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POTENTIAL GEOTHERMAL RESOURCES IN HAWAII: A PRELIMINARY REGIONAL SURVEY

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ABSTRACT

A regional geothermal resource assessment has been conducted for the major islands in the Hawaiian chain. The assessment was made through the compilation and evaluation of the readily accessible geological, geochemical, and geophysical data for the Hawaiian Archipelago that have been acquired during the last two decades.

The geologic criteria used in the identification of possible geothermal reservoirs were age and location of most recent volcanism on the island and the geologic structure of each island. The geochemical anomalies used as traces for geothermally altered groundwater were elevated silica concentrations and elevated chloride/magnesium ion ratios. Geophysical data used to identify subsurface structure with possible geothermal potential were aeromagnetic anomalies, gravity anomalies, and higher-than-normal well and basal spring discharge temperatures.

Geophysical and geochemical anomalies that may be the result of subsurface thermal effects have been identified on the islands of Hawaii, Maui, Molokai and Oahu.

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INTRODUCTION

The objectives of Phase I of the Western States Cooperative Direct Heat Resources Assessment Program have been to:

(1) Review all available data on groundwater geochemistry for the State of Hawaii.

(2) Compile existing data on those shallow groundwater sources having geochemical anomalies normally associated with geothermal reservoirs.

(3) Collect and compile existing data on geothermal gradients throughout the State.

(4) Assist in the compilation of geologic and geophysical data pertinent to geothermal resource assessment.

(5) Identify those areas in the State of Hawaii that may have geothermal resources and provide a preliminary assessment of their potential.

The State of Hawaii is comprised of a chain of five major and several minor islands stretching across more than 2000 km of the Pacific Ocean. The geologic and hydrologic conditions in Hawaii are unique to an island environment and are substantially different from those prevalent in continental terrain. Many of the techniques commonly used in regional surveys in the western United States have been found to be inapplicable to Hawaii, and thus it has been necessary to modify many of the methods to suit the requirements of the Hawaiian setting. The assessment of the geothermal potential for Hawaii has been based on the following: age of the island under consideration, proximity to centers of recent volcanism on the island, observed geophysical anomalies indicative of structural features (e.g., buried magma chambers and fracture systems) normally associated with geothermal reservoirs, and geochemical anomalies indicative of thermally altered groundwaters.

Geologic setting

The Hawaiian Archipelago is formed by a chain of tholeiitic shield volcanoes that have erupted sequentially from the central Pacific sea floor (Fig. 1). The origin of the intraplate volcanism that formed the islands is thought to be a "hot spot" or "mantle plume" beneath the Pacific plate; the northwestward migration of this plate during the last 25 million years has resulted in a northwest-southeast lineation of islands and

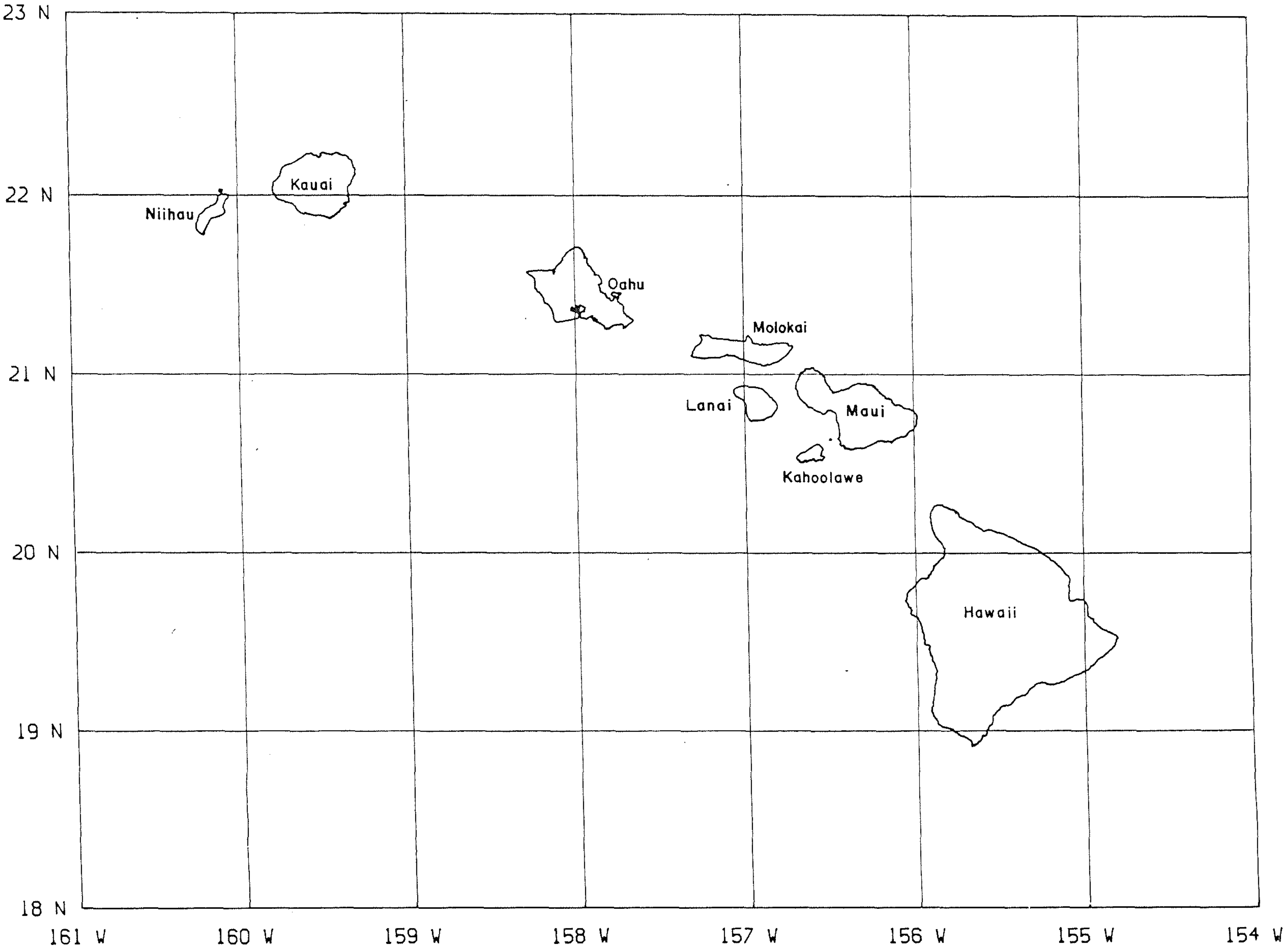


Fig. 1. Map of the Hawaiian Archipelago High Islands.

sea mounts increasing in age from Hawaii at the south end of the chain to Midway at the north end.

Each island consists of one or more volcanoes that have built steep-sided cones from the ocean floor to heights of more than 9000 m above the basement rock. Although there are some exceptions, Hawaiian volcanoes are usually formed from many thousands of thin lava flows erupted from a summit caldera complex or along two or more rift systems radiating away from the center of the shield. The calderas, where they have been exposed by erosion, have been found to consist of a system of closely spaced parallel and crosscutting dikes and have a generally circular ground plan (Macdonald and Abbott, 1970). The summit diameter of the caldera systems is usually of the order of three to five kilometers. Geophysical studies conducted on several of the caldera systems have indicated that the near-surface dike systems are underlain by dense volcanic necks or plugs that extend to depths of several kilometers below the surface (Adams and Furumoto, 1965). These dense volcanics probably represent the near-surface portions of a crustal magma chamber that existed beneath the caldera during its active phase. The rift zones radiating out from the summit calderas are closely spaced assemblages of dikes and stocks with vertical or near-vertical dip angles and have an overall width of from one to three kilometers. The dike density in the rift zones is on the order of several hundred per kilometer, with dike widths ranging from a few inches to several feet (Macdonald and Abbott, 1970).

