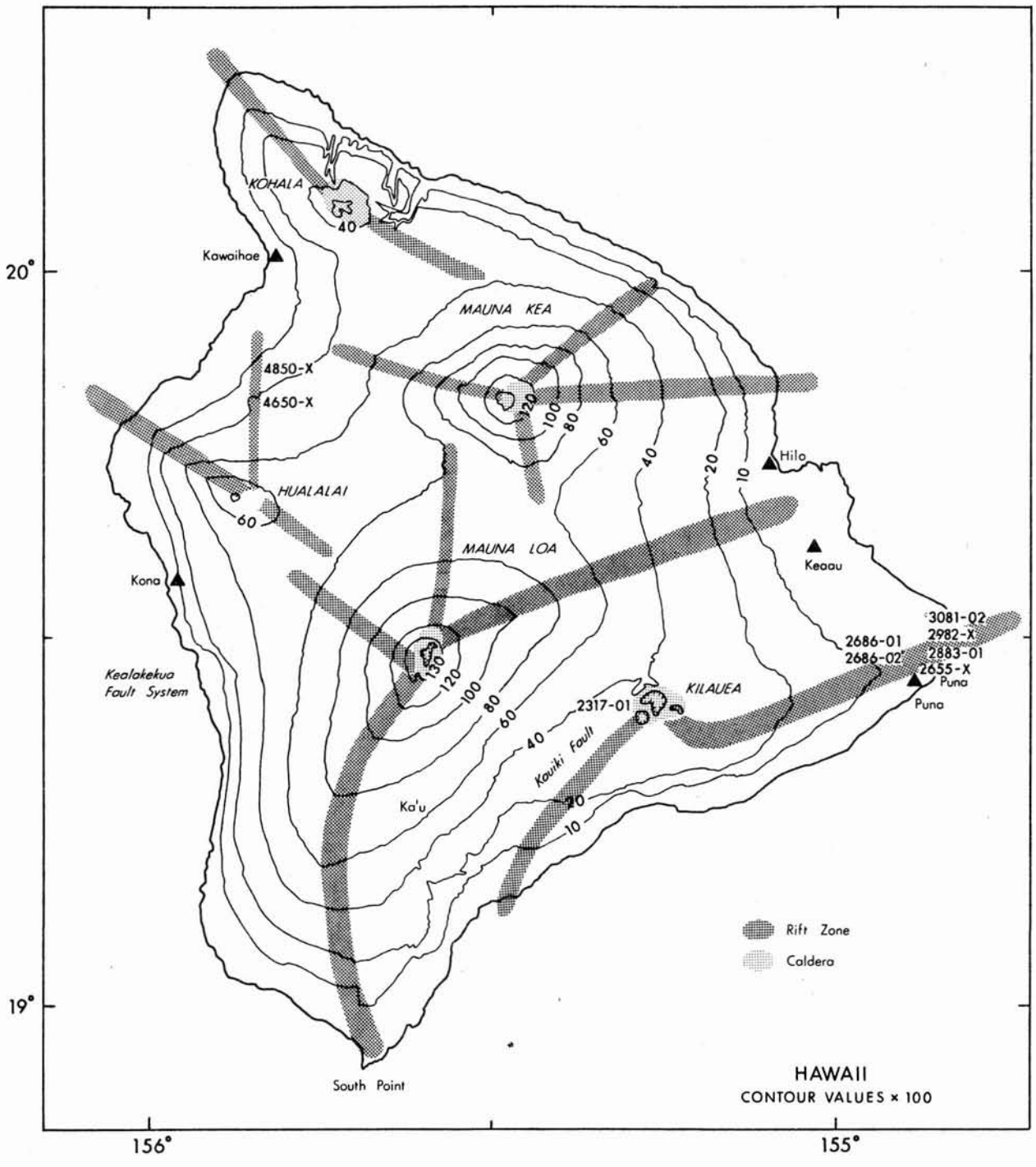

Figure 1.1 Map of the island of Hawaii with approximate locations of geothermal exploratory wells.

capped and abandoned. Subsequent to this effort the majority of geothermal exploration done in Hawaii, until very recently, has been government sponsored research into the nature and occurrence of geothermal systems in Hawaii. In 1973 the National Science Foundation sponsored a geothermal research project conducted at the summit of Kilauea volcano by Dr. George Keller of the Colorado School of Mines. A research well located 1.1 km (0.68 mi) south of Halemaumau Crater, was drilled to a depth of 1,262 m (4,140 ft) (approximately 160 m (525 ft) below sea level)[9]. The maximum temperature encountered at the bottom of the well was 135°C (275°F) and the temperature gradient (the increase in temperature with depth) observed over the last 150 meters (482 ft) of the well was approximately 370°C/km (1,123°F/mi)[9]. If drilling had continued to only slightly greater depths much higher temperatures almost certainly would have been encountered. However, this well was drilled for basic research purposes, and was not intended for commercial exploitation, thus no subsequent efforts were made to deepen the well.

During this same period the University of Hawaii, under a research grant from the National Science Foundation and State of Hawaii began an exploration program for a second geothermal research well. Although geophysical and geochemical surveys were initially conducted in several parts of the island of Hawaii, the initial data acquired indicated that the east rift zone of Kilauea volcano had the greatest potential for success and thus the majority of the detailed exploration work was confined to this area[10,11]. Although no single site could be positively identified from the geophysical data acquired, several areas along the lower east rift zone were indicated to have conditions suggestive of a geothermal reservoir. Despite some disagreement over

interpretations of the subsurface conditions, a decision was made to drill a single deep research well into the lower east rift approximately 1 km west of the prehistoric cinder cone Puu Honuaula. This location was chosen primarily on the basis of numerous shallow warm water wells in the vicinity, nearby resistivity and self-potential anomalies, and the availability of land for a drilling site[12]. Drilling was initiated in December, 1975 and was completed by late April, 1976. Downhole temperature measurements made after the well was completed indicated that the well (named HGP-A[13]) was definitely hot and, on July 2, 1976, the well was artificially induced to discharge a mixture of steam and hot water. Numerous tests conducted on HGP-A since 1976 have shown that it is by far the hottest exploitable geothermal well in the United States, having a maximum bottom temperature of approximately 358°C, and that the well is capable of producing over 45,000 kg/hr (100,000 lbs/hr) of steam (55%) and water (45%)[14,15,16].

Construction of a 3 megawatt wellhead generator facility is presently underway as a proof of feasibility project, and is jointly sponsored by the U.S. Department of Energy, the State of Hawaii, the County of Hawaii, and the local utility company. The installation of the generator is expected to be completed in mid-1981 with production of electric power scheduled to begin in late 1981. The objectives of the Wellhead Generator Project are to identify and surmount both the real and the perceived barriers to the production of power from the Kilauea east rift and thereby stimulate private interest in the development of the discovered resource.

Subsequent to the successful completion of the HGP-A well the U.S. Department of Energy and the State of Hawaii, jointly sponsored an exploration effort to identify and characterize other potential geothermal resources throughout Hawaii. The initial phase of this work compiled available data relevant to the identification of potential geothermal areas. On the basis of this data survey, twenty areas within the State were selected as targets for more extensive detailed field surveys[17]. This exploration effort is presently under way and a detailed summary of the results obtained to date are presented in a subsequent chapter of the present work.

Private interest in geothermal exploration and development in Hawaii increased substantially after the successful completion of HGP-A in 1976. The Puu Waawaa Steam Company financed exploratory drilling of two wells[8] on the northwestern flanks of Hualalai volcano on the western side of Hawaii Island in the early part of 1978. Prior to drilling, several geophysical surveys were conducted around the Puu Waawaa cinder cone by a mainland-based exploration group; several geophysical anomalies were observed in this area and, on this basis, two exploratory wells were drilled[8]. Neither well encountered significantly elevated temperatures to depths of more than 2,000 m (6,600 ft) and thus both were abandoned shortly after completion. More recently, several permits for exploratory wells in the immediate vicinity of HGP-A have been obtained by other private groups. Three of these wells have been completed and all are believed to have encountered high subsurface temperatures. However, since these wells were privately financed, virtually no specific information is available concerning subsurface temperatures or the nature of the resource encountered.

Although several other private groups have expressed interest in conducting exploratory drilling, both in Puna and in other parts of Hawaii, legal and jurisdictional conflicts have arisen that may prove to be more difficult to overcome than the technological problems encountered in earlier drilling efforts.

1.2 Geothermal System Types

Geothermal energy, very simply defined, is that energy which can be obtained from heat within the earth. It is generally understood that the solid, relatively cool crust of the earth is underlain by several progressively hotter and denser layers of material. The source of the earth's heat is a combination of the thermal energy released when the original protonebular dust cloud coalesced to form the earth and the energy released by the small concentration of radioactive elements trapped within the earth. The temperature of rocks beneath the earth's surface gradually increases with depth; the rate of increase (the geothermal temperature gradient) that is observed through the earth's crust averages about $20^{o}C$-$30^{o}C$ per kilometer (68^{o}-$86^{o}F$/mi) in depth[18]. Thus, under normal circumstances economically exploitable geothermal temperatures are not present above 5-10 km depth in most areas of the earth. In several places, however, the normal stability of the mantle and crust has been upset resulting in the formation of bodies of molten rock (magma) which migrate upward into the crust. When this molten magma reaches the surface of the earth, volcanic eruptions occur and the heat energy carried up from the earth's mantle is very rapidly dissipated into the atmosphere[19]. However, if the molten magma body begins to solidify before it reaches the surface, its thermal energy is slowly released to the near-surface rocks and groundwater. Under favorable conditions

a relatively long-lived (thousands to millions of years) geothermal system can be formed by the interaction between slowly cooling magma bodies and near-surface groundwater.

Several types of geotheral systems that have been identified in relation to volcanic and subvolcanic processes[20]. The most common type is the water-dominated system characterized by a reservoir of warm to very hot water confined by a low permeability cap rock or by the hydrostatic pressure of an overlying layer of cooler groundwater. If sufficiently high temperatures are present both hot water and steam can be recovered from these systems by drilling into the reservoir. Such liquid-dominated geothermal systems are known to exist in several parts of the United States (including Hawaii) as well as in New Zealand, Japan, and numerous other countries around the world[20].

A second, less common type of thermal reservoir is the vapor-dominated system; it is characterized by both a very high heat flow and a low groundwater permeability. Geothermal fluids in vapor-dominated reservoirs are often nearly 100% steam with only very small amounts of liquid wter (and other naturally occurring volatile compounds). Vapor-dominated systems are known to occur in relatively few places around the world such as Larderello, Italy, and Geysers, California; none, however, are presently known to exist in Hawaii.

A third major class of geothermal resource is the hot dry rock system. This type is similar to the vapor-dominated sytem since it is also characterized by a low groundwater permeability. However, so little groundwater is present and the permeability is so low that, in order to extract heat from this type of system, it is necessary to artificially induce permeability by fracturing the rock strata and then circulating water through the induced fractures from the

surface. Development of the technology necessary for exploitation of this type of resource is still in the experimental stage. Direct extraction of heat from molten magma bodies (a subclass of the hot dry rock system) is also being considered. The techniques for accomplishing this include both the emplacement of metal or ceramic heat exchangers into the molten rock, through which surface water is circulated, as well as the injection of water directly into a chilled zone of solidified rock within the magma body. However, even though such near-surface bodies are known to exist in Hawaii (e.g. Kilauea east rift zone), the technology for economically exploiting this type of heat source is still several years away.

1.3 Geology of Hawaiian Volcanic Geothermal Systems

Geothermal systems in Hawaii are controlled to a large degree by the processes which formed the volcanoes of the Hawaiian island chain. It is presently believed that a thermal instability, or "hot spot," is present in the earth's mantle beneath the crustal plate which forms most of the north Pacific basin. This "hot spot" has existed for several millions of years and, as the plate has moved northwestward over it, molten magma has leaked out and built up on the floor of the Pacific Ocean to form the chain of volcanic islands that extends from Kuraetoll at the north end to Hawaii Island to the southeast. This process is occurring even now, both on the island of Hawaii and on Loihi seamount south of the Big Island[21]. Thus, as one moves southward along the island chain and toward the inferred "hot spot" the age of the volcanism which formed the individual islands becomes progressively younger.

Each major island in the Hawaiian chain is made up of one or more volcanic systems and each volcano evolves through a relatively well defined life cycle (Fig. 1.2)[21]. Initially, magma is erupted onto the floor of the Pacific Ocean. Sea water, at very high pressure, rapidly chills erupted magma which form very dense and impermeable beds of pillow lavas. As the summit of the submarine volcanic edifice nears the ocean surface, activity becomes more explosive and the lava flows formed are more porous and fractured. Continuing activity forms a broad shield shaped volcanic island with a roughly circular depression, a caldera, at its summit. The later stages of eruptive activity in a mature volcano becomes more sporadic with long periods of weathering and marine erosion interspersed with short periods of scattered, and somewhat more explosive, post-erosional activity. It is generally believed that the magma extruded during this latter stage of activity rises very rapidly from a great depth beneath the volcano and thus the magma source may have little relation to the original magma chamber and rift zone structure of the younger volcano.

During the earlier phases of eruptive activity, when the lava extrusion rate is quite high, a well defined system evolves within the volcanic edifice. A roughly cylindrical conduit and magma chamber are formed near the center of the volcanic edifice and, radiating outward from this conduit, are usually two or three well defined fracture systems, or rift zones (Figs. 1.3 & 1,4). As the volcano continues to grow, magma migrates first up into the near surface magma chamber at a depth of 2 to 4 kilometers beneath the summit, and from there is erupted at the summit or is injected into the rift zone where it may either remain and slowly solidify or rise to the surface on the flank of the volcano.

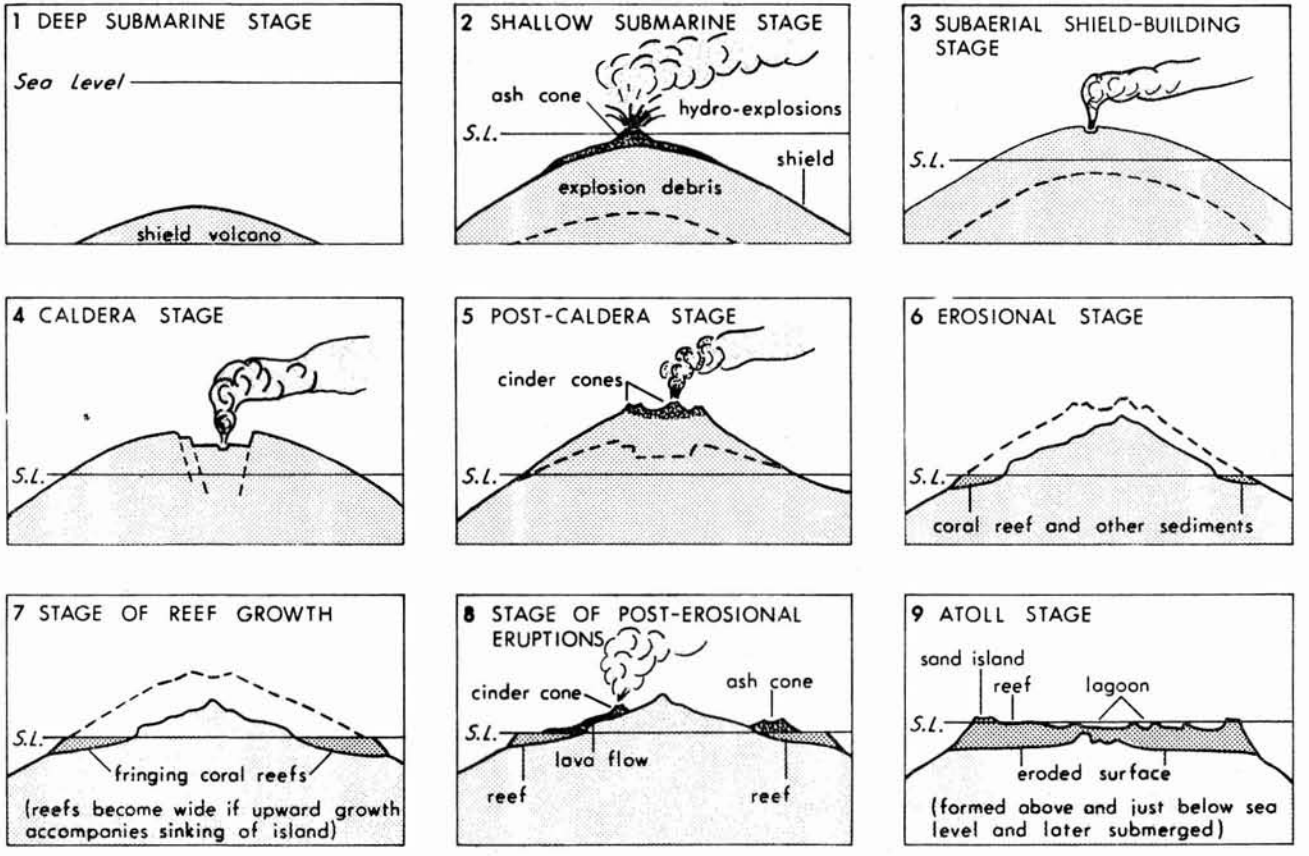

Figure 1.2 Life cycle of a mid-oceanic volcanic island; from Macdonald and Abbott, 1970.