The lavas produced by Hawaiian volcanoes generally evolve from basaltic tholeiites in the earlier stages of activity to more viscous alkalic rock types during the final phases of activity. The very fluid basaltic flows erupted during the initial stages of activity produce thin, layered flows resulting in broad, flat shields characteristic of the younger Hawaiian volcanoes (Mauna Loa, Kilauea). The more viscous alkalic lavas erupted near the end of a volcano's activity often leave a steeper-sided cap of ash and dense, blocky lava flows on the older systems (Mauna Kea, Haleakala).

Meteorology

Typical of an island environment, the climatic conditions in Hawaii are primarily a function of topography and prevailing wind conditions. The northeasterly trade winds persist throughout most of the year and have the effect of providing higher mean annual rainfall and lower mean temperatures on the windward (northeast) sides of the islands. The local rainfall distribution is a function of both the location on the island as well as the overall altitude of the island; an idealized representation of the orographic effects on rainfall distribution is presented in Figure 2 (Takasaki, 1978).

Temperature distributions show similar topographic variations: nearshore temperatures average approximately 22°C to 24°C and decrease by 6°C per kilometer increase in elevation to below 0°C at an altitude of 4200 m (Mauna Kea summit).

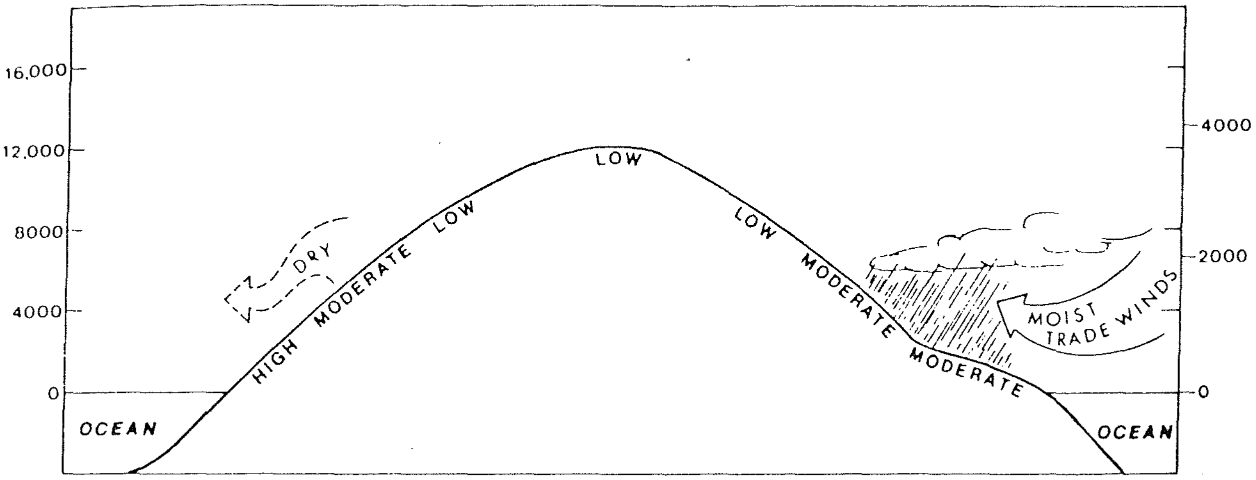
Groundwater hydrology and geochemistry

The groundwater hydrology in Hawaii is primarily controlled by aquifer type, soil cover, and local rock permeability and consequently, is a function of both the age of the island and location on the island. A diagrammatic representation of the important hydrologic types found in the State is presented in Figure 3 (Takasaki, 1978).

The prevailing conditions on the younger volcanic systems are similar to those shown on the left-hand side of the figure. The rock types above sea level are permeable, allowing rapid percolation of rainfall down to the freshwater lens that floats above the denser salt water in the basal aquifers. The hydrologic head of the basal water table increases by 0.5 m/km inland, which is typical of a Ghyben-Herzberg lens system.

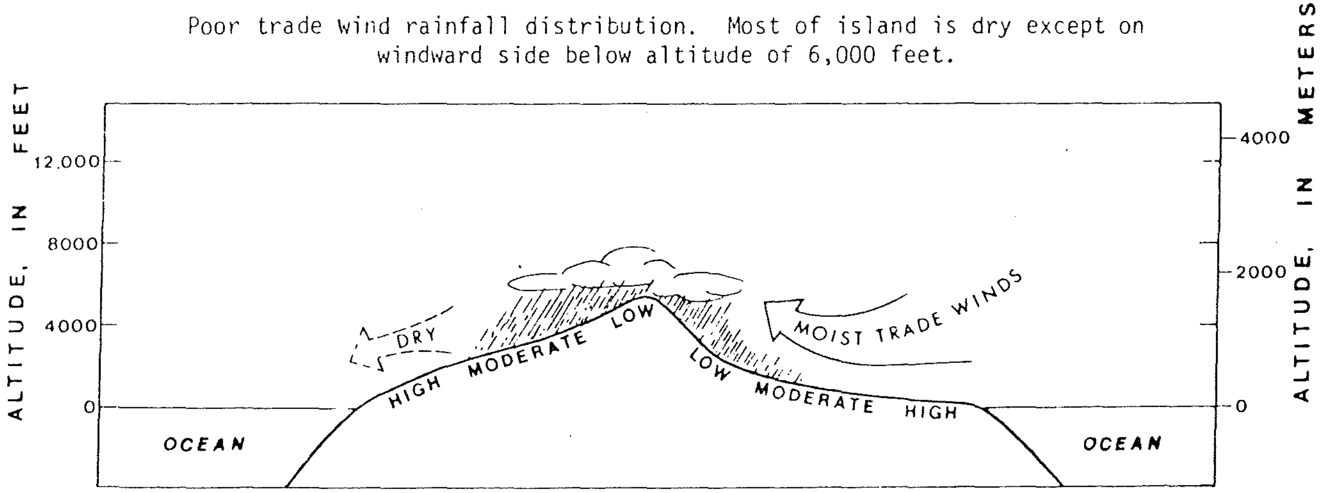
Impermeable ash beds are commonly found interbedded with the more open fractured basalt lava flows. These have the effect of impeding the downward flow of meteoric recharge, and thus produce a localized perched water table. The near-vertical dip angles of the dike systems within rift zones and calderas generally hinder the seaward flow of groundwater through the basal aquifer; this restriction results in an elevated water table upslope of the dike zone and depressed water levels downslope. High-level dike-impounded aquifers also occur in areas where crosscutting dike complexes perch local recharge (Stearns and Macdonald, 1946).

The hydrology of the older islands (right-hand side of Fig. 3) is affected by alluviation and soil formation as well as by erosional exposure of high-level aquifers. The formation of relatively impermeable sediment layers fringing the lower and submarine slopes of the island has the effect of restricting the outflow of fresh water from the basal aquifers, resulting in a much thicker freshwater lens beneath the island (Stearns and Vaksvik, 1935). Impermeable soil cover at the surface hinders the downward percolation of meteoric water, thus increasing surface discharge rates. Erosional exposure of ash-bed perched water tables and dike-impounded aquifers



HIGH VOLCANIC DOMES

Poor trade wind rainfall distribution. Most of island is dry except on windward side below altitude of 6,000 feet.



MEDIUM HIGH VOLCANIC DOMES

Ideal trade wind rainfall distribution. Rainfall decreases rapidly from maximum near crest. Rainfall in coastal areas depends on distance from rainfall maximum.

Fig. 2. Orographic effects on rainfall (from Takasaki, 1978).