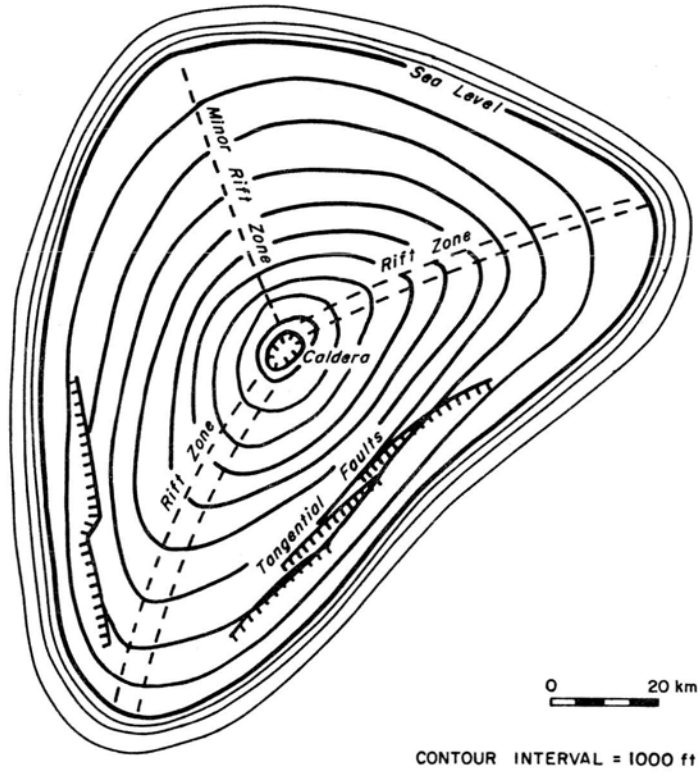

Figure 1.3 Plan view of typical oceanic shield volcano and associate rift zones; from Macdonald and Abbott, 1970.

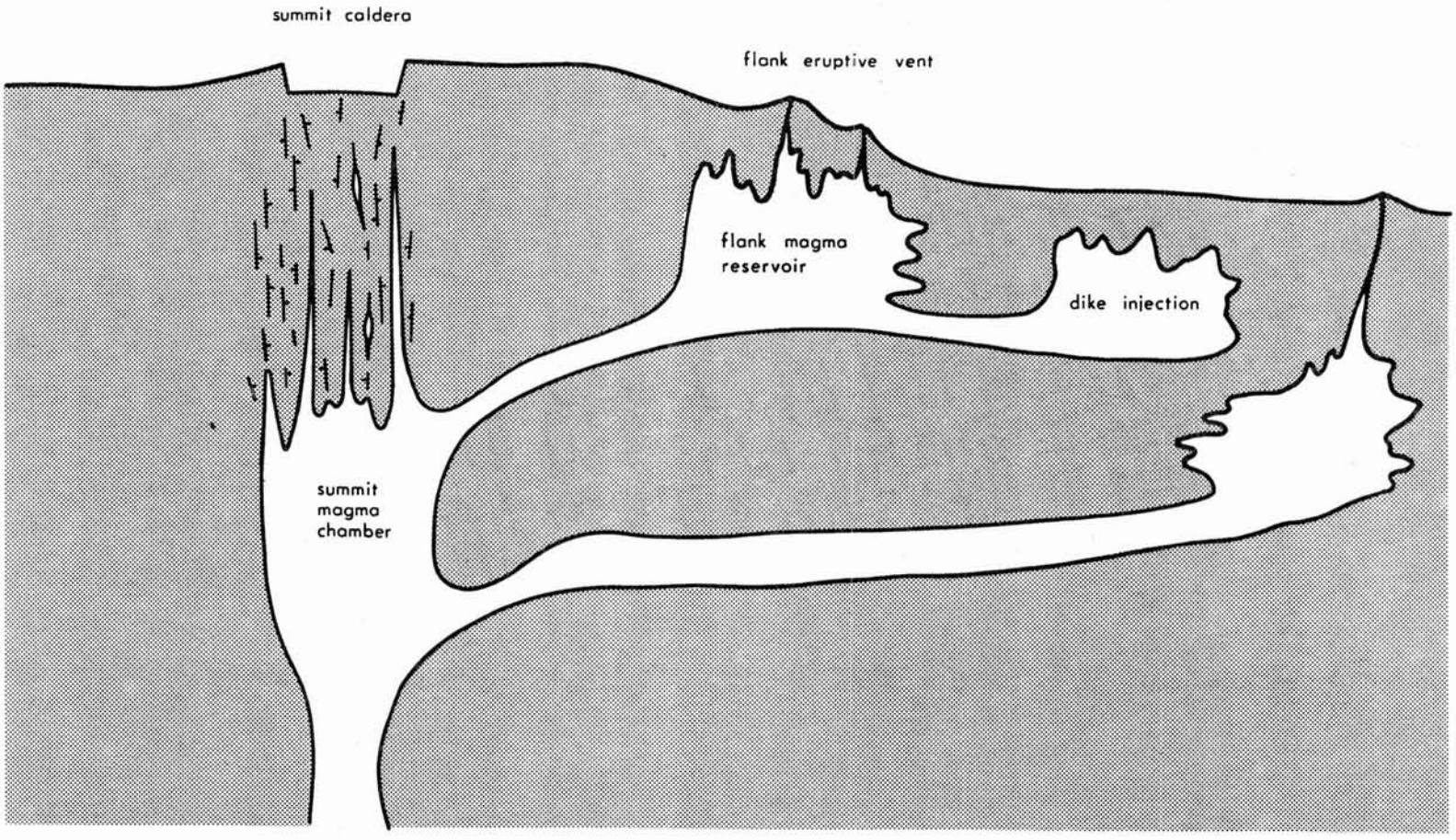

Figure 1.4 Cross-section, parallel to the rift, of a typical oceanic volcano magma chamber-rift zone system.

During the entire eruptive life of the volcano a substantial amount of thermal energy is brought into the near surface environment. This heat energy is dissipated very rapidly in the lava flows that are erupted in the submarine and subaerial environment and, generally within a matter of a few hours to a few years, the temperature of these flows is equal to that of the groundwater or sea water that circulates through them. However, molten material in the magma chambers and material that has intruded into the deeper parts of the rift zones retains its heat for a much longer period of time. It is these areas that have the greatest potential for development of geothermal systems.

I.4 The Nature of Hawaiian Geothermal Systems

As mentioned briefly above, at least two types of geothermal systems exist in Hawaii: molten magma and water-dominated systems. Molten magma is known to be present near the summit of Kilauea volcano both in the summit magma chamber and in the rift zones radiating out from the central caldera. Even though vast quantities of heat are stored in these bodies of molten rock, exploitation of this heat directly is not presently considered to be economically feasible. However, as these magma bodies cool, their heat is transferred out into the surrounding rocks which are often saturated with water. In rocks of high permeability the heat can be dissipated in a very short time to rapidly circulating groundwaters; however, if the cooling magma is surrounded or overlain by rocks of low permeability the heat loss occurs much more slowly. In cases where the heated groundwater is well below the surface of the local water table (1-2 kilometers, 3,000-6,000 feet), the weight of the overlying water (hydrostatic head) may also be sufficient to prevent this heated water from boiling and dissipating the available thermal energy. Under some conditions the

deeply circulating groundwaters dissolve minerals from rocks in the highest temperature zones and redeposit them as the thermal fluids enter the cooler rock strata[22]. This process can obstruct the flow channels in the cooler rocks and thus confine the heated waters in a self-sealed geothermal reservoir (Fig. 1.5). It is not presently known whether self-sealed geothermal systems exist in the Hawaiian geologic environment. However, it is known that high temperature hydrothermal systems do form at depths as shallow as 2,000 meters[7,12,15].

A major concern regarding hydrothermal systems in Hawaii is their longevity. The lifetime of a thermal system is controlled to a large degree by the size of the cooling magma body as well as the rate at which heat is removed by circulating thermal fluids or by conduction through adjacent rock. A thin dike of molten magma injected into cold near-surface rock would lose most of its heat in a matter of weeks or months; a massive body of molten rock such as a magma chamber in the core of a volcano could take thousands and possibly even millions of years to cool to ambient temperatures. Thus, it is highly possible that most high temperature geothermal systems in Hawaii will be located deep within recently active rift systems or in the slowly cooling magma chambers of the younger volcanic systems. The older volcanic systems, such as those on Molokai, Oahu, and Kauai, may still have thermal energy within their magma chambers, however, the probability for finding useful heat at economically viable depths decreases substantially as the age of these systems increases.

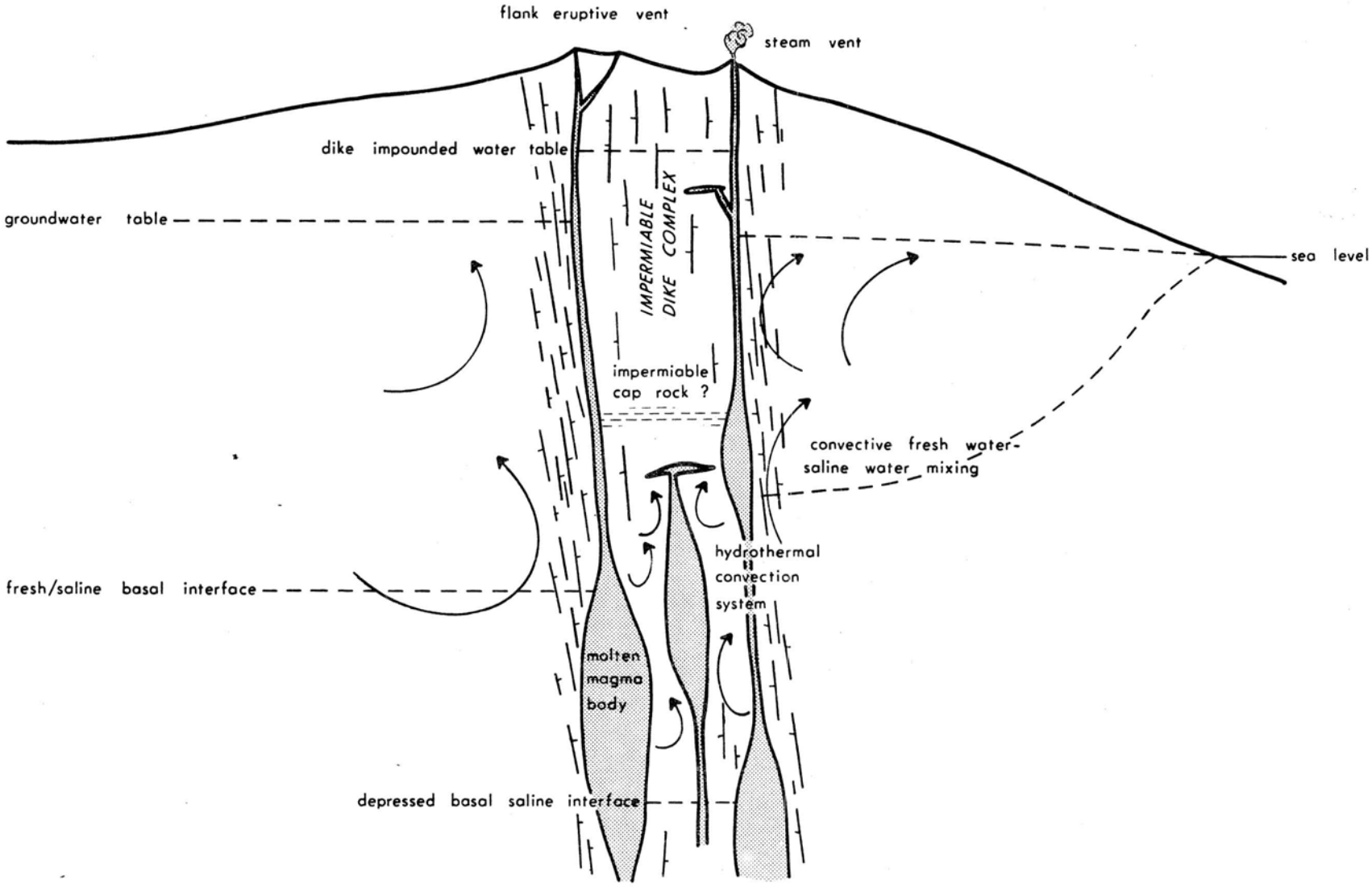

Figure 1.5 Cross-section of an idealized geothermal system which might form on and around a rift zone and dike complex in Hawaii.

I.5 Methods of Identification of Geothermal Systems

There are several methods by which a geothermal resource can be identified. Drilling, the only certain method, is extremely expensive and therefore is usually done after the completion of other, considerably less expensive and, unfortunately, less certain, surface exploration techniques. The application of surface exploration techniques is based largely upon the unique geochemical and geophysical conditions found in a geothermal reservoir. The geologic conditions for a reservoir have been discussed above and are the initial constraints placed upon site selection for exploration work. The geophysical and geochemical characteristics of a geothermal reservoir, although highly variable from one system to another, can usually be distinguished from nearby, non-geothermal terrain through the use of one or, more generally, several sophisticated measurement techniques. The geophysical techniques normally applied in exploration work are usually considered to be remote techniques wherein, secondary characteristics of a potential geothermal area (those not directly associated with the thermal energy in the reservoir) are measured at some distance from the reservoir. Geochemical techniques, on the other hand, most often rely upon directly measuring leakages or emissions from a geothermal reservoir. A number of the individual geophysical and geochemical techniques typically used for geothermal exploration in Hawaii include the following:

Gravity. Very precise measurement of the gravity field at the ground surface can identify (1) very dense bodies of rock required for the existence of a long-lived reservoir, (2) areas in which hydrothermal alteration has filled in fractures and pores normally found within the rock, or (3) areas in which hydrothermal

alteration has removed significant quantities of the denser minerals originally present and replaced them with less dense clays and hydrothermal precipitates.

Resistivity. The electrical resistivity of subsurface rock strata is strongly affected by the salt content and temperature of the groundwaters circulating through them. Thus rocks saturated with warm saline geothermal fluids have a lower resistivity than those saturated with colder groundwaters.

Magnetics. Rocks at very high temperature that have been altered by circulating thermal fluids have a substantially lower magnetic susceptibility than do normal rock strata. These changes are reflected in small but detectable changes in the earth's magnetic field above and around thermal areas.

Passive Seismic. Geothermal reservoir rocks (either because of cooling and contraction or a lowering of their mechanical strength) tend to fracture more readily than cold rock strata and thus generate more seismic noise than colder rocks.

Self-Potential. The exact mechanism of the generation of self-potential anomalies (large variations in the natural voltages at the earth's surface) in Hawaii is not clearly understood. However, self-potential anomalies have been found to be correlated strongly with known thermal anomalies at the Kilauea summit and along the Kilauea east rift.

Temperature/Heat Flow. Geothermal systems often leak high temperature fluids into the near-surface environment creating anomalously warm ground or shallow groundwaters. These thermal anomalies can be detected by direct measurement or by airborne infrared imaging.

Groundwater Chemistry. Water at high temperature tends to dissolve selected minerals out of reservoir rocks and thus thermally altered groundwater has chemistry substantially different from cool groundwaters having, for example, different concentrations of silica, sodium, potassium or calcium.

Trace Element Chemistry. The leakage of geothermal fluids into the near surface tends to create anomalous concentrations of trace and volatile elements (e.g. mercury and radon) at or near the ground surface.

Isotope Chemistry. Geothermal fluids often have a unique isotopic character due either to high temperature isotopic exchange between groundwater and reservoir rocks or by the unique character of the minerals and gases dissolved from the reservoirs rock (e.g. methane or helium).

Although each of these techniques has proven to be useful for indicating a geothermal reservoir, it should be noted that each is subject to difficulties of interpretation or to interferences. It follows from this that no single technique can unambiguously confirm the existence of a thermal reservoir and it is therefore necessary to apply a number of techniques in any potential resource area in order to ascertain whether results observed by one method can be substantiated by other techniques.

1.6 Geothermal Exploration in Hawaii

Although geophysical and geochemical exploration work is not yet complete for most survey areas in Hawaii, substantial amounts of data have been acquired on the geothermal potential of Hawaii's volcanic systems. An initial compilation of existing geophysical and geochemical data completed in 1978[17] identified approximately 20 areas throughout the State (Fig. 1.6) which warrant further, more detailed, field investigations. Geochemical and geophysical exploratory investigations have been completed in some of the identified target areas and are currently under way in several others; a summary of available data from this work follows.

The island of Kauai (Fig. 1.7) was formed by one large volcano of approximately 3.5 to 5.5 million years age. Numerous post-erosional volcanic vents, which were active 1 to 2 million years before the present, are scattered over the eastern and southeastern half of the island. Only a few groundwater geochemical anomalies have been identified on Kauai, and, even though it is presently believed that the potential for discovering a viable thermal resource on this island is quite low, field surveys in the vicinity of the post-erosional volcanic centers will be necessary to confirm this preliminary conclusion.

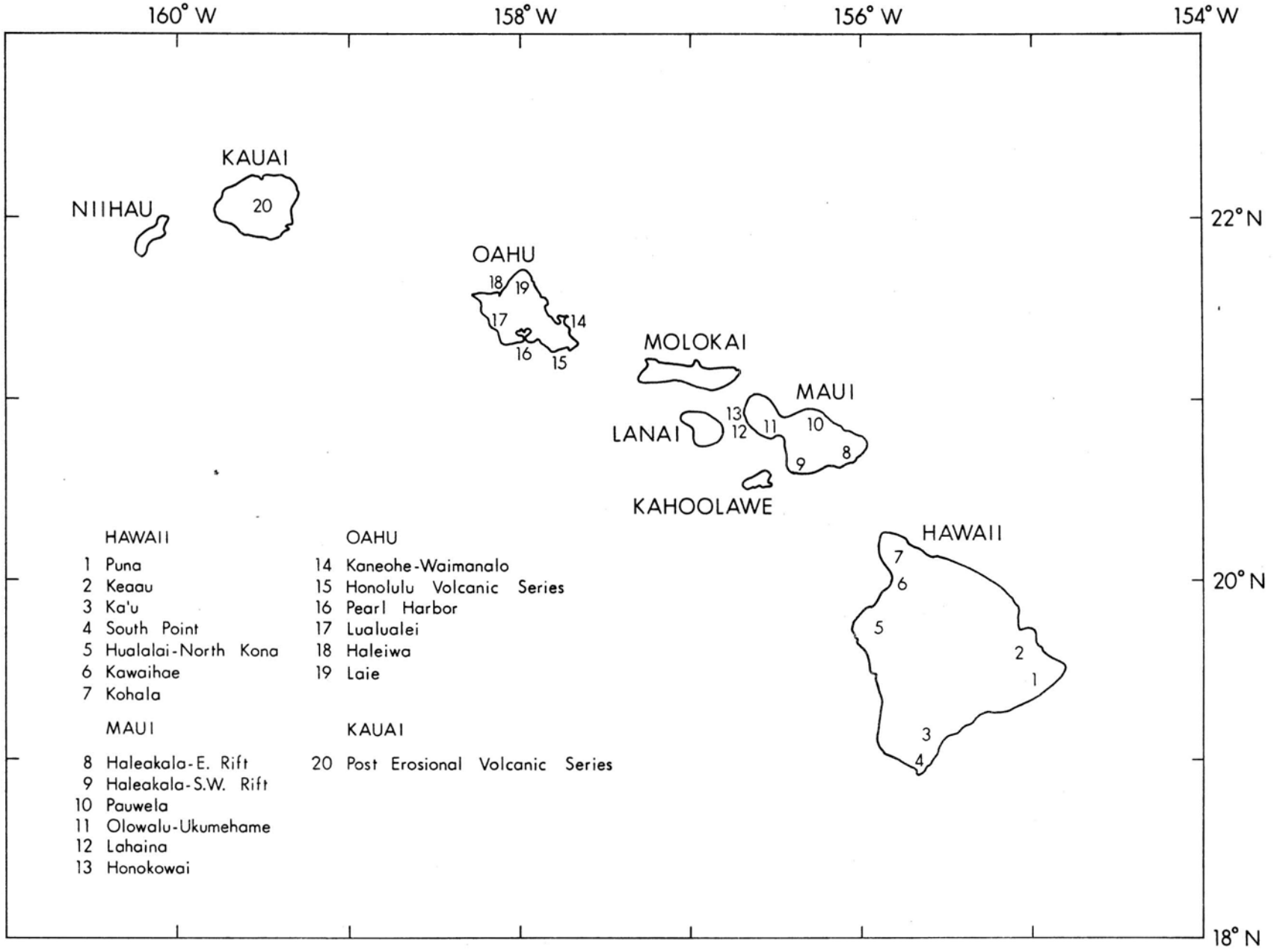

Figure 1.6 Location map of identified geothermal exploration areas on the major islands of the Hawaiian Chain.

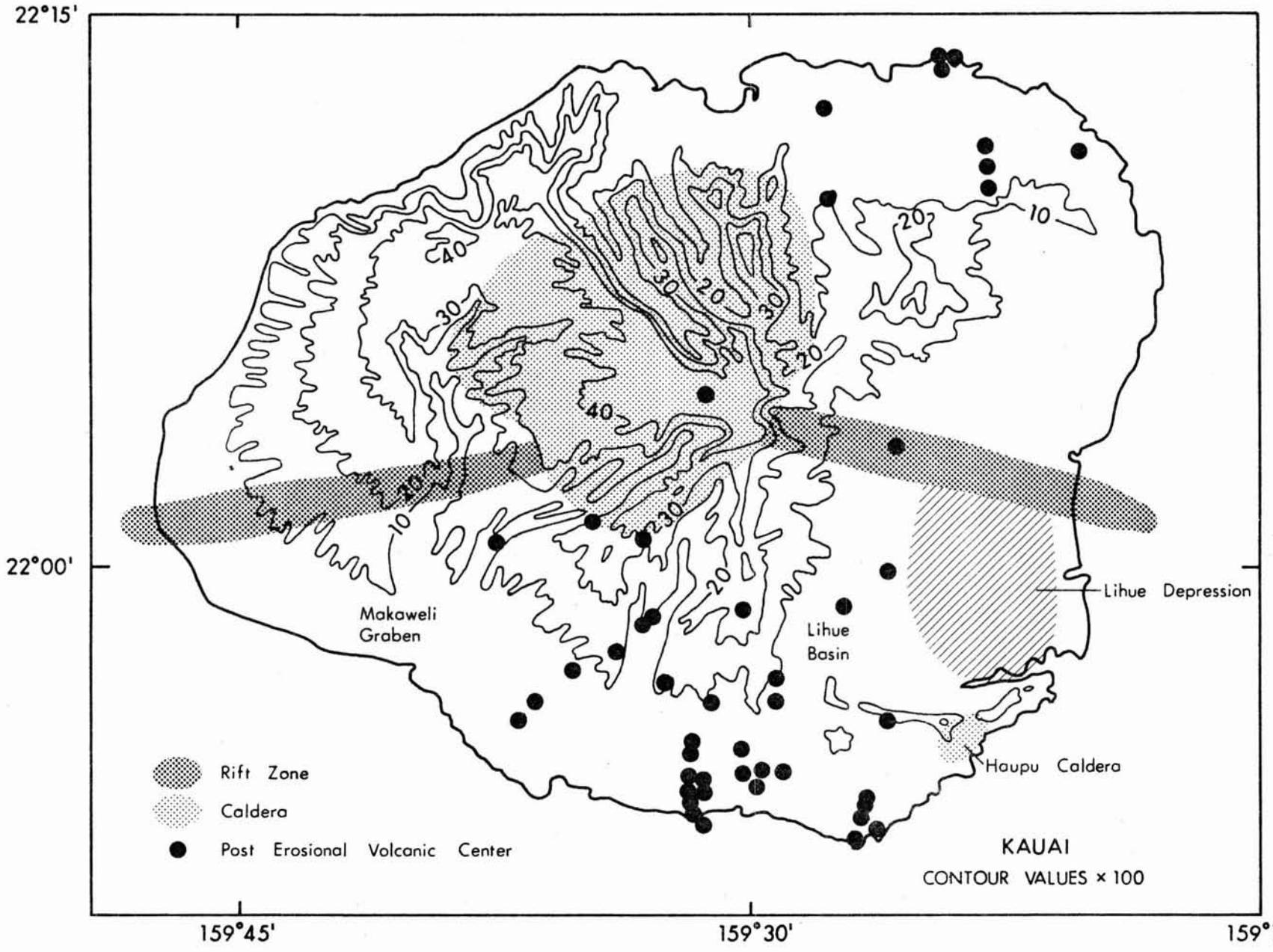

Figure 1.7 Map of the island of Kauai: showing caldera and rift zones of Kauai Volcano and the more recently active post-erosional eruptive centers of Kauai.

The island of Oahu (Fig. 1.8) is made up of two major volcanic edifices: Waianae shield formed approximately 2.5 to 3.5 million years ago and the Koolau Shield, active from 2.5 million to 20,000 years ago. This latter activity includes numerous post-erosional eruptive centers scattered across the southeastern end of Oahu such as Diamond Head and Koko Head. Preliminary assessments of Oahu's geothermal potential identified six separate areas on the island which warranted further investigation. Although the overall appraisal of the island's potential is generally low, due to the relatively great age of both of the major eruptive centers, field investigations conducted in the vicinity of the Waianae caldera in 1978 were much more encouraging than initially expected[23]. The geophysical and geochemical techniques applied in the Waianae caldera (Fig. 1.9) included resistivity, groundwater chemistry and temperature, soil mercury and radon, structural and petrological mapping, and alteration mineralogy. The results of these surveys identified several areas around the inferred caldera boundary where anomalous conditions were indicated to be present (Fig. 1.10). Although several alternative explanations are possible for the data, the most reasonable interpretation of the coincident anomalies is that they are arising from at least a low-level heat source within the Waianae caldera system. On the basis of the results obtained five sites were identified for possible future exploratory drilling. The U.S. Navy, the present landowner, has taken these recommendations under advisement but plans no exploratory drilling at present.

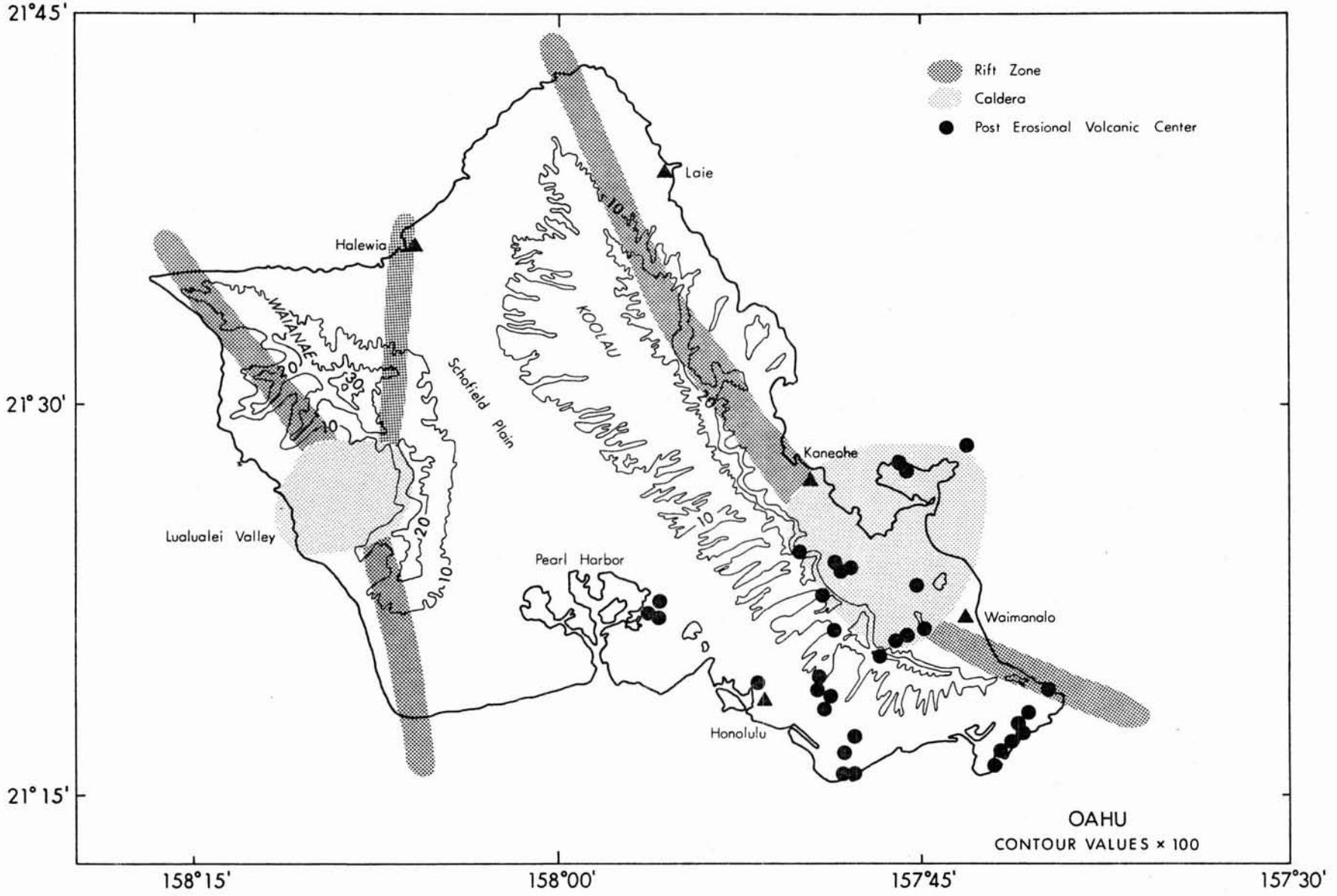

Figure 1.8 Map of the island of Oahu: showing the calderas and rift systems of the Waianae and Koolau volcanoes as well as the post-erosional eruptive centers of Koolau volcano.

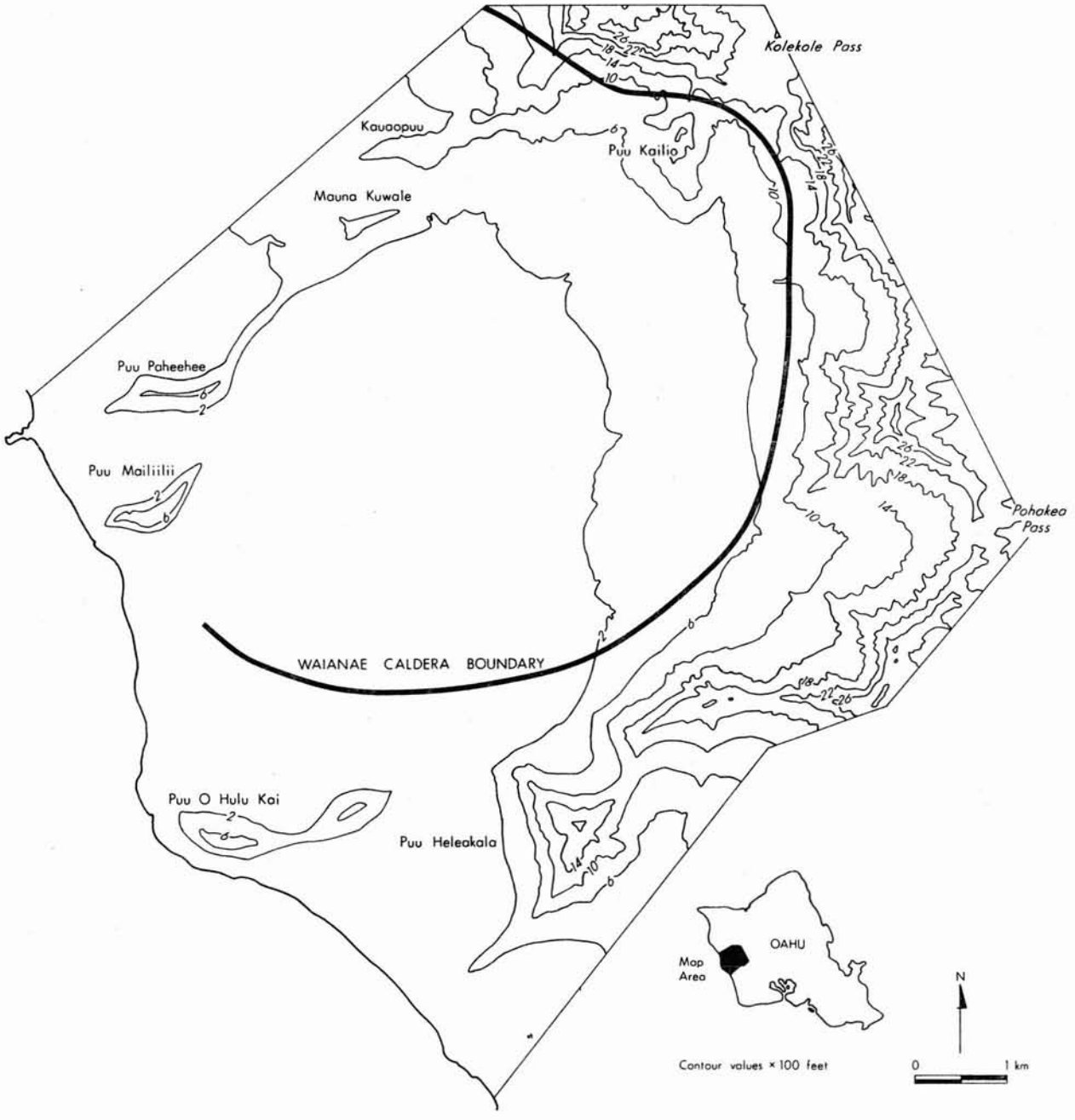

Figure 1.9 Map of the geothermal survey area of Lualualei Valley on Oahu.