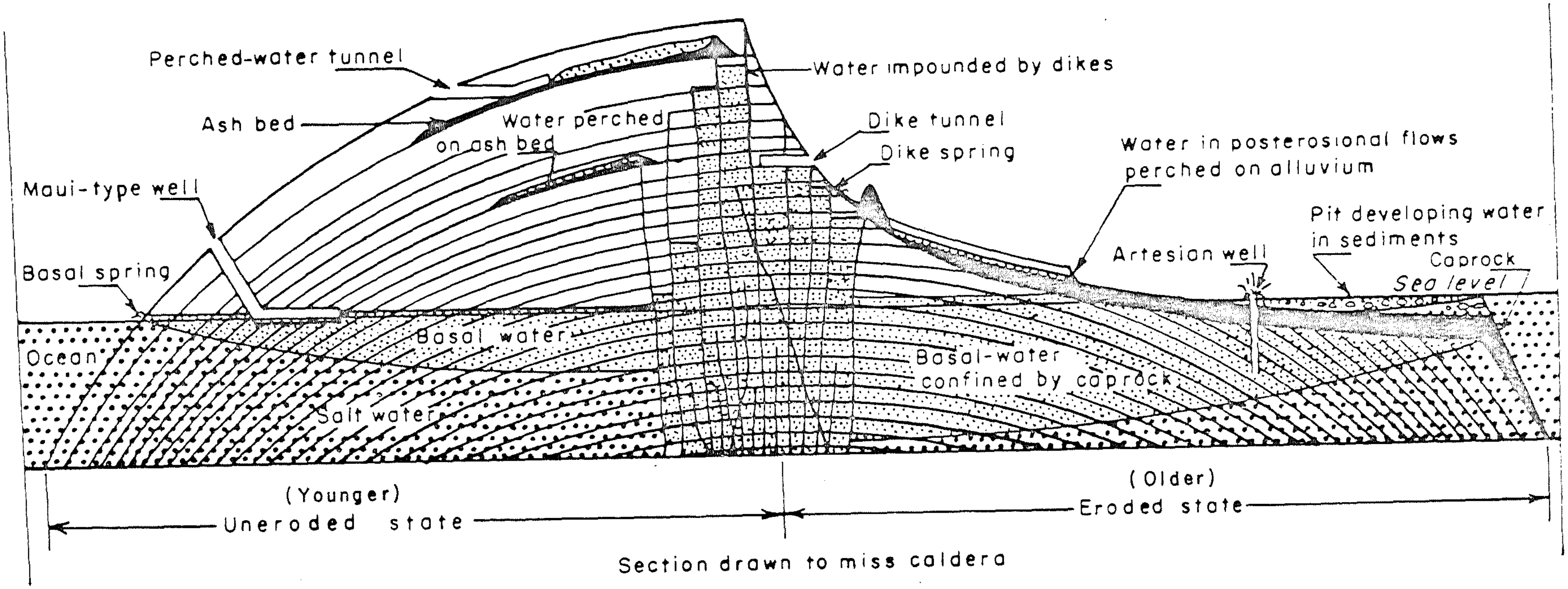


Fig. 3. Hydrologic types in Hawaii (from Takasaki, 1978).

has produced perennial, high-level spring discharge, which also increases surface discharge of freshwaters.

In general, groundwater geochemistry has been found to be highly localized. It is strongly controlled by aquifer type, rock type, soil cover, surface land usage, and recharge-discharge rates. In younger islands having high recharge rates, basal outflow is very rapid; rock water interactions are minimal and thus groundwater silica concentrations are relatively low. Since sea water encroachment into the basal lens is significant only in nearshore aquifers, most salts are present only in very low concentrations in the inland areas. On those parts of the younger islands where recharge is low, the groundwater chemistry is much different. Both tidal mixing and upward migration of sea water salts into the basal aquifers considerably elevate the concentrations of dissolved salts; longer residence times of the groundwaters also increases silica concentrations. Thermal effects such as those arising from a hot intrusive body also serve to increase the salts concentrations; mixing of saline and freshwaters is accelerated by thermal convection, and dissolved silica concentrations commonly increase with high groundwater temperatures.

Soil cover and longer groundwater residence times on the older islands increase median silica concentrations by approximately a factor of two above those observed on the younger islands. Agricultural effects, particularly irrigation recharge, also elevate silica concentrations. The concentrations of other salts can be highly variable: high-level, dike-impounded meteoric water will have very low concentrations as will some inland basal waters. In nearshore basal aquifers, where heavy groundwater withdrawal has accelerated sea water migration into the freshwater lens, waters are brackish to saline (Macdonald and Abbott, 1970).

Assessment criteria

The variability of the local geologic structures and consequent complexity of the groundwater hydrology and geochemistry have made it impossible to rely on a single set of rules for the identification of potential geothermal reservoirs. The present assessment is based on information obtained from several types of regional surveys which have been carried out in Hawaii during the last 15 to 20 years. Our appraisal of the potential for each area will be a qualitative assessment based on the following types of information:

(1) Surface geology. Surface manifestations of rift zones, calderas, and recent eruptive activity are

easily identifiable, although, except in areas of obvious thermal activity (springs and fumaroles), they provide little information concerning subsurface conditions.

(2) Infrared studies. Infrared imagery of land surface and nearshore ocean waters can identify thermal spring discharges and above-ambient ground temperatures. At present, infrared surveys have been conducted only over the island of Hawaii.

(3) Seismic studies. Passive earthquake monitoring can identify structural features such as fractures and rift zones normally associated with thermal systems. Relatively few passive seismic data are available for any island other than Hawaii, for which there is excellent coverage. Seismic refraction surveys can be used to identify buried magma chambers and intrusives; studies of use to the present survey have been conducted only on the Koolau volcanic pipe zone on Oahu.

(4) Magnetic field studies. Aeromagnetic surveys have been used to identify magnetic field anomalies associated with buried rift zones and calderas. Although aeromagnetic studies have been made for all the major Hawaiian islands, most of the surveys were flown at high altitudes, thus having a depth of penetration on the order of 10 km.

(5) Gravity surveys. Gravity data can provide information on the locations of dense intrusive bodies and dike zones. Regional and reconnaissance gravity surveys of the type done on Hawaii can provide little information on conditions of the identified systems at depth.

(6) Groundwater temperature data. Near-surface waters having temperatures significantly above ambient are strong evidence of a nearby geothermal reservoir. Groundwater temperatures in Hawaii can vary by several degrees depending on the altitude and temperature at which the water entered the subsurface aquifer. Further, the routinely available data (from the U.S. Geological Survey, State of Hawaii Board of Public Health and Department of Land and Natural Resources, and the counties' Boards of Water Supply) were found to be of variable reliability and thus were of only marginal utility.

(7) Groundwater geochemistry data. Near-surface waters can have geochemical anomalies (i.e., unusual salts concentrations) that arise from high temperature rock-water interaction. The salts commonly used as indicators of thermally altered groundwater are: silica (SiO_2)--total concentration is a function of temperature; sodium, potassium, calcium (Na, K, Ca)--equilibrium concentrations in thermal waters are related to the empirically derived equation:

$$\log (Na/K) + \log (Ca/Na) = \frac{1647}{273 + T°C} \beta - 2.24$$

$$\beta = 1/3,\ T>100°C; \qquad \beta = 4/3,\ T < 100°C$$

(Fournier and Truesdell, 1973); chloride, magnesium (Cl, Mg)--chloride ion concentrations are commonly elevated in thermally altered groundwaters by contamination from magmatic volatiles, whereas magnesium ion concentrations are reduced by reaction with clay minerals. Cl/Mg ion ratios can be used to differentiate between cold, thermally altered water and fresh water mixed with sea water. Difficulties in interpreting the groundwater geochemical data arose from reliability of the available data, variations of silica concentration with local geologic setting (see above), and sea water contamination of near-surface aquifers with brackish (see above).

Results

The data compiled during Phase I of the Direct Heat Resources Assessment Program are presented below and consist of a brief outline of the regional geology and geophysics as well as a topographic-meteorologic-hydrologic profile of each island. The groundwater chemistry data are presented in the form of edited, computer-generated maps for each island of all wells having silica concentrations significantly above the median for the island. Included with the maps are tables of the most recently available chemical data for each of the identified water sources. Areas on each island with elevated Cl/Mg ratios are also denoted on the map plots.

The data presentation for each island is followed by an interpretation and qualitative assessment of the geothermal potential for the island based on all the information presented.

HAWAII

The island of Hawaii is the youngest and largest of the Hawaiian chain (10,438 sq. km) and is made up of five known volcanic systems (two earlier volcanic eruptive centers are thought to have been covered by more recent activity of Mauna Loa). The oldest rocks exposed on the island surface are those of the Ninole Volcanic Series (Fig. 4) and are about 500,000 years old; the youngest volcanic system on the island is Kilauea, which last erupted in September of 1977. The other volcanic systems on Hawaii (in order of increasing age) are Mauna Loa, Hualalai, Mauna Kea, and Kohala. A summary of the surface geology of the island of Hawaii is presented in Figure 4.

Hawaiian volcanism takes place in a series of relatively distinctive phases, several of which are exemplified by the volcanic systems on Hawaii (Stearns, 1967). Kilauea (altitude: 1231 m) is presently in the midst of its youthful shield-building phases--very active, either erupting continuously over long periods of time or at intervals of the order of eighteen months. The very fluid basaltic lavas produced are released from the summit caldera or along two major rift zones radiating to the east and southwest from the summit caldera (Fig. 5). Flows of the Kilauea shield are thin (averaging a few centimeters to five meters in thickness) and are interlaced with lava tubes; the rocks are generally quite porous and highly fractured. There is little soil cover over most of the Kilauea shield and the entire system has a high permeability to rain water.

Mauna Loa (altitude: 4169 m) is considerably older and larger than Kilauea and is probably in the mature shield-building stage. Until recently (1950), Mauna Loa erupted frequently with a periodicity of approximately three years. Since 1950, only one eruption has occurred, that of July 1975. The rock type and structure of Mauna Loa is not significantly different from that of Kilauea. The predominant centers of activity on Mauna Loa are at the summit caldera and along a south and an east rift zone. The rock units are fractured and undoubtedly are as porous as those of Kilauea, although minor ash bedding occurs which presents some resistance to downward percolation of high-level precipitation (Stearns and Macdonald, 1946).

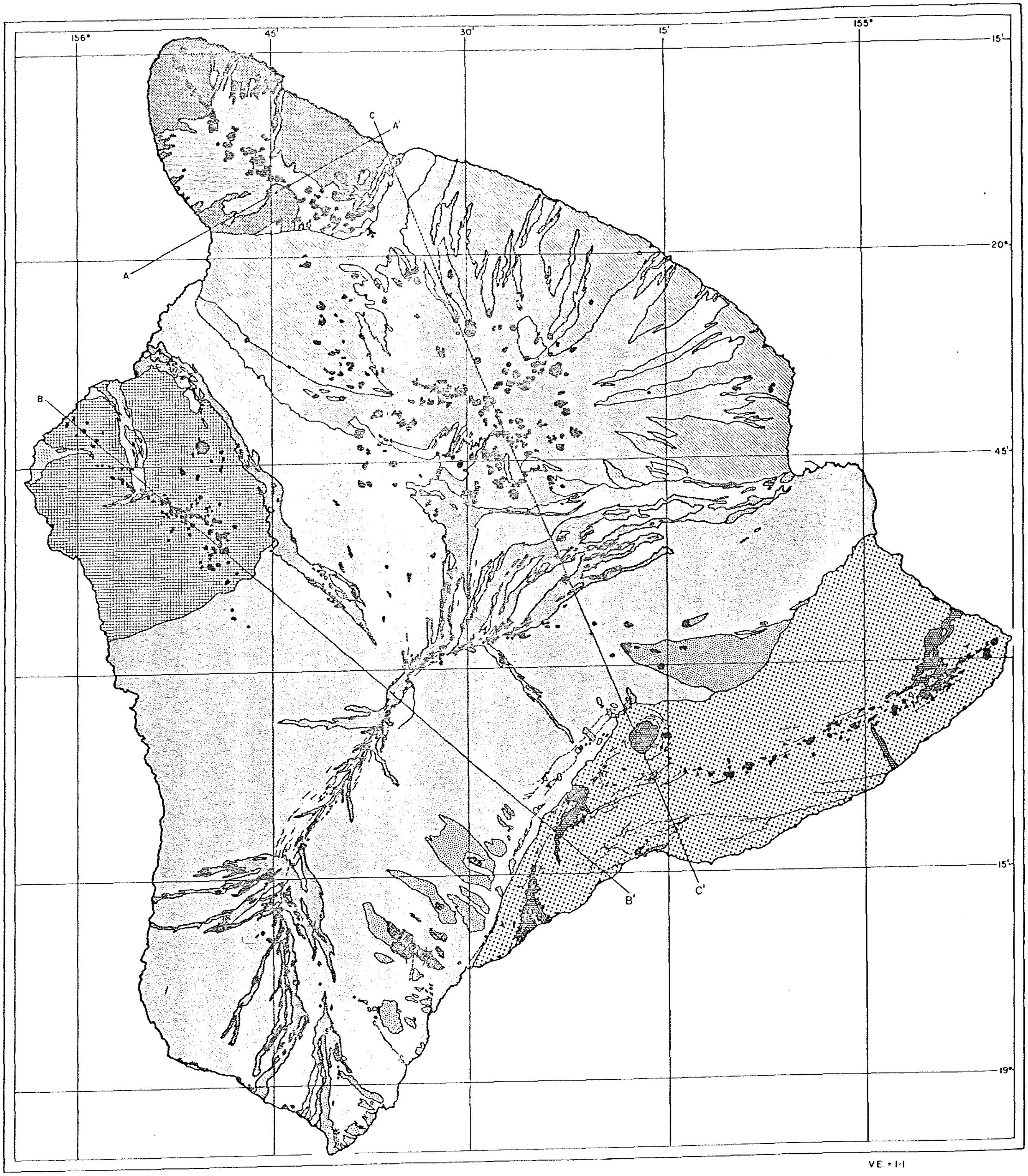
Hualalai (altitude: 2521 m) is to the northeast of Mauna Loa and appears to be in a late mature or post-caldera stage of activity, although at present it is uncertain whether a caldera ever existed for this system. The most recent activity from Hualalai, in about 1801, produced a relatively small lava flow that was exceptionally rich in dunite xenoliths (Macdonald and Abbott, 1970). Most surface flows on this system are highly differentiated and are more alkaline than those found on Mauna Loa or Kilauea. Although there is some evidence that typical rift zone eruptive activity occurred on Hualalai, the rift zones are not clearly defined by surface manifestations. Substantial ash layers are found over parts of the Hualalai shield, but soil development is not very advanced because of the extremely low rainfall in this part of the island.

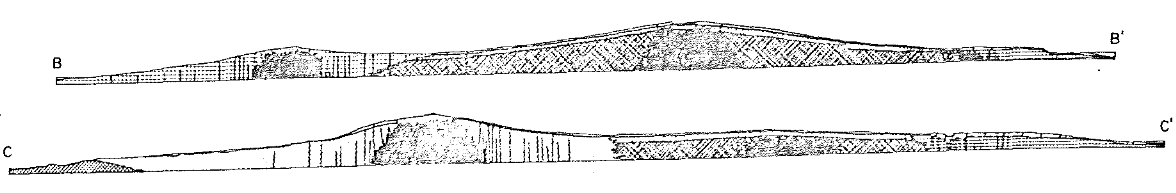
Mauna Kea (altitude: 4205 m) is in its post-caldera stage of activity; the late-stage lavas are more differentiated alkalic olivine basalts, ankaramites, and hawaiites, whereas the older lava comprising the original shield are typical Hawaiian olivine basalts. Extensive ash layers were produced by the later, more explosive, volcanics and although a caldera and rift system were present at one time on Mauna Kea, these features have been covered by the more recent activity. The strikes of the rift zone of Mauna Kea have been determined both by the lineation of the parasitic ash cones and by aeromagnetic and gravity surveys (Fig. 5). Extensive soil formation has taken place in the lower-altitude areas where there is extensive ash cover, but at the higher elevations, where there is little rainfall or biological activity, soil development is negligible.

The Kohala volcanic system (altitude: 1672 m) is considerably older than Mauna Kea and has already undergone extensive dissection and subsequent post erosional volcanic activity. Soil and ash cover are quite extensive on this system; stream erosion has cut deep valleys (in some cases over 400 m deep) in the windward side of what remains of the original shield. Much of the high-level groundwater feeding the spring and stream systems is from dike-impounded aquifers along the northwest-southeast trending rift system of Kohala (Stearns and Macdonald, 1946). The earlier volcanic series of Kohala is made up of tholeiitic basalts and tholeiite olivine basalts interspersed with ash layers. The younger and older series are separated by an erosional unconformity; in some places as much as 15 m of soil and weathered rock are found beneath the younger lavas, indicating that there was a substantial period of quiescence between the two episodes of volcanism (Stearns and Macdonald, 1946).