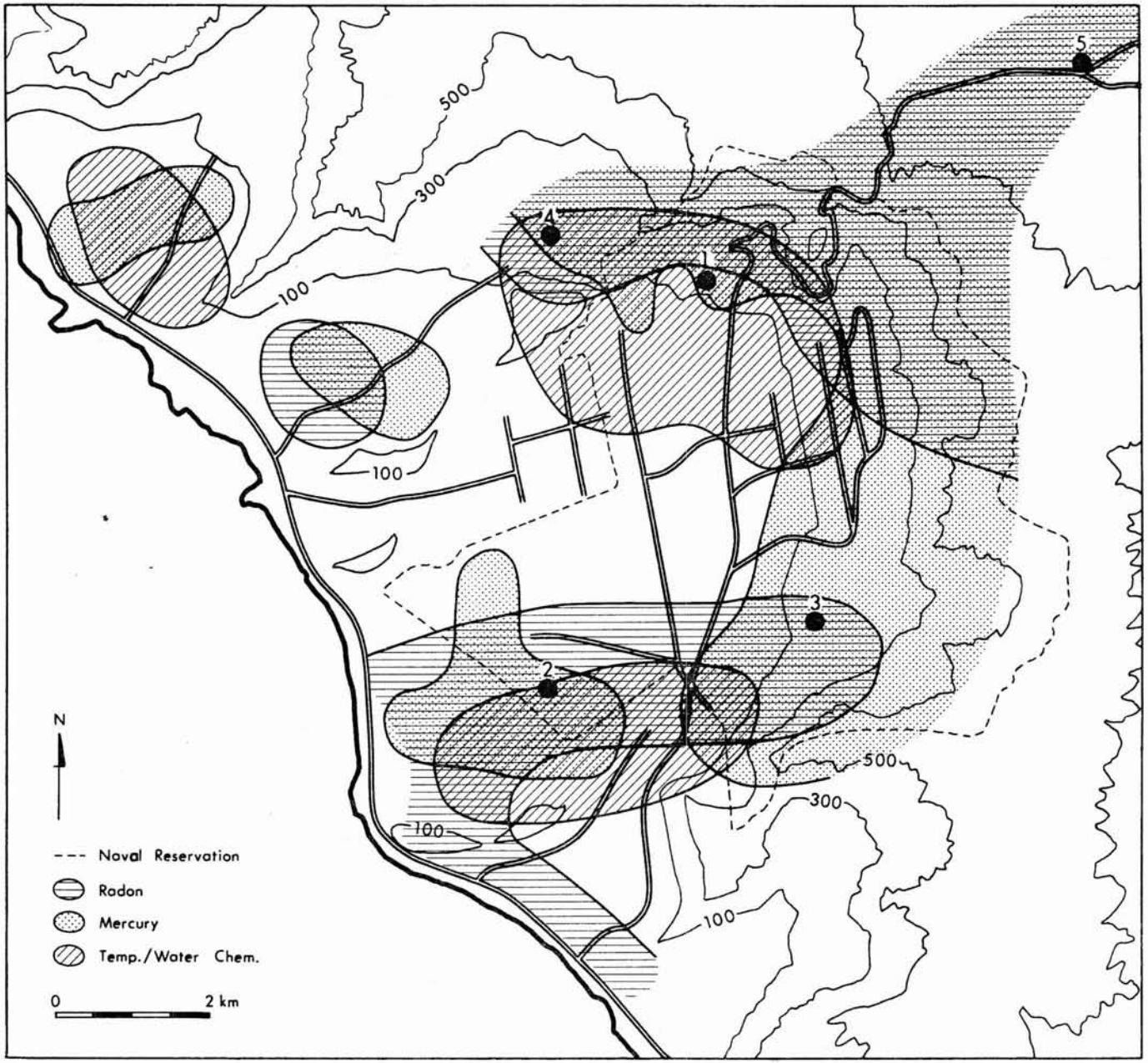

Figure 1.10 Map of geochemical and geophysical anomalies observed in Lualualei Valley. Numbered locations are recommended drill sites for acquisition of subsurface temperature and lithology data.

One other potential geothermal area on Oahu has been investigated; a detailed survey of the Mokapu Peninsula, near Kaneohe, was completed in mid-1981. Even though this area is on the outer edge of the Koolau caldera and is the site of relatively recent post-erosional activity, detailed geochemical and geophysical surveys were not able to detect any significant anomalies that could reasonably be interpreted to be geothermally derived. Geothermal exploration in other parts of the Koolau caldera and in the other identified potential areas on Oahu, have been forestalled for the present primarily due to a combination of the limited probability for finding a high-temperature resource and the rather high population density, and resultant difficulty in conducting field surveys in these areas.

Molokai (Fig. 1.11) is made up of two major volcanic units: the west Molokai volcanic series from 2.25 to 1.75 m.y. of age and the east Molokai series from about 2 m.y to 1.25 m.y. The large post-erosional Kalaupapa series on the north coast of the island is thought to have an age of between 30,000 and 500,000 years. An initial evaluation of Molokai's geothermal potential identified one documented warm water source on west Molokai and several groundwater geochemical anomalies in other parts of the island. The overall assessment of Molokai's potential is that a low-temperature resource may well be present on west Molokai, however, due to the relatively small market for geothermal energy on Molokai, no further field surveys have been conducted on the island.

The island of Maui (Fig. 1.12) is made up of two major volcanic systems. West Maui is the older and smaller of the two and has an age of substantially greater than 1.25 million (the oldest dated surface flow) to about 600,000 years; post-erosional activity on West Maui occurred between about 80,000 and

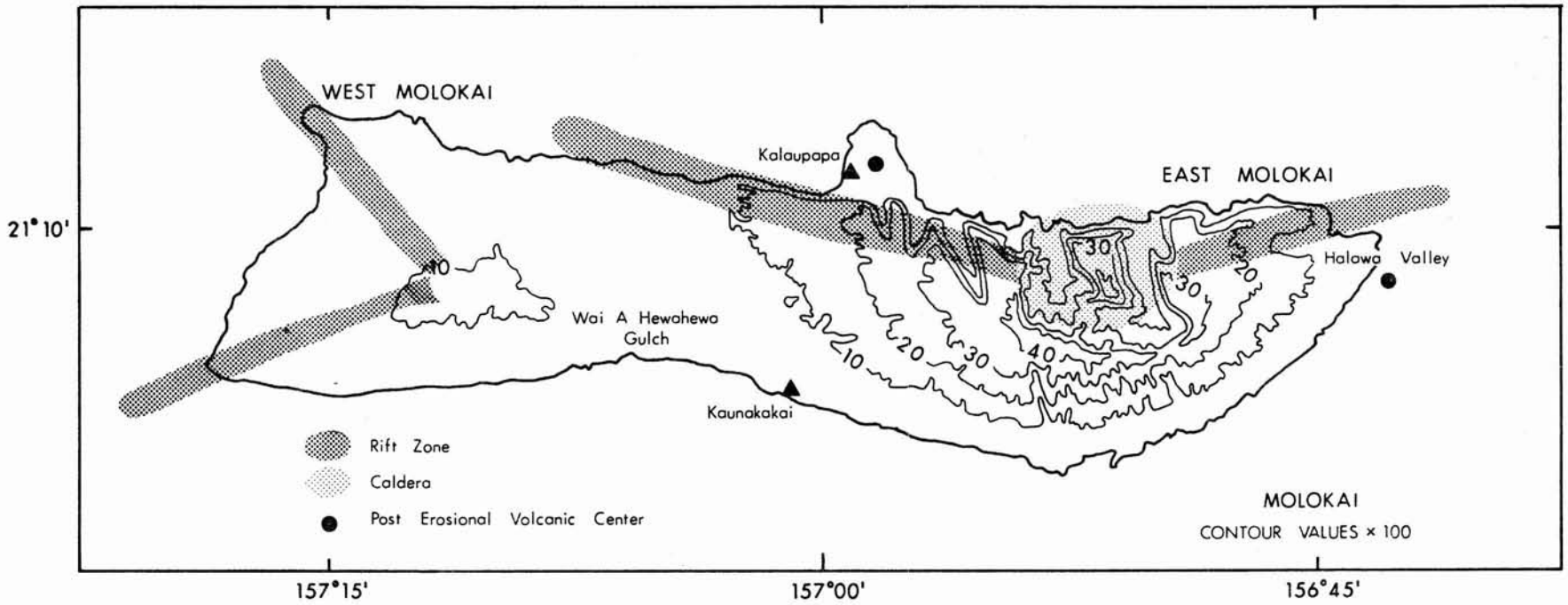

Figure 1.11 Map of the island of Molokai: showing the rift zones and caldera of West Molokai and East Molokai volcanoes. The post-erosional vents of East Molokai are also noted.

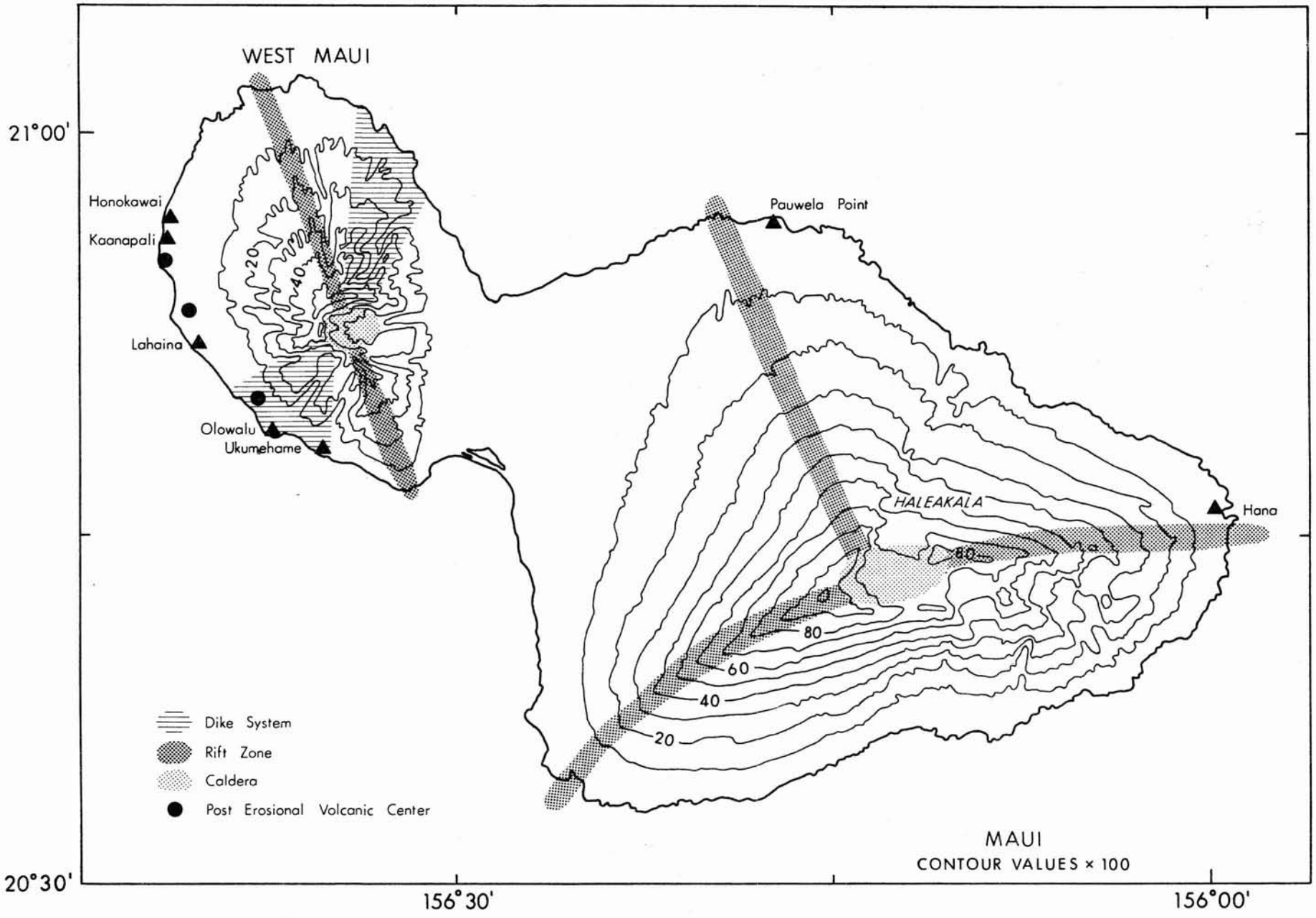

Figure 1.12 Map of the island of Maui: showing rift zones, calderas and post-erosional vents of West Maui and Haleakala volcanoes.

20,000 years b.p. Haleakala volcano (East Maui) is substantially larger and younger than West Maui; the bulk of the Haleakala shield was built between 1.5 and 0.5 m.y. ago. Post-erosional volcanism on Haleakala has continued up until the present time with the most recent eruptive activity on Haleakala occurring in 1790 along the lower southwest rift system.

A preliminary geothermal assessment of Maui identified six areas with some potential for a geothermal resource (Fig. 1.13). These potential areas were identified on the basis of groundwater geochemical and temperature data as well as location and age of most recent volcanism. A geothermal evaluation for four of these areas (Lahaina-Kaanapali, Ukumehame-Olowalu canyon, Haleakala northwest rift and the Haleakala southwest rift) is presently nearing completion. Presently available results for the areas being surveyed are as follows.

Lahaina-Kaanapali. Low-level groundwater chemical anomalies have been identified in two locations east of Kaanapali. Roughly coincident with these are anomalous soil mercury and radon concentrations possibly associated with nearby post-erosional eruptive centers. Geophysical surveys in this area, however, have been less encouraging. Resistivity soundings and self-potential surveys both indicate normal or near normal subsurface conditions[24]. Further, more detailed work using other geochemical and geophysical techniques will be necessry in this area before the apparent conflict in the data can be resolved.

Olowalu-Ukumehame. Groundwater geochemical and temperature data strongly suggest that a thermal anomaly is present in or near Ukumehame canyon; one Maui type water tunnel near the mouth of the canyon has groundwater with a temperature of 33°C (91°F), significantly above the expected ambient groundwater temperature, which also has a substantially altered chemical composition. In

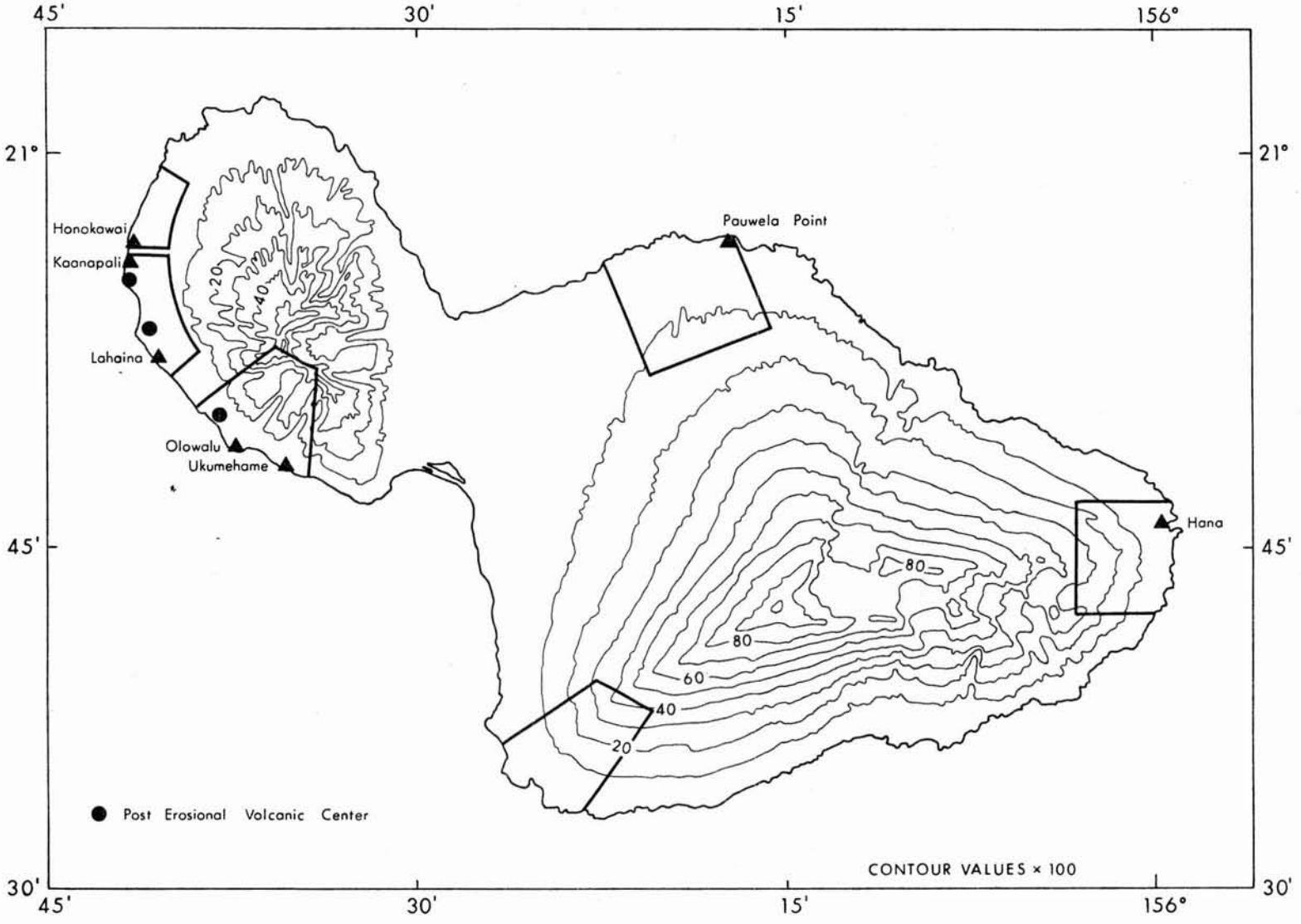

Figure 1.13 Map of prospective geothermal areas identified on the island of Maui.

addition, geophysical surveys conducted in this area have identified apparent resistivity and self-potential anomalies. Although it is not presently possible to assign a temperature to the source of the inferred geochemical and geophysical anomalies, the estimated resource temperature may range from about 60°C (140°F) to as high as 170°C (338°F). Geophysical surveys are continuing in this area in an effort to further characterize the nature of the observed anomaly.

Haleakala Northwest Rift. Initial data acquired in this area indicated that both groundwater chemistry and temperature anomalies were present. More recent soil mercury and radon data have tended to substantiate the initial anomalous interpretation. However, limited geophysical surveys as well as more recent groundwater studies suggest that the earlier geochemical evidence may be the result of other, non-geothermal, processes associated with the northwest rift zone. Further geochemical and geophysical surveys, as well as detailed hydrologic modelling of this area are under way in an effort to resolve these discrepancies.

Although the three areas discussed above all seem to have some geothermal promise, preliminary data acquired for both the east and southwest rift systems on Haleakala indicate that these rift systems may have a greater potential for a geothermal resource than any of the other identified areas on Maui. This evaluation is based primarily on the geological evidence of post-erosional eruptive activity along the rift systems. The most recent activity on Maui occurred in 1790 on the lower southwest rift of Haleakala and several of the other cinder cones on the Haleakala flanks are believed to be less than a few thousand years old. Although relatively little other geophysical and

geochemical data are available for the rift systems, more detailed field surveys for the southwest rift is presently underway.