Geophysical surveys

Extensive aeromagnetic surveys have been conducted over the island of Hawaii in an effort to define the deeper structure of the volcanic systems. A total force aeromagnetic map of Hawaii (Malahoff and Woollard, 1965) is presented in Figure 6





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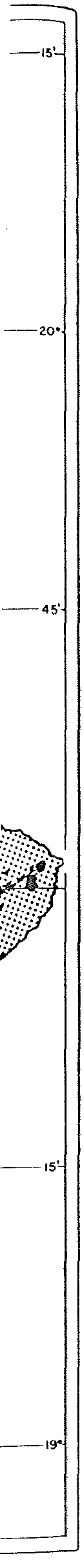


HAWAII

HUALALAI

HISTORIC	░	Olivine basalt	HISTORIC MEMBER	HUALALAI VOLCANIC SERIES
RECENT and PLEISTOCENE	▦	Olivine basalt, trachyte	PREHISTORIC MEMBER	

KOHALA MOUNTAIN

PLEISTOCENE	░	Andesite, trachyte	HAWI VOLCANIC SERIES
PLIOCENE	▤	Olivine basalt	POLOLU VOLCANIC SERIES

MAUNA LOA

HISTORIC	▤	Olivine basalt, basalt, picrite basalt, & hypersthene basalt	HISTORIC MEMBER	KAU VOLCANIC SERIES
RECENT	░		PREHISTORIC MEMBER	
PLEISTOCENE	▒	Olivine basalt, basalt, picrite basalt		KAHUKU VOLCANIC SERIES
PLIOCENE	▩	Olivine basalt, basalt, picrite basalt		NINOLE VOLCANIC SERIES

MAUNA KEA

RECENT	░	Andesite	UPPER MEMBER	LAUPAHOEHOE VOLCANIC SERIES
	▤	Andesite, olivine basalt	LOWER MEMBER	
PLEISTOCENE	▨	Andesite, olivine basalt, picrite basalt		HAMAKUA VOLCANIC SERIES

KILAUEA

HISTORIC	▓	Olivine basalt, basalt	HISTORIC MEMBER	PUNA VOLCANIC SERIES
RECENT	⁞		PREHISTORIC MEMBER	
PLEISTOCENE	▦			HILINA VOLCANIC SERIES

☼	DOME
⬭	CRATER
●	CONE
⁄	DIKE

Fig. 4 (left and right). Surface geology of Hawaii (redrawn from Stearns and Macdonald, 1946 by R. Rhodes).

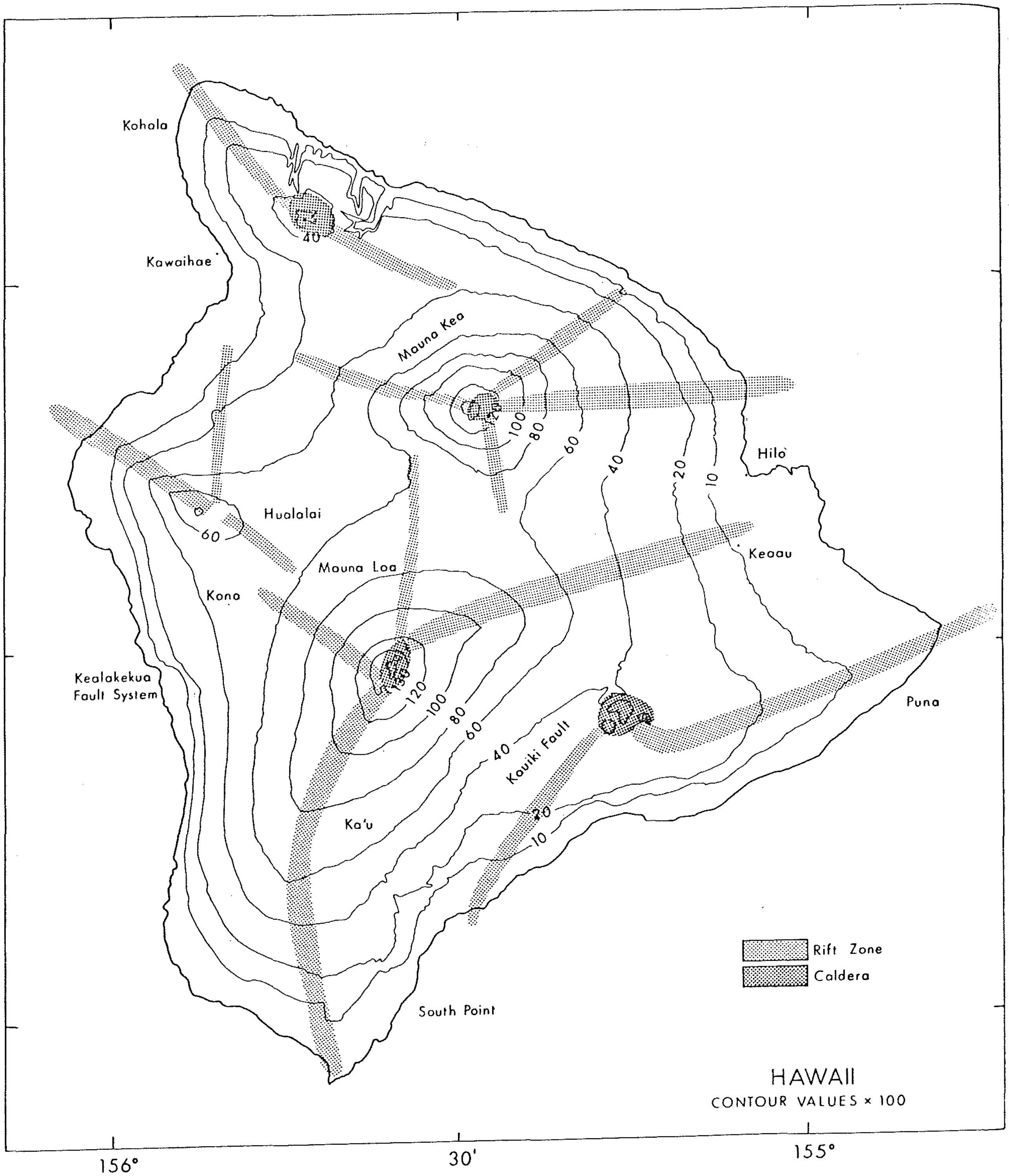


Fig. 5. Topography and rift systems of Hawaii.

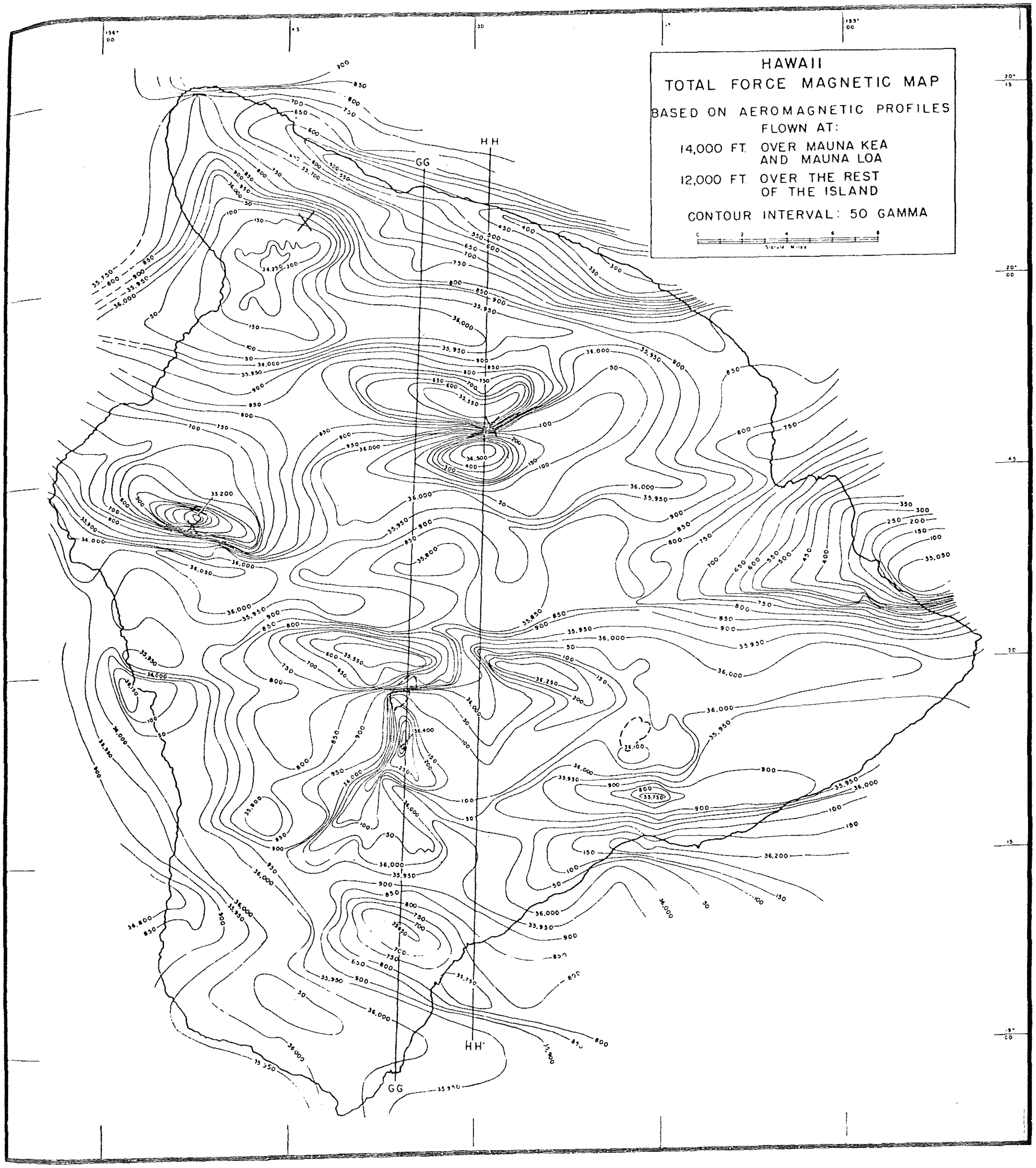


Fig. 6. Total force magnetic map of Hawaii (from Malahoff and Woollard, 1965).

and their interpretation of the magnetic data in Figure 7. Two types of magnetic anomalies are outlined in the figure: elongate anomaly zones and more confined "volcanic vent systems". There are substantial differences between the anomaly and vent systems in Figure 7 and the near-surface structural and rift features found on Hawaii. The observed differences are primarily due to the flight elevation of the survey and consequent recognition of magnetic properties of deeper features (5 to 10 km deep). Thus the anomaly zones outlined by Malahoff and Woollard probably arise from crustal features rather than the near-surface structure of the island. Although the volcanic pipe zones outlined by the aeromagnetic surveys are associated with the near-surface caldera systems, the delineation of several "volcanic vent zones" which have no surface manifestations indicates a strong crustal control over these anomalies as well.

Gravity surveys carried out on the island of Hawaii agree with the surface features of Hawaii somewhat better than do the aeromagnetic surveys. Figure 8 presents a Bouguer gravity anomaly map of the island (Kinoshita, 1965). Gravity highs are observed near the calderas of most of the volcanoes, indicating the presence of a large mass of dense material within the main vent system and magma reservoir. Hualalai is a notable exception to this trend; the absence of an observable caldera complex and the extreme differentiation of the lavas of Hualalai (indicative of a small and perhaps deep magma chamber) is consistent with the absence of a well-defined gravity high in this area. One other gravity anomaly that may also be of interest in the present study is the elongate feature to the south of Hualalai. Although there is no known rift system associated with the gravity anomaly, it is in an area of high seismic activity. There is a fracture system through this district (Kealakekua fault system [Macdonald and Abbott, 1970]), and it is possible that there is an intrusive mass at some depth beneath the surface fault.

Seismic coverage of the island of Hawaii is quite extensive, and far more data have been acquired over the last several years by the Hawaii Volcano Observatory than could reasonably be summarized here. Recorded earthquakes on Hawaii number in the thousands per year, and we feel that a data set covering two years gives a sufficiently accurate distribution of earthquakes for the purpose of the present discussion. Figures 9 and 10 are epicenter plots of all detected earthquakes on the island of Hawaii during 1976 and 1977 (Hawaii Volcano Observatory, Summary 76 and 77, respectively). The region of highest activity is along the southeast rift and Puna area of Kilauea. Other regions of high activity are found along the Kaoiki Fault System (an area of high tectonic earthquake activity rather than volcanic) and the southwest rift of

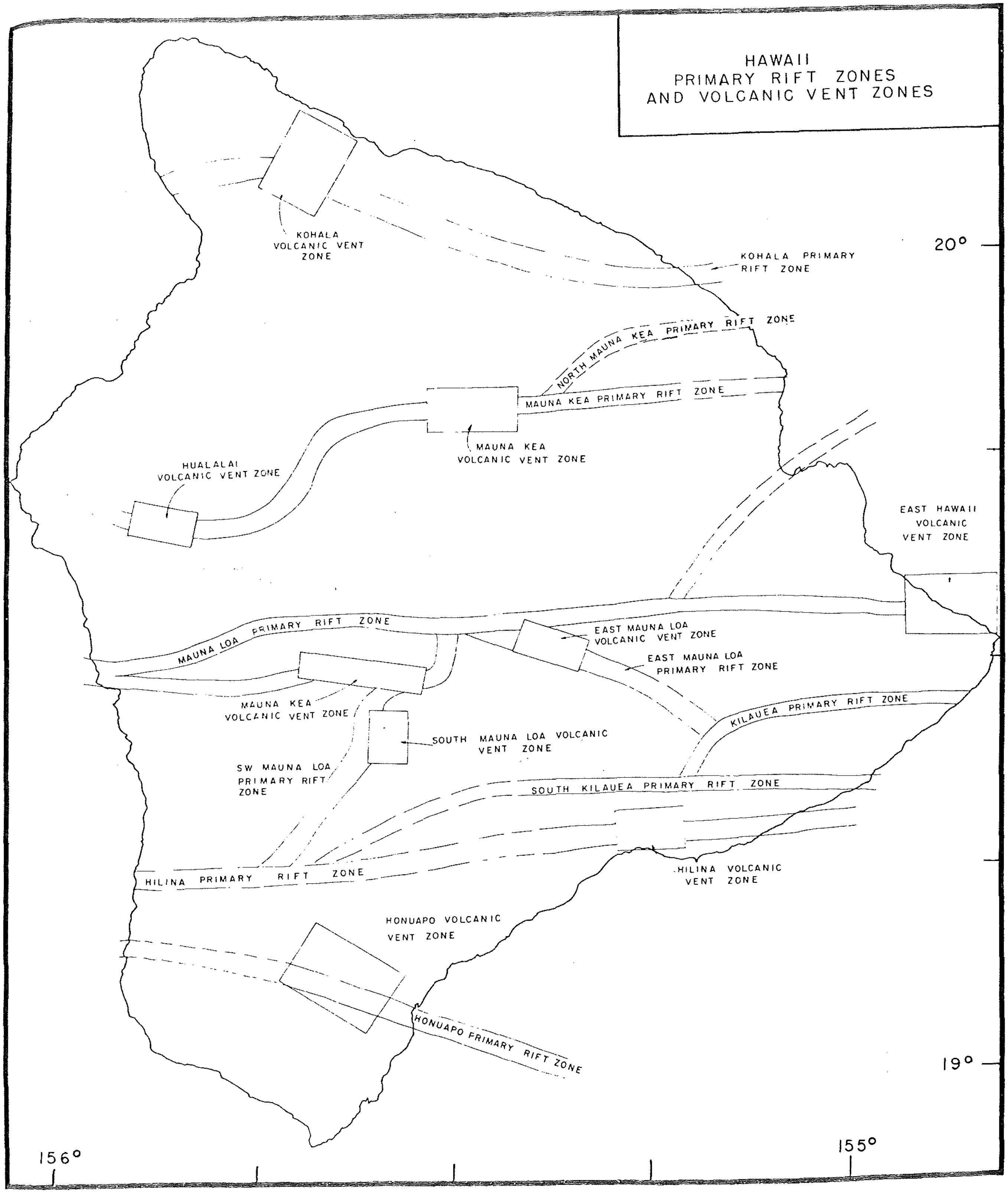


Fig. 7. Primary rift zones and volcanic pipe zones of Hawaii (from Malahoff and Woollard, 1965).