The island of Hawaii (Fig. 1.14) is both the youngest and the largest of the Hawaiian Chain. The island is made up of five volcanic systems: Kohala is the oldest and is considered extinct; Mauna Kea is the next oldest and is considered dormant; Hualalai, Mauna Loa, and Kilauea have all had eruptive outbreaks during the last two centuries and thus are considered to be still active. The approximate range of ages for each of these volcanic systems are as follows:

Kohala. 1.0 million to approximately 0.080 million years b.p.

Mauna Kea. 1.0 million years to approximately 3,000 years.

Hualalai. 750,000 to 180 years.

Mauna Loa. 900,000 years to the present.

Kilauea. 100,000 years to the present.

A preliminary survey of the geothermal potential of Hawaii Island identified seven areas which had some evidence for potentially exploited geothermal resources. One of these seven areas, the Kilauea east rift zone, was studied intensively prior to the siting of the University's well HGP-A; three others, Keaau, Kawaihae, and North Kona, are currently being investigated. Based on the data presently in hand, the appraisal of the geothermal potential of each of these areas is as follows:

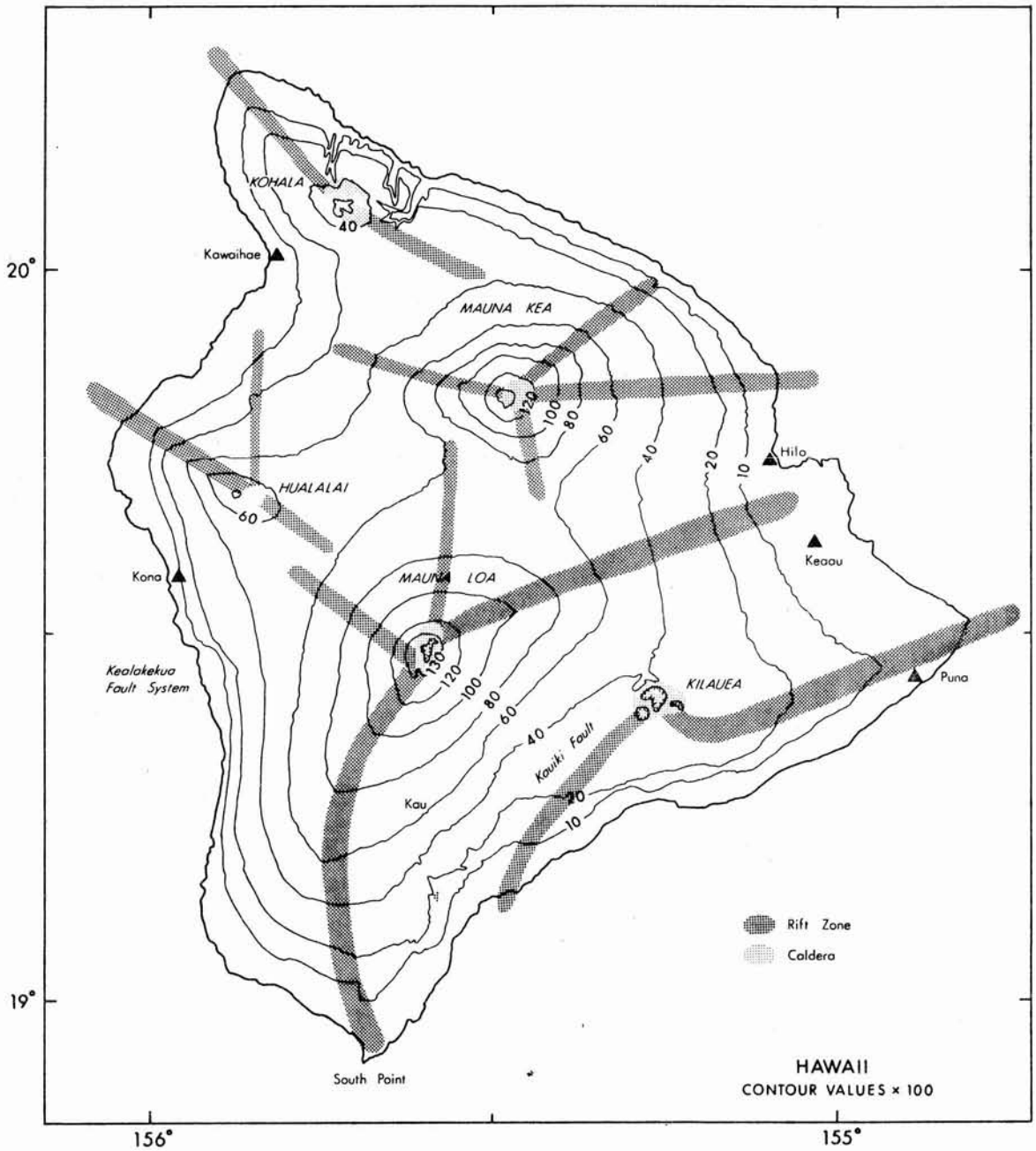

Figure 1.14 Map of the island of Hawaii showing the rift zones and calderas of the island's five major volcanic complexes.

Kilauea East Rift. During the last decade numerous geochemical and geophysical studies have been conducted along the east rift zone of Kilauea volcano and a considerable body of data concerning this area is publically available[25]. The early survey work, conducted by the Hawaii Geothermal Project at the University of Hawaii, identified a number of geophysical and geochemical anomalies along the rift zone that were inferred to be evidence of an extensive geothermal system (Fig. 1.15). These studies ultimately led to the citing of an experimental research well, HGP-A, which penetrated an extremely hot (358°C, 675°F) reservoir at a depth of approximately 1,960 meters (6,450 ft.). Subsequent geophysical evaluation of the rift zone has suggested that elevated temperatures may be present along the entire rift at depths of 1 to 3 kilometers below sea level[26,27]. Since 1980, three more privately financed exploratory geothermal wells have been drilled into the Puna District of the Kilauea east rift; all have encountered moderate-to-high temperatures (>250°C, >480°F) at depths of 2,500 meters (8,200 ft) or less. In addition, several more exploratory wells are planned both on the lower east rift as well as to the west near the summit of Kilauea.

The long term viability of the Kilauea resource, however, is currently unknown. Testing of, and production from, both the University's experimental well and the privately funded wells has been quite limited to data. (A wellhead generator facility is currently installed on the HGP-A well and long term (2-5 years) production of fluids is expected to begin in the near future). Thus, as a result of the highly variable nature of the data available concerning the extent and longevity of the resource, present estimates of the geothermal potential of the Kilauea east rift zone range from less than 100 MWE[28]-centuries

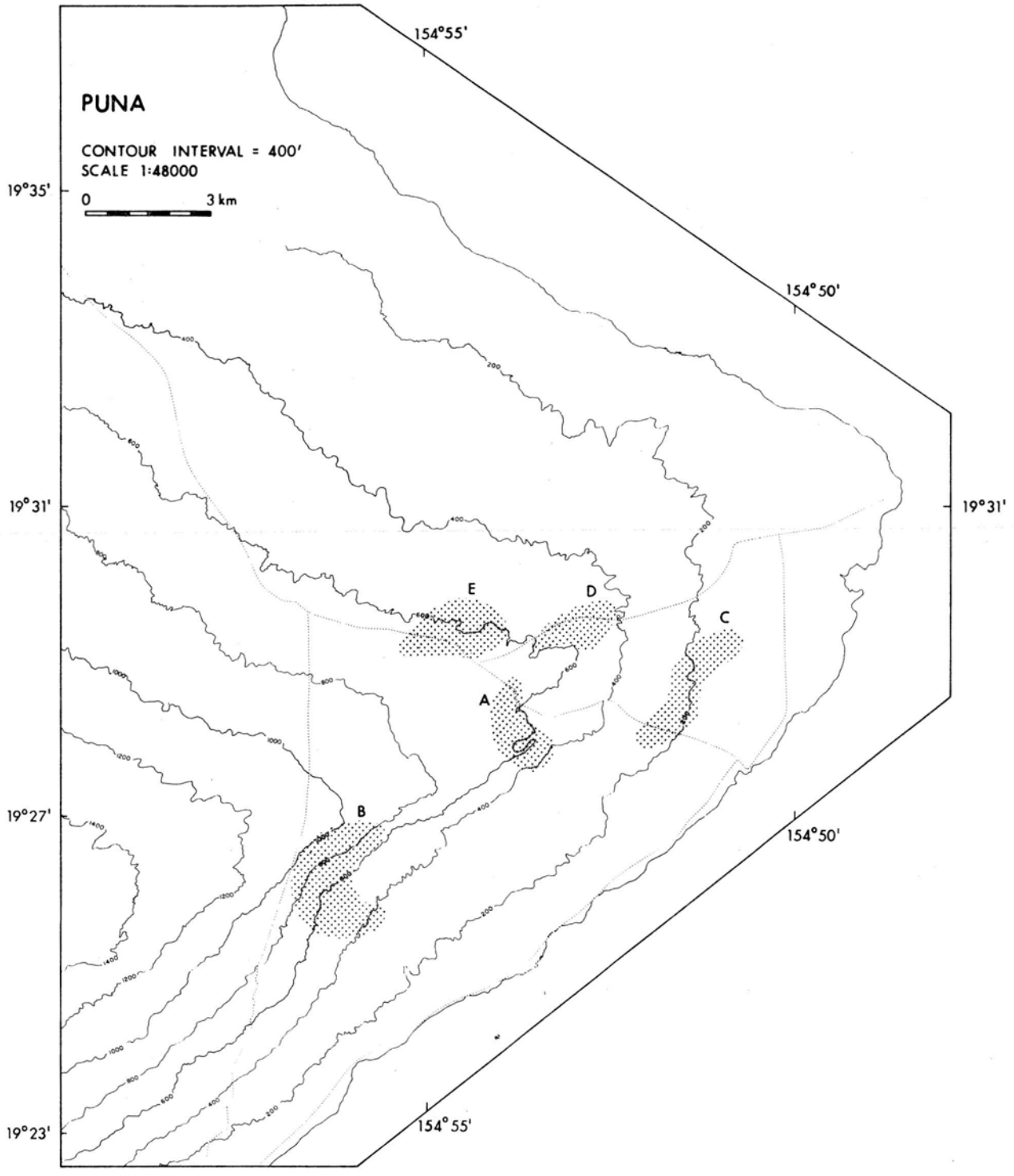

Figure 1.15 Map of the Puna district of the island of Hawaii identifying five exploratory drilling areas recommended by the Hawaii Geothermal Project.

to more than 3,000 MWE[29]-centuries.

Keaau. Initial groundwater chemistry data collected near Keaau indicate that thermally altered groundwater, possibly associated with the Mauna Loa east rift, might be present in this area. Subsequent extensive geophysical and geochemical field surveys conducted around Keaau, however, indicate that the anomalous groundwater chemistry is probably the result of other, non-thermal processes and therefore the presence of thermal resource in this area is not considered highly probable.

Kawaihae. This area was originally identified as a potential geothermal area on the basis of groundwater chemistry and temperature data from wells to the east of Kawaihae Bay. More recent surveys have confirmed the original data obtained and have tentatively located a possible source of the thermal anomaly; geophysical surveys identified a highly resistive layer approximately 8 km (5 mi) east of Kawaihae Bay and below sea level that is interpreted to be an intrusive body associated with Puu Kawaiwai, a cinder cone formed during the Kohala post-erosional volcanic activity. More extensive geophysical and geochemical surveys are presently under way in an effort both to confirm this interpretation and to characterize more fully the inferred resource.

North Kona-Hualalai. Preliminary surveys of the North Kona district identified both water chemistry and thermal infrared anomalies along the coastal areas. More extensive trace element geochemical surveys near Kailua Kona have also identified apparent anomalies thought to be associated with Hualalai volcano. Although geophysical exploration in the North Kona area has been severely hampered by power lines, buried pipes, and other cultural interferences, detailed geophysical surveys conducted to the north of Kailua,

near the Hualalai summit, indicate that a conductive zone, possibly the result of a layer of warm, geothermally altered groundwater, is present a few hundred meters below the surface. In addition, a second subsurface low-resistivity zone has been identified along the lower northwest rift of Hualalai near the cinder cone Puu Mau. Although both of these areas are thought to have a potential thermal anomaly present, considerably more exploration work is required to confirm their existence.

Relatively little recent data are available for other areas on Hawaii that are considered to have some potential for a thermal resource: South Point, Kilauea southwest rift, Mauna Kea and Kohala. But, both South Point and the Kilauea southwest rift are thought to have a high probability for a resource since both have been volcanically active during recorded history (Mauna Loa in 1890 and Kilauea in 1920) and thermal manifestations have been reported along both rifts[30,31]. However, since few detailed geophysical surveys have been conducted over either area and virtually no geochemical data are available for soil or groundwater on either rift system, it is not yet possible to provide a more precise estimate of their potential. Mauna Kea and Kohala volcanoes are relatively young (compared with Waianae or West Maui) and on this basis may be considered to have some geothermal potential. Until more geophysical and geochemical studies are conducted on all of these volcanic systems, however, no valid appraisal of their potential can be made.

1.7 Summary

In summary, it is apparent that several of the volcanic systems which form the Hawaiian Island Chain have some evidence for the existence of a geothermal resource. Although only one of these areas can be considered to have a proven geothermal reservoir (the Kilauea east rift zone), recent field surveys provide data which strongly suggest some geothermal potential in several others. However, in order for the full potential of Hawaii's resources to be realized, evaluation and characterizaion of the identified geothermal systems must be continued and exploration for as yet unidentified geothermal areas should be pursued. The production capacity of the one proven geothermal reservoir in Hawaii, the Kilauea lower east rift zone, has been estimated to be of the order of 100 to as much as 3,000 megawatt centuries; however, the actual production capacity of this area, as well as of all other identified geothermal resources in Hawaii, will be determined only by much more extensive exploratory drilling and production from each individual reservoir.

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CHAPTER 2

ENVIRONMENTAL CONSIDERATIONS ASSOCIATED WITH GEOTHERMAL DEVELOPMENT IN HAWAII

2.1 Potential Environmental Impacts of Geothermal Development

Potential environmental impacts from the development of Hawaii's geothermal resources have been, and will continue to be, of major concern to business community, the state, and the public at large. Hawaii's ecosystem is both unique and fragile and has already suffered substantial alteration, first by the relatively limited number of flora and fauna introduced into Hawaii by the early Polynesian colonists, and more recently by the much larger number of exotics introduced by Asian, European, and mainland U.S. immigration. Increased industrialization and urbanization accompanying higher population densities have similarly effected change by altering or completely removing habitats necessary for the survival of some highly specialized links in the Hawaiian ecological chain.

The environmental impacts resulting from geothermal development in Hawaii will depend on a number of different factors. The most important consideration is the type of activity being pursued (e.g. exploration, field develoment, production, etc.) because, in part, this will control the nature, and the total volume, of the potential pollutants being produced as well as the degree to which the potential pollutants can be effectively abated. Also of concern is the location of the development activity; in pristine areas where few exotic species are already present, the introduction of any significant development activity would be a substantial intrusion, whereas the same level of activity in an area already exposed to

prior agricultural or industrial use, would produce an insignificant impact. The specific impacts associated with the various stages of exploration and development of geothermal resources follow.

2.2 Field Exploration

The development process for a geothermal field can be divided into several phases and specific environmental concerns are relevant to the activities associated with each phase. Preliminary field exploration activities range from geochemical and geophysical sampling and measurements made at the ground surface to shallow temperature gradient drilling to depths of a few hundred meters. Field sampling and measurement surveys are considered unlikely to produce any significant environmental damage since two or three people can conduct them with a minimum of field equipment. Temperature gradient drilling, which is not normally done in geothermal exploration in Hawaii, could result in somewhat more damage since vehicular access is required. The magnitude of the potential impacts of vehicle entry would depend heavily upon site specific conditions, however, the introduction of exotic plant species as well as increased fire hazard and erosional damage are considered to be of particular concern. The drilling operation itself would have some temporary impact arising from the noise and other activities associated with operating a drill rig. Shallow depths and small diameters (5-10 cm) of the gradient holes, however, would result in virtually no long-term damage, and environmental recovery could be very rapid if simple precautions are taken in the clearing and drilling and subsequent restoration operations.

2.3 Exploratory Drilling

The second phase in a geothermal development program is deep exploratory drilling. This activity is similar to that which occurred at the HGP-A well site in Puna during 1975 and 1976. Vehicular access roads and approximately two to four acres of land must be cleared and graded for the drilling equipment and platform and thus the location of the operation becomes a significant consideration in the long-term environmental effects of the activity. In an area such as Puna, where numerous exotic species are already present and environmental recovery is relatively rapid, the long term impacts of exploration drilling would probably be negligible. However, in an area where there are few exotics, or where low rainfall or some other condition limits the recovery rate, the long-term effects are of more concern. Under the latter circumstance, significant effort will be required to limit or alleviate protracted damage to the drill site area. Major impacts of the drilling activity could result from: noise and diesel fuel and exhaust from the drilling rig, drilling muds dumped at the surface or injected into near-surface water supplies, or potential contamination of near-surface water supplies by deeper, more saline fluids. The noise created by drilling operations will depend upon the procedures used; air drilling can be expected to produce approximately 114 dB(A)at 8 meters[1] (26 ft) (see Table 2.1), whereas mud drilling produces approximately 85-95 dB(A)[2] under normal operating conditions. It has been demonstrated, however, that properly designed abatement equipment can reduce drilling noise levels appreciably for mud drilling to 60 dBA or lower.

Table 2.1 SOUND LEVELS FROM VARIOUS SOURCES

Source	dB(A)
Quiet wilderness area	20-30
HGP-A muffled discharge (January, 1980) at a distance of 8 m (26 ft)	44
Quiet suburban residence	48-52
Business Office	50-60
100 MW geothermal turbogenerator building at a distance of 8 m (26 ft)	72
Noisy urban area	80-90
HGP-A discharge with open stack separator at 10 m (33 ft)	95-110
Geothermal well drilling with pressurized air/steam discharge	114
Jet airplane at 30 m (98 ft)	120-130

From: Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety; U.S. Environmental Protection Agency, 550/7-94-004 and Amended Environmental Data Statement, Geysers Unit 13; Union Oil Co., March, 1975.

Drilling mud, in and of itself, is relatively benign: it is usually a type of clay to which various materials have been added to achieve desired lubricating and density characteristics. Under ideal conditions, the mud is continually recycled and none leaves the drill bore or surface piping. In Hawaii, however, most near-surface rock strata are extremely porous and considerable quantities of drilling fluid are usually lost to shallow aquifers. Although the toxicity and mobility of drilling mud are considered to be generally low, and therefore poses little risk of contamination of water supplies at significant distances from the bore hole itself, relatively little data is available concerning the long-term effects of these muds on shallow groundwater supplies. It is presently believed, however, that impacts from lost drilling fluids into shallow rock strata will be slight.

Migration of deep saline waters up a well bore into shallow surface water supplies is of substantial concern in any drilling operation. The potential for long-term, persisting, degradation of near-surface water supplies is further increased by the fact that the deeper geothermal fluids are generally warmer and at a higher pressure than fluids in shallow aquifers and thus convective circulation through a well bore can take place spontaneously. For this reason very stringent specifications and requirements must be followed in order to drill a deep geothermal well. Of particular importance are rules which specify the casing depths and grouting materials for anchoring shallow casing. If existing regulations[3] are followed for exploratory and production drilling, the potential for contamination of surface groundwater supples will be minimal.

In the event of an unsuccessful deep exploratory well, the general procedure is to pump one or more cement plugs into the well bore to seal it off, and to remove surface piping and equipment, leaving only a small concrete pad. Thus long-term environmental effects will be limited to the area cleared which, depending on the type of envronment, and the restoration procedures applied, could recover in a matter of a few years. However, if the exploratory well is successful, a well testing phase will commence.

2.4 Well Testing

Most well testing procedures will require the release of geothermal fluids (steam, water, and gas) to the atmosphere for periods of several days to several weeks. Potential pollutants from testing a geothermal well include noise, dissolved salts in the water phase, and volatile compounds found in the steam phase. Noise levels produced by a freely discharging steam well can be extremely high. For example, sound levels produced by HGP-A during the initial testing phases were of the order of 125 db(A) at a distance of approximately 15 m (49 ft)[4]. Installation of a silencer/separator and muffler of a type commonly used in other geothermal fields reduced these levels to approximately 91 db(A) at 15 m (49 ft)[5]. More recent testing at HGP-A employed a below-grade rock-and-pit type muffler which was found to be substantially more effective, reducing noise levels to approximately 44 dB(A) at 20 m (66 ft). Thus, with proper abatement procedures, the environmental and nuisance effects of well testing noise can be reduced to generally acceptable levels.

The environmental effects of geothermal waters discharged during testing (and later production) will be largely a function of the types and concentrations of salts dissolved in these fluids. Unfortunately, fluids from only one geothermal well in Hawaii have been sampled and analyzed and, even though a substantial amount of information concerning these fluids has been obtained, it is quite probable that other geothermal fluids in other locations in Hawaii will have significantly different elemental concentrations. Nonetheless, presently available data can provide a general indication of the concentrations of some of the elements typically associated with geothermal systems. Table 2.2 presents the results of several analyses conducted on HGP-A fluids sampled in January 1980. For purposes of comparison, the concentrations of the same elements found in seawater and other geothermal fluids are also presented. The major element chemistry (Nos. 1 through 11) is similar to a dilute (15%) solution of seawater with only minor modifications brought about by high temperature water/rock reactions. The major element constituents do not include any that are exceptionally toxic, however, the concentrations found in the HGP-A fluids are generally above EPA drinking water standards (Table 2.3) and thus could pose problems for surface disposal of large quantities of geothermal water. In areas of moderate-to-high rainfall, it is extremely unlikely that the volume of fluids produced during well testing (100-200 gal/min) could pose a significant hazard. In drier climates or where aquifers receive only limited recharge, precautions can be taken in the disposal of the well fluids that will protect public and private water supplies from contamination.

Table 2.2 Chemical Analyses of Geothermal and Other Related Fluids

No.	Element/ Compound	HGP-A Brine	Seawater	15% Seawater	Iceland (approx. avg.)	Wairakei Well 24	Salton Sea (approx. avg.)	Geysers
1	Sodium (Na)	1694	10,500	1440	5798	1250	50,400	12
2	Potassium (K)	239	380	59.7	922	210	17,500	5
3	Calcium (Ca)	55.3	400	67.5	983	12	28,000	47
4	Magnesium (Mg)	0.21	1300	194	4.5	0.04	54	281
5	Lithium (Li)	0.46	0.2	0.03	0.3	13.2	215	
6	Barium (Ba)	2.1	0.02	0.003				
7	Strontium (Sr)	1.13	8	1.2				
8	Boron (B)	$\leq$0.5	4.5	0.7	7.6	29	390	3.1
9	Chlorine (Cl)	2920	19,500	2925	12,070	2210	155,000	0.5
10	Sulfate (SO_4)	81	2650	407	4.5	28	5	5710
11	Silica (SiO_2)	875	4	0.9	447	670	400	225
12	Copper (Cu)	$\leq$0.01	0.67	0.1		1.3	5500	
13	Cadmium (Cd)	0.10	0.13	0.02			2000	
14	Zinc (Zn)	$\leq$8.0	2	0.3		1.5	520,000	
15	Lead (Pb)	16	0.05	0.008			91,000	
16	Arsenic (As)	0.085	0.4	0.06		4.5	12	
17	Antimony (Sb)	$\leq$2	0.33	0.5		70	400	
18	Mercury (Hg)	0.4	0.03	0.0045			6	
19	Carbon Dioxide (CO_2)	900	130	19.5	436	17	7100	1242
20	Hydrogen Sulfide (H_2S)	825	Tr	Tr	1.5	1	16	33
21	Nitrogen (N_2)	195	15	2.25				
22	Hydrogen (H_2)	10.2	Tr					9.5
23	Helium (He)	Tr	Tr					
24	Argon (Ar)	Tr	Tr					
25	Radon (Rn)	7.7	Tr				41	120

Element Nos. 1-11 given in milligrams per liter (parts per million)
Element Nos. 12-18 given in micrograms per liter (parts per billion)
Element Nos. 19-24 given in milligrams per liter (parts per million)
Element No. 25 given in picocuries per liter (10^{-9} curies per liter)

Table 2.3 EPA Recommended Limits

		Drinking Water mg/l(ppm)	Irrigation Water mg/l(ppm)
1. Na	(sodium)	.115	3-9
2. K	(potassium)	1000-2000	3-9
3. Ca	(calcium)	150-1800	---
4. Mg	(magnesium)	125	---
5. Li	(lithium)	---	0.075-2.5
6. Ba	(barium)	1.0	---
7. Sr	(strontium)	---	---
8. B	(boron)	20	0.75-2
9. Cl	(chloride)	250	140-350
10. SO_4	(sulfate)	250	---
11. Cu	(copper)	0.05	0.2-5
12. Cd	(cadmium)	0.01	0.01-0.05
13. Zn	(zinc)	5.0	2-10
14. Pb	(lead)	0.05	5-10
15. As	(arsenic)	0.05	0.1-2
16. Sb	(antimony)	0.01	
17. Hg	(mercury)	0.002	---

From: Water Quality Criteria 1972, EPA R3-73-033, March, 1973.

Trace element chemistry (Nos. 12 through 18) may be cause for somewhat more concern since several of these elements are extremely toxic and have a tendency to become concentrated in the food chain. Nonetheless the concentrations of most of these elements have generally been found to be quite low in the HGP-A brines, especially when compared with other types of geotherml systems in non-basaltic terrain. In fact, the concentrations of these elements in HGP-A fluids are similar to those found in seawater and are generally below the EPA recommended limits for drinking wter. It is thus reasonable to assume that the environmental hazard posed by most of the trace elements, with the possible exception of mercury, is no greater than that from any other somewhat brackish water source.

Mercury, however, is deserving of more attention for two reasons: it is present in higher concentrations than other trace elements, and it has a high volability. Even though it is present originally in the water phase, when the geothermal fluids are flashed to steam mercury tends to be emitted with the steam phase rather than with the liquid brine. A detailed review and discussion of the geochemistry and biochemistry of mercury has been presented elsewhere[6] and will not be repeated here. However, the salient points of this earlier mercury study include:

1) mercury is emitted in the volatile phase from geothermal discharges in Hawaii;

2) the natural background of mercury concentrations is generally high in and around active and recently active volcanic areas of Hawaii;

3) natural sources of mercury emission (e.g. Sulphur Banks Fumarole, Halemaumau, or Heiheiahulu on Kilauea volcano) produce far more mercury than limited duration discharges from a geothermal well.

Thus, even though mercury is expected to be present in geothermal fluids in Hawaii, natural mercury background levels are such that the effect of adding geothermal well fluids to the near-surface atmosphere is considered to represent an insignificant increase in total concentrations present.

The other gaseous emission (Nos. 19-25) from a geothermal well test are also of concern. Helium, hydrogen, and nitrogen are present in low concentrations in the steam phase and are generally considered to be environmentally benign. But the remainder of the noncondensable gases, carbon dioxide, hydrogen sulfide, and radon, are normally considered to be potential pollutants. Carbon dioxide is a major constituent of the noncondensable phase; nonetheless, its concentration after mixing with air is well below toxic levels for flora and fauna[2]. Hydrogen sulfide is the second most abundant compound in the noncondensable gas phase; its concentration in the steam plume is also well below concentrations generally considered to be toxic to flora and faunal[6]. However, hydrogen sulfide has a very strong, irritating odor (usually described as a rotten egg smell) even at part per billion concentration levels.

Thus, although the sulfide concentrations are well below harmful limits, hydrogen sulfide poses a substantial nuisance impact (Table 2.4). During early testing of the HGP-A well, hydrogen sulfide concentrations in the steam phase of the discharge were measured at moderately high levels; however, concentrations in the steam plume immediately downwind of the separator stacks (approximately 30 meters (96 ft) average) were measured at levels of less than 10 parts per million. Nonetheless, residents living approximately 1 km downwind found the sulfide smell intolerable. During a subsequent test of the well, when pollution abatement equipment was installed, hydrogen sulfide emissions were reduced by approximately 98% and little, if any, smell attributable to the well discharge could be detected downwind of the test site[7]. Thus, it is entirely feasible to reduce sulfide emissions to acceptable levels during initial testing of well discharge characteristics.

Radon, a radioactive daughter product of the decay of naturally occurring concentrations of uranium is also present in the geothermal steam. Radon emission rates during production from HGP-A were estimated to range from 23.9 microcuries of radon per hour to 52.8 microcuries of radon per hour. This can be compared with an average estimated radon emission rate of 919 microcuries of radon per hour per square kilometer for natural radon emission from soils and rock in Hawaii[8]. On this basis it would seem that radon emission associated with a short term geothermal discharge will not constitute a significant addition to radon emitted from naturally occurring uranium in the soil.

Table 2.4 Hydrogen Sulfide Effects on Man

Concentrations (parts per million)	Effects
0.0007 to 0.030	Odor threshold
0.33	Distinct odor; can cause nausea
2.7 to 5.3	Odor offensive and moderately intense
20 to 33	Odor strong but not intolerable
100	Can cause loss of smell in a few minutes
210	Smell not as pungent; olfactory paralysis
667	Can cause death quickly due to respiratory paralysis
750	Virtually no odor sensation; death can occur rapidly upon very short exposure

From: U.S. Public Health Service; Preliminary Air Pollution Survey of Hydrogen Sulfide - A Literature Review; Consumer Protection and Environmental Health Service; APTD69-37; 1969.

Long term effects of well testing on the surrounding environment is to be quite limited; the relatively small volume of geothermal fluids produced should be diluted rapidly by rainfall recharge to underlying aquifers, whereas the noise and hydrogen sulfide nuisance problems will be limited to the duration of the test. Recent testing done in Hawaii and elsewhere have shown that even the acute short-term effects can be mitigated to a substantial degree. Disposal of saline brines, if necessary, can be effected by reinjecting the spent fluids into deep aquifers lying well below the bottom of the Ghyben-Herzberg freshwater lens. Although this technique is very expensive, it would preclude any possibility of contamination of near surface water supplies by the geothermal brines. Abatement of the noise produced by geothermal discharges can be accomplished by passing the fluids through proper silencing and muffling equipment. An extremely effective, albeit expensive, technique for short-term (test phase) abatement of hydrogen sulfide has been found to be treatment with caustic soda (with or without hydrogen peroxide)[7]. However, this technique is far too expensive to be used economically for long term plant production.

2.5 Development of a Geothermal Field

The final steps in geothermal development include drilling of several (10-20) production wells, constructing a steam gathering line, and building an end use facility (either a turbogenerator plant or some other direct use operation). Since the environmental effects of constructing a large generation plant, or any other type of industrial facility, are not peculiar to geothermal development, and have been well documented elsewhere, their impacts will not be addressed here. Of interest for the present are only those environmental impacts specific to geothermal development on a large scale.

Drilling of a production field of ten or more wells will not differ from exploratory drilling in the kinds of resultant environmental effects, it is primarily the magnitude that will change. The total land area required for a geothermal field can range up to several square kilometers; however, with well separations of the order of 60 meters (200 ft) to 300 meters (1,000 ft), the majority of the land surface will remain relatively untouched. In places such as the Imperial Valley, where land is at a premium, it has been estimated that between 1% and 3.3% of the agricultural land would have to be removed from production to accommodate 5,000 MW of production[9]. Undoubtedly the environmental effects of drilling a production field would extend over substantially more than the small area required for the individual drill pads, nonetheless, production drilling would not necessarily cause irreversible or wide ranging damage to the immediate environment. Testing of individual field development wells would be conducted on a somewhat more limited basis than the initial field

exploration testing. However, even though smaller volumes of fluids would be released from each individual well, the total volumes for the entire field would be similar to, or greater than, those for extended testing conducted on the initial exploratory wells. Thus the total environmental impacts, although similar in kind to the initial testing, will be equivalent to or greater than those associated with exploratory well testing.

Construction of steam collection lines would produce some limited environmental impacts in the immediate vicinity of the lines. Since Hawaii has no large migratory mammalian population with which steam lines would interfere, the impact of these pipeways would be restricted to the immediate vicinity of the pipeline right of way. These lines emit little, if any, noise or steam when operating properly and thus the impacts would be restricted largely to clearing for and construction of the pipeways. After installation, the major impact would be visual; suggested mitigation measures in other geothermal areas have included both burial of the pipeways or camouflaging with naturally occurring plants and shrubs[9].

Installation of a geothermal electrical generating plant differs from that of a coal- or petroleum-fired plant in one major respect: a geothermal plant must be installed near a source of steam, whereas a coal or petroleum-fired plant can be built anywhere that fuel can be shipped. Thus, if a geothermal resource is discovered in an environmentally sensitive area or in an area with conflicting land use[6], geothermal development will have to occur within 5-10 km of the resource or not at all. This could pose a substantial impediment to future development of Hawaii's resources; many of the State's identified potential geothermal resource areas are located

within or near State conservation lands, in largely agricultural areas, and near some residential areas. Undoubtedly some of the more sensitive areas will preclude geothermal development, however, experience at the Geysers geothermal field and in Imperial Valley, California, indicates that significant geothermal development can take place in agricutural and other non-industrial districts with relatively minor impact on competing land uses.

2.6 Long Term Production from a Geothermal Field

Potential effects on the environment related to large-scale geothermal electrical generation or other direct use will be similar to those produced by the activities leading up to development; however, the magnitude of the impacts may be considerably larger. The composition of the geothermal fluids produced for electrical or direct applications have been detailed above. The concentrations of salts and metals in the brines for large-scale development will be approximately equal to those produced by exploration test wells, the total quantities, however, will scale up in direct proportion to the total brine volume produced for a geothermal facility. Disposal of the spent liquids will have to be accomplished in such a manner as to prevent their entry into near surface aquifers necessitating either coastal/offshore outfall or deep reinjection. The potential environmental effects of each option would have to be evaluated individually on the basis of location, quantity, and exact composition of the liquid wastes to be disposed of. Presently available data suggest that outfall disposal of untreated geothermal brines would have an effect similar to a stream or brackish spring discharge on marine flora and fauna. The potential

environmental impacts of deep reinjection of geothermal fluids in Hawaii is presently unknown.