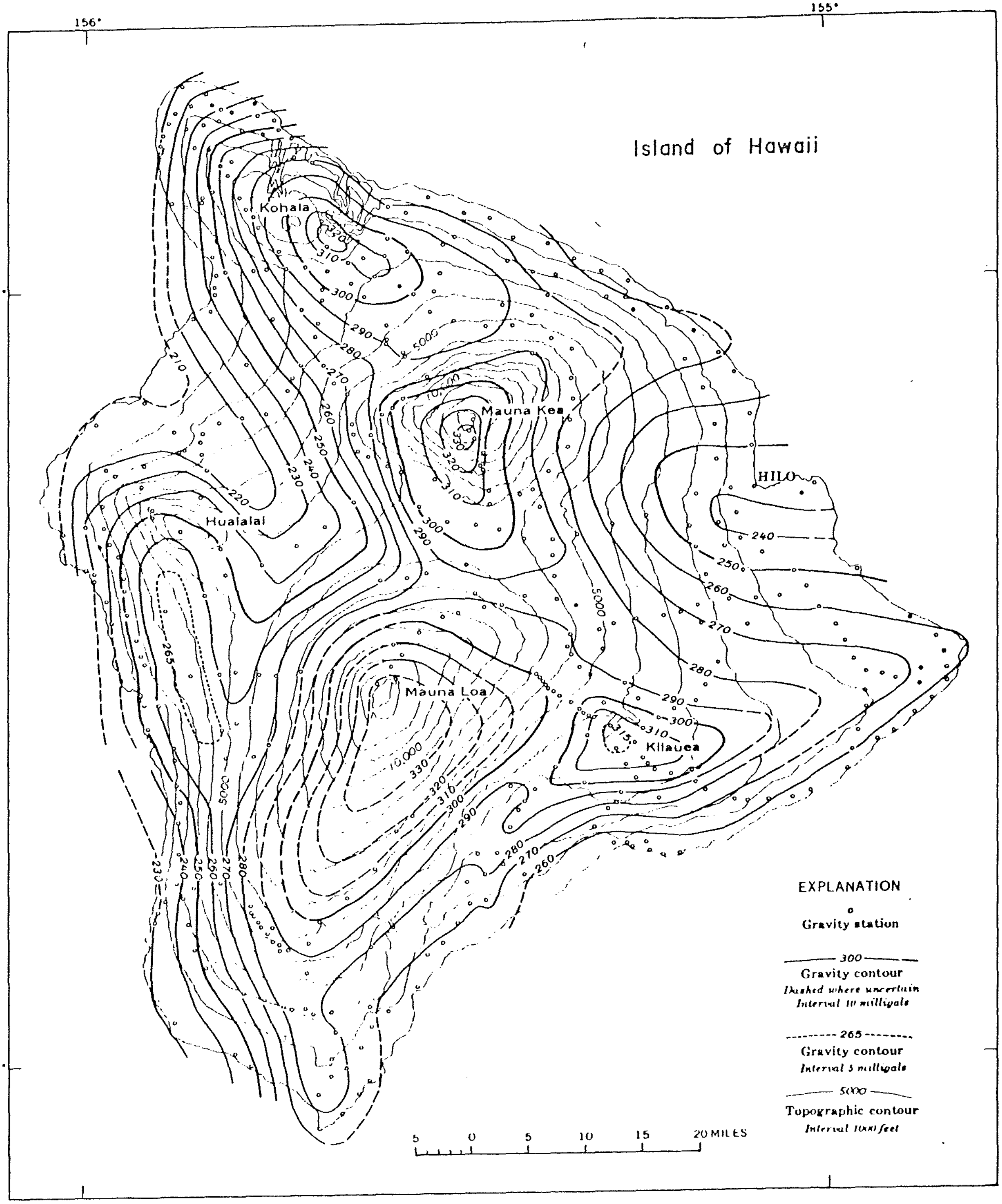


Fig. 8. Bouguer gravity anomaly map of Hawaii (from Kinoshita, 1965).

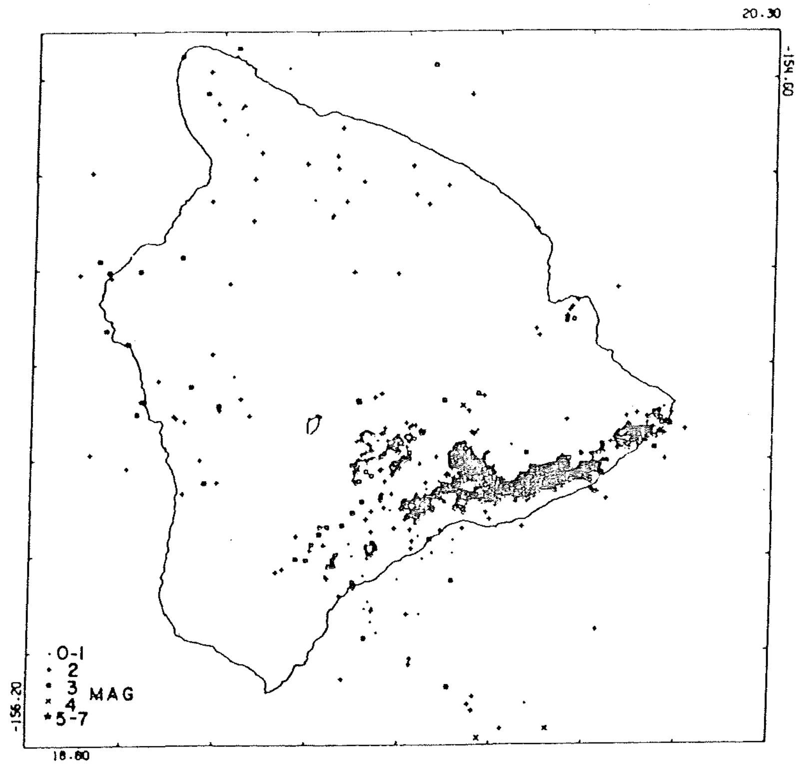


Fig. 9. Earthquake epicenter plot for Hawaii, 1976 (from Koyanagi et al., 1978a).