Disposal of the relatively large quantities of gaseous discharge from geothermal plant-sulfur gases, mercury, radon - is of somewhat more concern. Several technologies are presently available or are under consideration for the abatement of hydrogen sulfide[1,10]. These systems have been detailed elsewhere, however, a brief summary of some of their characteristics is warranted. One element common to all the sulfide techniques is that all are directed toward the oxidation of hydrogen sulfide to another less offensive compound. The caustic soda/peroxide system, for example, is an excellent, although expensive, means of abating hydrogen sulfide during well testing. Compounds formed by this process are relatively benign, $NaHSO_3$ (sodium bisulfite) and Na_2SO_4 (sodium sulfate), and are easily disposed of. However, the cost and logistics involved in handling the large quantities of relatively hazardous starting chemicals (caustic soda and peroxide) precludes the use of this technology in large volume production plants. The remainder of the sulfide abatement technologies use a variety of catalysts and produce elemental sulfur, sulfur dioxide, or any of a number of other sulfate compounds. Some of the older abatement technologies, when retrofitted into existing plants, have been able to abate hydrogen sulfide to between 60 and 90% of unabated levels. More recent technology, presently under development[10], promises to provide abatement levels of 95 to 99% of initial sulfide concentrations. If one assumes a hydrogen sulfide concentration similar to that found in HGP-A steam and 99% level of abatement, 300 MW of electrical generation would produce approximately 0.6

tons of sulfur per day; this compares with natural sources of emission (Kilauea summit fumaroles) which produce a minimum of 12 to 20 tons of sulfur per day during noneruptive periods. Thus the potential addition of sulfur to the atmospheric background by properly abated geothermal development would be relatively minor in the vicinity of Kilauea. Similar emissions from development in other areas would have to be evaluated in light of initial concentrations, abatement levels, and existing backgrounds for each area.

Mercury emissions from a geothermal plant will undoubtedly be higher than those for a single well, but the increase in mercury emissions will not be one to one with the increasing number of wells feeding a plant. The most promising of the newer (upstream) hydrogen sulfide abatement procedures has been found to be very effective in the removal of other volatile trace elements (such as mercury) from the steam emissions in addition to hydrogen sulfide. Thus even with much larger plant size and production rates, mercury emissions are expected to remain well below existing ambient levels in and around Hawaii's geothermal system.

Radon emission rates, however, will scale up on a one-to-one basis. Radon is an inert gas and will remain with the other non-reactive gases (He, N_2, etc.) through the entire plant and will be dispersed with the other off-gases from the facility. Experience at the Geysers geothermal field has shown that proper dilution and stacking of the gas emissions prevents hazardous concentrations of radon from accumulating either inside or outside the power plant.

The noise levels associated with a geothermal plant have been reviewed extensively elsewhere[11]. Installation of a geothermal power plant in a quiet rural or agricultural area will unquestionably be an intrusion into what otherwise would be an extremely quiet environment. However, the levels produced are not considered to be extreme and, in any event, are no greater than those associated with an electrical or industrial plant of similar scale not employing geothermal energy. The very loud noise associated with direct steam discharge would be absent in a normally operating power facility. The primary sources of noise from a turbogenerator will be the mechanical noise associated with the turbine, fan noise from the cooling towers, and valve noise associated with steam step down valves. Both the turbine and valve noise can be abated by proper acoustic shielding of the turbogenerator building and the step down valves; the noise generated by the cooling towers, however, will be very difficult to abate significantly. Present estimates of the total noise created by a single large power plant ($\sim$ 100 MWE) range from 60 dB(A) to 80 dB(A) at a distance of 8 m (26 ft) outside the turbogenerator building[1].

2.7 Relative Environmental Impacts of Geothermal Development

Finally, a somewhat broader perspective on the environmental effects of geothermal power generation can be obtained by comparing geothermal power production with other technologies capable of producing base load electricity in Hawaii. Tables 2.5 and 2.6 present air pollutants and water pollutants, in grams per megawatt (electric) hour, for geothermal, coal, and petroleum power plants. The major constituents being produced

Table 2.5 AIR POLLUTANTS (g/MWhr)

	Geothermal		Coal		Oil	
	Total	Abated	Total	Abated	Total	Abated
CO_2	8.2×10^3	8.2×10^3	1.03×10^6	1.03×10^6	7.3×10^5	7.3×10^5
S (as SO_2)	1.4×10^4	1.4×10^2	5.6×10^3	5.6×10^3	7.2×10^3	3.7×10^3
NO_4	Nil	Nil	NA	3.3×10^3	NA	3.9×10^2
Particulates	Nil	Nil	NA	4.6×10^2	NA	22
As	Nil	Nil	NA	2.4		
Cd	Nil	Nil	NA	2.8×10^{-2}		
F	Nil	Nil	NA	21		
Hg	1.5×10^{-2}	7.5×10^{-3}	NA	3.6×10^{-2}		
Pb	Nil	Nil	NA	13.0		
Se	Nil	Nil	NA	0.57		
^{222}Rn	7.7	7.7	NA	0.09 Ci/MWhr		

Table 2.6 WATER POLLUTANTS (g/MWhr)

	GEOTHERMAL	COAL	OIL
Na	1.54×10^{4}	4.7	
K	2170	NA	
Ca	502	NA	
Mg	1.9	3.8	
Li	4.2	NA	
Ba	19.1	NA	
Sr	10.3	NA	
Cu	$<9.7 \times 10^{-5}$	0.17	
Cd	9×10^{-4}	3.8×10^{-4}	
Zn	$<7.3 \times 10^{-2}$	12.4	
Pb	0.14	3.8×10^{-4}	
As	7.7×10^{-4}	3.8×10^{-4}	
Sb	1.8×10^{-2}	3.8×10^{-4}	
B	<0.454	1.67×10^{-2}	

are carbon dioxide, sulfur (presented as grams of sulfur dioxide) and nitrogen oxides (NO). Geothermal emissions, when using the best available sulfur abatement technology, are lower than coal or petroleum plants for CO_2 and sulfur by a factor of approximately 100 and approximately 50, respectively. Nitrogen oxides have not been detected in geothermal emissions. Mercury and radon are the only other two volatiles found in significant concentrations in the gaseous geothermal emissions. Although mercury is lower than for coal emissions by a factor of about 4, radon is higher by a factor of approximately 100. Nonetheless, geothermal radon emissions are still considerably below natural radon emission levels (919 microcuries of radon per hour per square kilometer).

Water pollutants produced by geothermal emissions are, in some cases, higher than other technologies and in other cases, lower. The major elements in the brine are factors of 10 to 1,000 higher in geothermal fluids, whereas the trace and toxic transition element concentrations are of approximately the same order as those for coal-fired power plants. In light of the critical importance of Hawaii's drinking water supplies, it is apparent that substantial effort will have to be expended in protecting shallow water supplies from potential contaminants in geothermal fluids. However, if the major and trace element concentrations in the geothermal brines are found to be similar to ocean water (as has been observed in recently drilled wells) offshore discharge of the spent geothermal fluids may prove to be an ecologically sound means of disposal. Thus, in terms of total environmental degradation, the development of 1,000 megawatts of electrical power from a geothermal resource may prove to be substantially

more acceptable both environmentally and economically than the development of an equivalent electrical capacity using coal or petroleum-fired power plants.

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CHAPTER 3

POTENTIAL GEOLOGIC HAZARDS ASSOCIATED WITH DEVELOPMENT OF GEOTHERMAL RESOURCES IN HAWAII

The geologic environment in Hawaii is in many respects unique, having few analogs anywhere in the continental United States. This singular environment not only provides potentially valuable geothermal systems, but also presents unique, and often misunderstood, types of hazards to life and property in Hawaii. The hazards that are of primary concern to future geothermal development in the state are those associated with volcanic and seismic activity, and with tsunamis (tidal waves).

3.1 Volcanic Activity

All of the islands in the Hawaiian Chain were formed by volcanic processes. Kauai, Oahu, Molokai, Maui, and Hawaii have all had eruptive activity in recent geologic history ($\leq$ 1 million years), and on this basis, all might be expected to have renewed activity in the future. However, only four volcanoes on the two southernmost islands have experienced eruptive activity during historic times: Haleakala erupted on Maui in about 1790 and, on Hawaii, Hualalai, Mauna Loa and Kilauea were last active in 1801, 1975, and 1979 respectively[1]. Thus, on the basis of past activity patterns, the areas of major concern with regard to volcanic hazards in Hawaii are the slopes of Mauna Loa and Kilauea and, to a somewhat lesser degree, Hualalai and Haleakala. In addition, it should be understood that volcanic activity is not randomly distributed over the entire volcanic edifice and thus the hazards associated with volcanic activity are not uniform over a given

volcanic system[2]; the degree of risk is greatest near the rift and caldera systems and decreases substantially with distance away from these areas.

The products of a volcanic eruption can be divided into several distinct categories, each of which has associated hazards[3]. The primary product of most Hawaiian volcanic eruptions is molten lava. Characteristics of Hawaiian lavas are quite variable: at high temperatures (1150°C, 2100°F) lava is quite fluids and can move rapidly (20 km/hr, 12 mph) down steep slopes; at lower temperatures (950°C, 1750°F) lava becomes quite viscous and flows at rates of a few meters per day or less. During most eruptive episodes lava flows originate in or near the calderas and rift zones of Hawaii's volcanoes and flow generally downslope. Although the exact route a lava flow will take is almost impossible to predict, several areas considered to be at risk from lava flows on the island of Hawaii[2] can be broadly outlined (Fig. 3.1). The degree of risk for these areas has been estimated based largely on recent eruptive history of each volcano. Zones designated f, the highest risk areas, have had roughly 3 to 8 % of the land area covered by lava flows during any given 20-year period since about 1830 (i.e. 92 to 97% of the land area within these boundaries remained free of lava flow hazard over this time period). Areas designated "e" experienced a coverage of only 0.5 to 3% during any given 20-year period. The other areas outlined ("de" through "a") are considered to have progressively less probability of lava flow coverage in the future. Thus, a facility with a 30-year plant life located even in the highest risk areas (area "f") would experience, at worst, a 12% probability of being endangered by a lava flow; in area "e" the probability drops to approximately 4%.

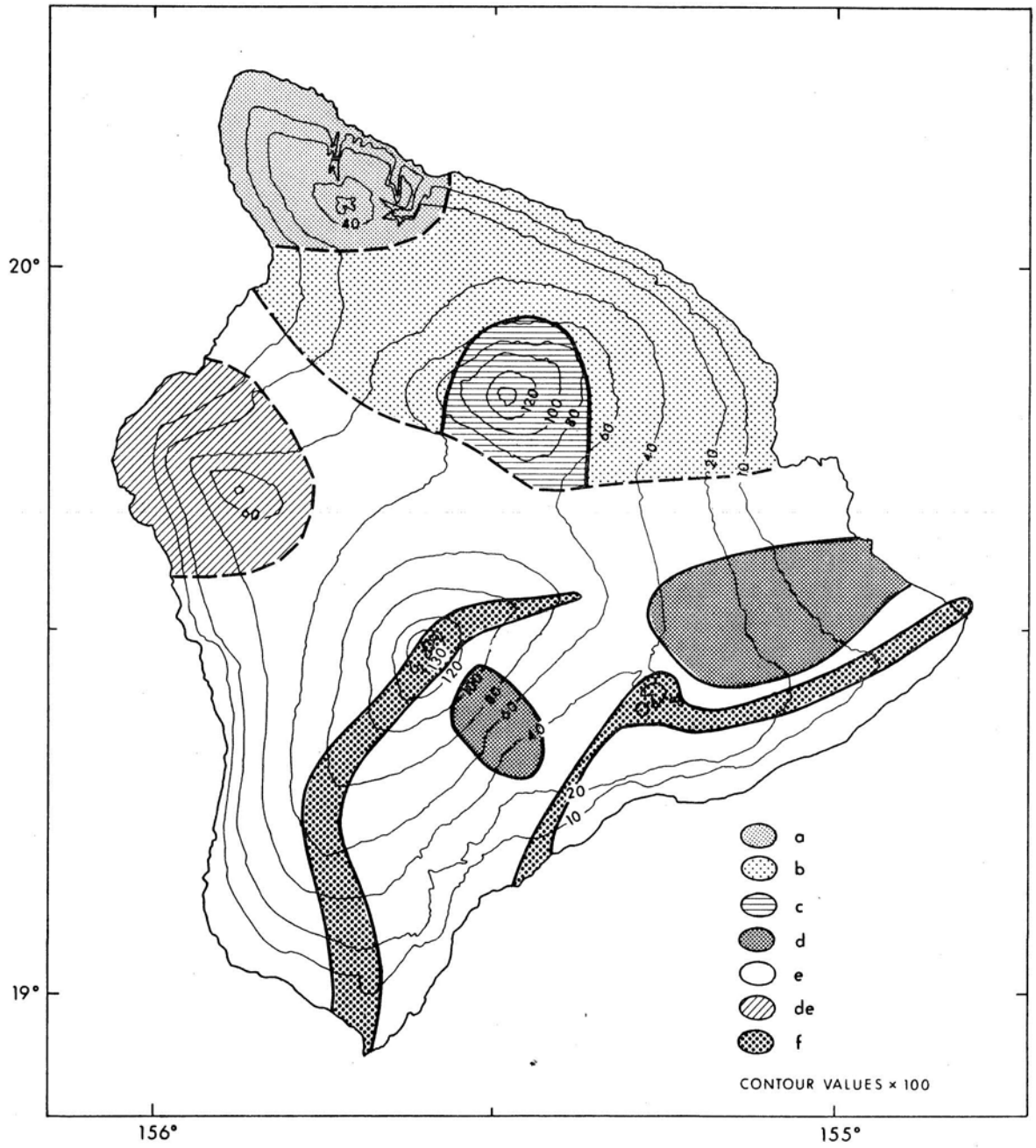

Figure 3.1 Map of the island of Hawaii outlining relative lava flow hazards on the five major volcanoes. Probable hazard is ranked from "f", areas having greatest hazard to "a", areas having least hazard (after Mullineaux and Peterson, 1974).

The hazards to plant equipment and facilities associated with the above lava flow probabilities can be reduced if appropriate mitigation measures are taken to minimize potential losses. In general, a period of several minutes to several hours of seismic activity will precede an eruptive outbreak, providing ample forewarning for evacuation of the general public. Removal of property would probably be restricted to that which could be mobilized in less than 24 to 48 hours and, even then, this strategy may be impractical for dismantling and removal of large equipment. Since there are no known methods by which to stop an eruption or to halt the progress of a lava flow, the only other possible mitigation measures available to protect property are diversion of a threatening lava flow or, where practical, by burial of exposed equipment. Diversion of a lava flow can take place either at the source vent or near the property being protected. The former method[4] generally entails destruction of natural levees formed on either side of a lava flow thus allowing the lava to spread over a greater area near the vent and reducing the supply of molten material to the head of an extended flow. Diversion of a flow near its head can be accomplished either by building dikes and levees to channel the flow toward a less destructive path or by pumping water onto the head of the flow forcing it to cool and solidify thus forming its own barrier which, under appropriate conditions could force the lava flow to change direction and more around the protected facility. All of the above diversion techniques have been attempted at one time or another[5] and, even though none has been entirely successful, some degree of success has been obtained with each when applied under suitable conditions.

Protection of a facility by burial, however, has never been attempted. Nonetheless, geothermal development provides a unique set of circumstances under which this technique might be appropriate. The most expensive piece of equipment in a geothermal field is the well bore itslf. Whereas protecting an entire field from potential flows is considered impractical, individual wellhead assemblies could more easily be protected by constructing the wellhead main valve assembly below ground level upon well completion. If threatened by a lava flow, the well would be shut in and the basement filled with cinders and covered with a concrete lid. The well could subsequently be "recovered" by excavating the overlying lava flow which, as a general rule in Hawaii, would be less than 2 to 3 meters thick. Similar precautions could also be taken with the major steam lines for the field, but the expense of preburial of these lines might well prove to be prohibitive.

It should also be pointed out that some of these mitigation measures may present difficulties themselves. Diversion of a lava flow at its source could leave the responsible parties open to suit by anyone whose property was subsequently covered by a secondary flow created by the diversion. A similar case could brought against someone attempting to divert a flow around his property at the head of the flow. To date neither of these issues has been tested in court.

The second major product of a volcanic eruption is drifting gases, which are typically composed of water vapor, carbon dioxide, hydrogen sulfide, sulfur dioxide, and lesser amounts of sulfuric, hydrochloric, and hydrofluoric acids. Although these gases are toxic and corrosive, their

hazard to human life is considered to be relatively minor. Substantial concentrations of some gases might build up near a vent in hollows and protected areas; however, air turbulence at the vent, as well as the near constant trade winds present in Hawaii make this a very unlikely occurrence. The threat to property presented by drifting volcanic gases arises largely from their corrosive nature; these gases could cause significant problems with electrical equipment or other delicate instrumentation. However, in order for significant damage to result from drifting volcanic gases, a facility would have to be sited less than about 2 to 4 km downwind of an active vent and the threat would exis only for the duration of vent activity. Thus the areal extent of the hazards associated with drifting volcanic gases would be quite similar to those for lava flows with bias toward greater risk to the leeward (southwest) of the lava flow zones. Mitigation of the effects of drifting gases could be affected by applying filtering and air treatment procedures in facilities housing sensitive equipment during periods of exposure.

Another risk associated with eruptive activity arises from falling rock fragments. During explosive eruptions, which are relatively infrequent in Hawaii, large amounts of material can be ejected from a volcanic vent. These ejecta range in size from blocks weighing several tons to gas charged clouds of fine particulate matter that can "flow" at high speed for quite long distances. Explosive eruptions, as a general rule, are confined to the main caldera area but they have also been known to occur at lower elevations where large volumes of groundwater gain access to the eruptive vent. A detailed appraisal of the hazards associated with falling fragment and

particle and gas clouds has placed the probability for damage to a plant facility located in a high risk area at about 1% over 30 years[6]. This analysis assumes that the greatest range at which significant damage is likely to occur is within a 5-mile radius of an eruptive vent. As in the case of lava flows, the danger to humans is thought to be minimal due to the usual forewarnings prior to eruptive activity. With the possible exception of reinforcing the supporting members in the plant design and construction no special procedures are known for the protection of property and equipment from falling fragments and particle and gas clouds; in any event, these procedures are not likely to be cost effective for the relatively minor risks encountered in most parts of Hawaii.

3.2 Seismic Activity

Seismic events in Hawaii can be divided into two distinct classes: those associated with volcanic activity and those associated with tectonic movement. Seismic activity associated with volcanic eruptions or with magma movement is quite frequent but usually very mild in Hawaii. The magnitude of these events is usually of the order of 4 or less on the Richter scale; most can be felt only if their epicenters are nearby and are considered to be more annoying than dangerous[7,8]. Tectonic seismic activity, for the present discussion, is considered to include those events associated with settling and shifting of the island mass as well as

Table 3.1 EARTHQUAKE ACTIVITY IN HAWAII

Date	Locality	Intensity (MMI)	Intensity at Puna
02/19/1834	Island of Hawaii		4-6
12/12/1838	Island of Hawaii		4-6
04/02/1868	Ka'u	10	7-8
11/02/1918	Mauna Loa	7	4-5
09/14/1919	Kilauea	7	5-6
03/20/1927	Island of Hawaii		4-6
08/03/1927	Island of Hawaii		4-6
09/25/1929	Kona	7	2-5
09/28/1929	Hilo	7	5-6
10/05/1929	Holualoa	7	2-5
12/02/1933	Hilo	6	4-6
01/22/1938	North of Maui	8	3-5
06/17/1940	North of Island of Hawaii	6	3-5
09/25/1941	Mauna Loa	7	4-6
12/27/1944	Mokuaweoweo	6	3-5
05/29/1950	Mauna Loa	6	3-5
04/22/1951	Kilauea	7	5-6
08/21/1951	Kona	9	4-6
11/08/1951	Mauna Loa	6	3-5
05/23/1952	Kona	6	2-4
03/30/1954	Kalapana	7	6-7
06/03/1954	Kilauea	6	4-5
03/27/1955	Kilauea	7	4-5
06/27/1962	Kaoiki Fault	6	3
04/26/1973	North of Hilo	8	6
11/29/1975	Kalapana	8	7-8

Table 3.2 SEISMIC FORECAST DATA FOR PUNA

Return Period	Site Intensity (MMI)	Peak Ground Acceleration (g Levels)
10	V (5.0)	0.04 g
20	VI (5.8)	0.06 g
50	VII (6.8)	0.12 g
100	VIII (7.6)	0.20 g
200	VIII (8.3)	0.33 g
500	IX (9.4)	0.70 g

those which occur much deeper in the earth's crust beneath and around the islands. This type of activity includes many small magnitude events but has also been responsible for several very large earthquakes that have occurred in and near Hawaii; the locations of some of these larger events during recorded history are listed in Table 3.1. A detailed analysis of the earthquake frequency and intensity data for the Puna area has provided an estimated intensity, return period (frequency of a specified magnitude event) expected for various magnitude events (Table 3.2)[7]. Even though these data apply to the Puna area specifically, similar evaluations could be done for other parts of the state. As a general rule one would expect similar frequencies and ground accelerations on most parts of the island of Hawaii and somewhat lesser frequencies on the other major islands. The effects of earthquake shaking on building structures and heavy equipment has been studied extensively[9,10,11] and the primary means recommended for preventing significant damage is through strengthening the footings and structures of buildings to a degree that would allow them to withstand the expected peak accelerations in a given area. The Uniform Building Code[12] has placed the island of Hawaii in a seismic hazard zone 3 classification in which the maximum expected earthquake intensity would be a magnitude 7, or above, seismic event on the modified Mercalli Index (Table 3.3). The islands of Maui, Molokai, Oahu, and Kauai are in zones, 2, 1, 1, and 0 respectively. Building code standards for Hawaii require that buildings within these zones must be constructed to withstand minimum earthquake intensities of: in zone 2, less than 7; in zone 1, less than 6; and in zone 0, less than 4 on the modified Mercalli Index.

Ground movement, or faulting, associated with seismic events is also of concern to future geothermal development. Subsidence of the seaward flanks of Hawaii's volcanoes is a continuing phenomenon and is evidenced by the steep slopes encountered at Hilina Pali or the Kealakekua Fault Scarp on Kilauea and Mauna Loa respectively. Normal faulting across these features is sporadic, and rather large movements can take place quite suddenly. This type of faulting could pose significant hazards to buildings or to plant facilities located immediately above a fracture system that is prone to subsidence (Fig. 3.2); however, a greater hazard may be experienced by steam gathering lines traversing an area in which normal faulting is common. Protection against subsidence damage to buildings is primarily through the choice of sites well removed from areas which have experienced subsidence in the past. Some protection for steam gathering lines may be had by designing them to withstand a maximum of transverse movement with a minimum of buckling stress. Concern has also been expressed regarding damage to well bores posed by normal faulting; it is presently considered unlikely a well could be damaged unless the plane of movement transected the well bore itself.

Another type of faulting which may be of concern is extensional ground cracking resulting from injections of magma into the rift systems or due to seaward slippage of the flanks of the volcanoes. Extensional movement over areas susceptible to ground cracking (Fig. 3.3) has been measured at rates as high as 1.3 meters (4 ft) over a period of 3 to 5 years[2]. In addition, sudden movements of up to 1 m (3 ft) are also considered to be possible. Techniques for mitigation of the effects of surface extensional movement are

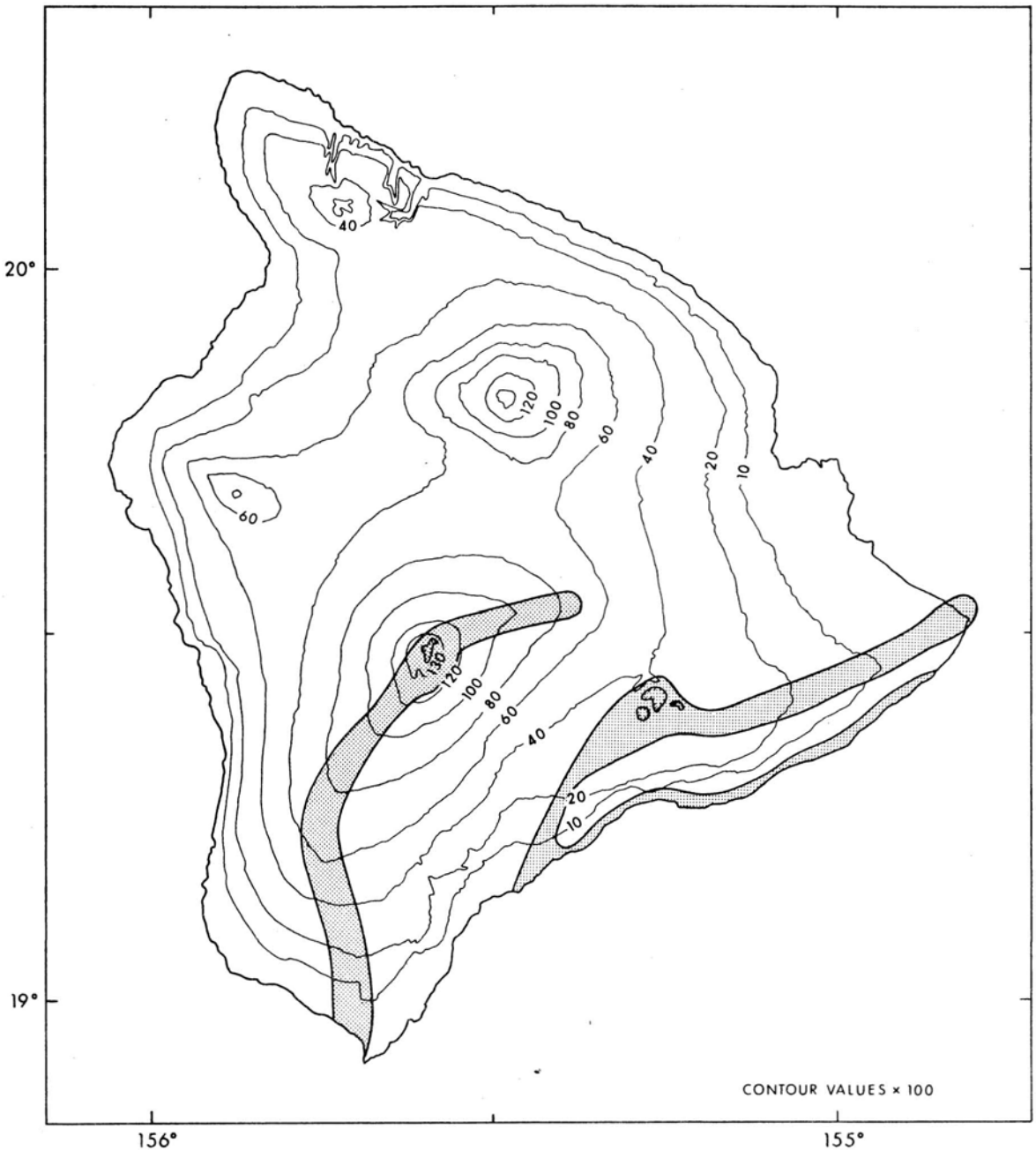

Figure 3.2 Map of the island of Hawaii outlining zones of potential subsidence risk (after Mullineaux and Peterson, 1974).

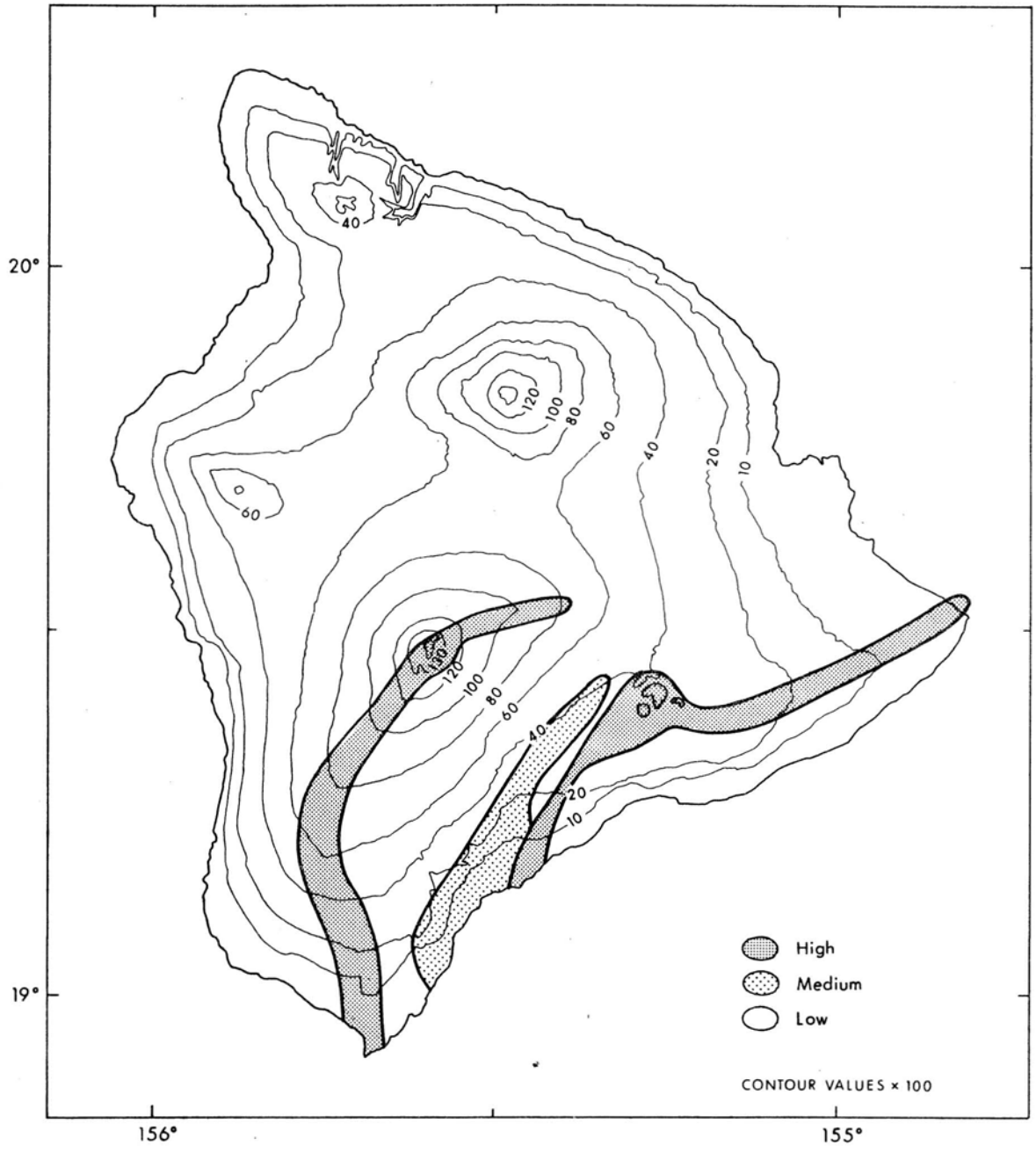

Figure 3.3 Map of the island of Hawaii outlining zones of potential hazard from extensional ground cracking (after Mullineaux and Peterson, 1974).

similar to those for subsidence; plant sites should be well removed from areas experiencing frequent ground movement and the flexibility of steam gathering lines crossing extensional fault systems should be increased. In addition, frequent monitoring of extensional, as well as transverse, stress on pipelines would allow for appropriate corrective action.

3.3 Tsunamis

Tsunamis (tidal waves) are a recurring hazard to Hawaii's low-lying coastal areas. These waves can be quite destructive and have taken many lives during the recent past. Tsunamis that strike Hawaii can be generated locally by seismic activity (e.g. the Halape tsunami resulting from the Kalapana earthquake of 1975) or by seismic events several thousand miles away (e.g. the 1960 tsunami originating in South America). Destruction caused by these waves is usually limited to coastal areas having elevations below about 20 to 30 meters (65 to 100 ft)[13,14]. The severity of a tsunami can be quite variable and highly unpredictable; in some cases the waves are characterized by a gentle withdrawal of water from the shore and a gentle return to heights of a foot or two the above normal high tide level whereas other occurrences have been reported (the 1960 tsunami) in which a wave struck at about 65 kilometers per hour (40 mph) and cleared everything in its path.

In response to the frequence (nine severe waves in 150 years) and destructiveness of tsunamis in Hawaii, an early warning system has been installed in most populated coastal areas. If distant seismic activity generates a sea wave that is detected by sensors in other areas in the Pacific Basin, the warning system is activated. Even though tsunami waves

are known to cross the open ocean at velocities of more than 400 miles per hour, sufficient warning is available to prevent loss of life. Locally generated tsunamis have also been quite destructive; unfortunately there is seldom enough time between the seismic event and the landfall of the sea wave to activate the presently installed warning system.

Mitigation of the effects of a tsunami on a geothermal facility rest almost entirely with the placement of the plant. As mentioned above, wave runup is seldom to elevations of more than 20 to 30 meters, although locally higher occurrences have been reported in steep-sided embayments and channel ways. Strengthening of plant facilities located in coastal areas might be advantageous, but instances have been reported in which 2" parking meter posts were bent over parallel to the ground by the force of an incoming wave[1]; under conditions such as these, no reasonable structural reinforcement will prevent substantial damage to installations in low-lying coastal areas.

3.4 Induced Volcanic and Seismic Activity

Finally, it should also be noted that some concern has been expressed regarding the possibility of geothermal development causing or inducing volcanic or seismic activity. Earlier discussions in the present work have summarized the basic structure of the Hawaiian volcanoes and the general progression of an eruption. From this discussion it should be apparent that drilling into a geothermal reservoir or into a molten magma body itself (as has been done in Kilauea Iki lava lake) would not in any way be sufficient to trigger an eruptive outbreak on the flank of the volcano or at its summit. The quesion of drilling activity triggering a seismic event is

somewhat more complicated however. There are well documented reports of seismic activity being generated by pumping fluids into subsurface aquifers; the interpretation of these events is that the water pumped into the subsurface aquifers acts to expand the porespace within clay sediments. These expanded sediments act as a lubricant in a fault system where substantial stress is already present. This type of occurrence is considered to be highly unlikely in Hawaii primarily because the subsurface rocks here are basalt with only very minor amounts of clay. Hawaii's basalts are already saturated with water (rain water or seawater) below sea level and, in addition, the water with which the basalts are saturated has virtually no effect on pore volume as it does in clay sediments. Thus injection of water into the subsurface environment, as may be required for brine disposal, will simply displace water already there and will not act as an added lubricant as was indicated to be the case in a continental environment. It is considered highly unlikely that drilling or brine withdrawl and reinjection in Hawaii's geothermal systems could cause seismic activity of any perceptible magnitude.

3.5 Summary

In summary, the primary hazards of concern to future geothermal development are those associated with volcanic and seismic activity and with tsunami inundation. Volcanic hazards are largely restricted to the caldera and rift systems of Mauna Loa and Kilauea volcanoes and mitigation of the potential hazards is possible provided the techniques applied are appropriate to both the location and the type of hazard. Seismic activity is also of concern on the island of Hawaii and to a lesser extent on the

other islands in the Hawaiian chain; however, building standards appropriate for anticipated magnitudes and frequencies can substantially reduce the probability of major loss. Tsunami inundation poses a significant hazard, although the areas at risk are restricted almost entirely to lowlying coastal areas and in valleys and embayments facing the open ocean. Construction of major plant facilities at a reasonable setback from the shorelines is almost certainly the most cost effective mitigation strategy available. Finally, it is considered highly unlikely that geothermal drilling or brine reinjection could, in any way, trigger eruptive or seismic activity on Hawaii's volcanic system.

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