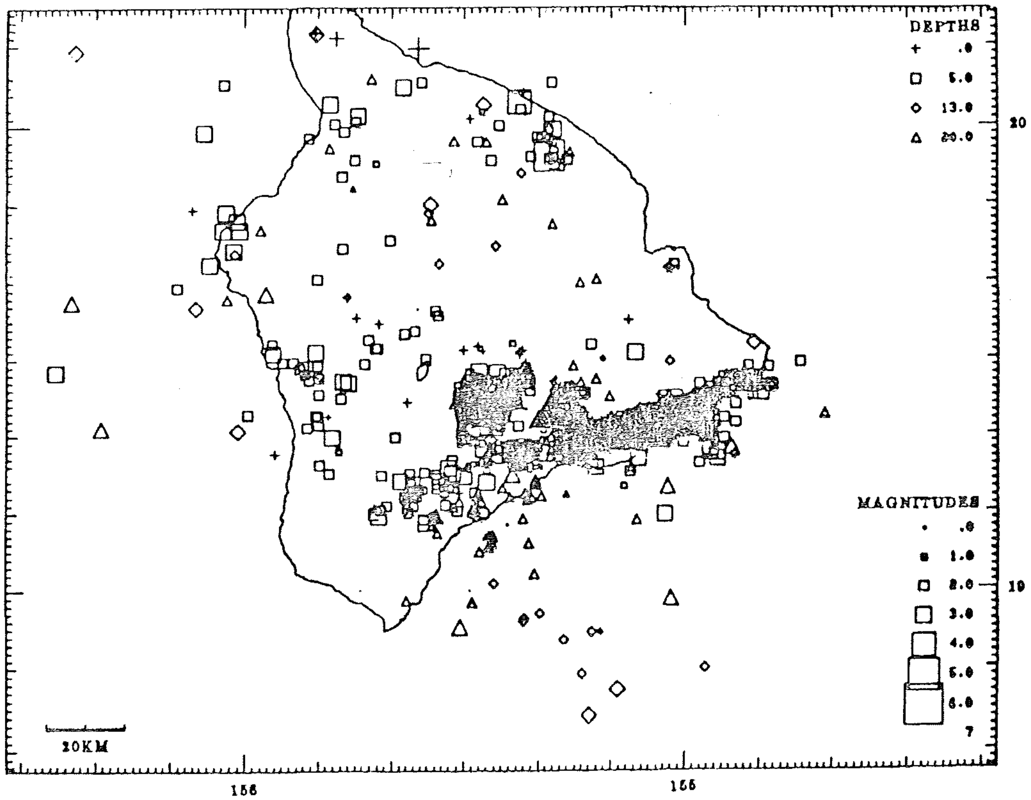


Fig. 10. Earthquake epicenter plot for Hawaii, 1977 (from Koyanagi et al., 1978b).

Kilauea. Significant activity also occurs along the Kealakekua Fault System in approximately the same location as the elongate gravity anomaly discussed above. Seismic activity is also somewhat elevated along the Hualalai and Mauna Kea rift systems; some minor activity occurs in the Kawaihae area as well. It is unlikely that the observed seismic activity arises directly from geothermal reservoirs in these areas; nonetheless, the presence of earthquake activity is thought to be indicative of other subsurface structural features (rift zones or fault systems) with which reservoirs may be associated.

Infrared surveys have been carried out over some of the near-shore areas of the island of Hawaii (Fischer et al., 1966) in an attempt to identify spring discharge of basal waters along the perimeter of the island. Although the original intent of the study was to identify springs with temperatures colder than surface ocean water, several warm water anomalies were observed. Figure 11 (after Fischer et al., 1966) presents a map of areas that were surveyed, as well as those parts of the island discharging warm water. Warm springs along the Puna and Ka'u coast are indicative of basal waters heated by the volcanic rift zones, as might be expected in an area of active volcanism. Thermal discharges along the Kona coast are somewhat more surprising in that there are no known active rift zones in the vicinity. The coincidence of warmer than expected groundwaters in an area having both gravity and seismic anomalies strongly suggests that thermal groundwater may be associated with a structural feature in the vicinity. No other significant infrared anomalies have been observed in the coastal discharges of Hawaii; however, in light of the limited nature of the study, a more detailed survey of Hawaii and the other islands may prove worthwhile.

Downhole temperature profiles have recently been obtained for several shallow wells around the island of Hawaii (D. Epp, HIG technical report in prep.). To ensure that the downhole temperatures were in equilibrium with the surrounding rock, the survey was restricted to wells that were not pumped on a regular schedule, and thus only a relatively small number of total wells on the island were surveyed.

A plot of the wells surveyed and the maximum downhole temperatures recorded are presented in Figure 12. Two areas of the island have obvious thermal anomalies: Puna and Kawaihae. The Puna district has a known high-temperature resource at a depth of approximately 2 km; the presence of thermal anomalies in shallow wells in this area may be indicative of a near-surface heat source that may be of use in direct heat applications. The presence of near-surface warm waters in Kawaihae

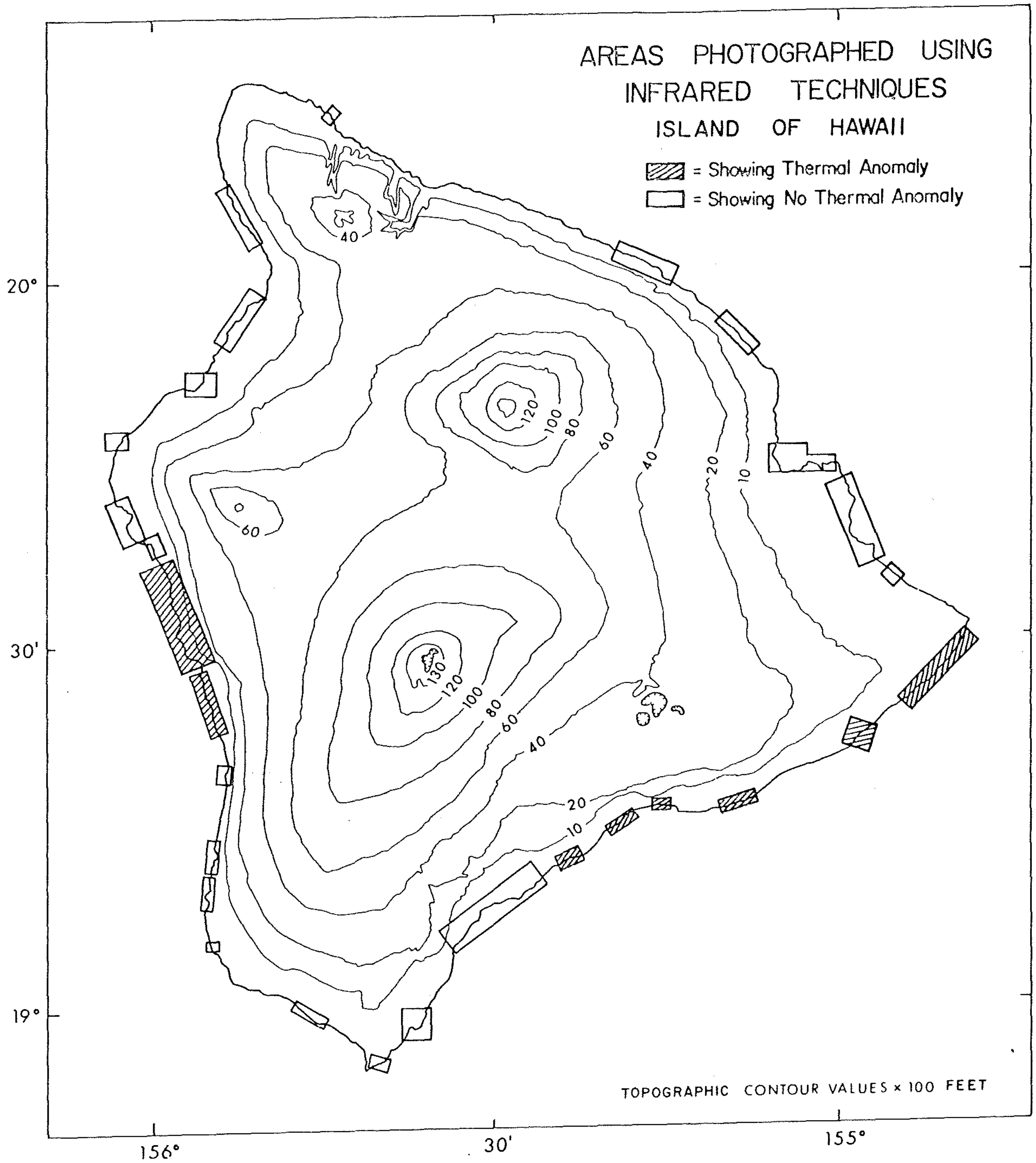


Fig. 11. Map of infrared surveys and anomalies on Hawaii (from Fischer et al., 1966).

Maximum temperature (°C) in measured wells.

Fig. 12. Map of wells on Hawaii for which temperature profiles have been made (from Epp, in prep.).

strongly suggests that a thermal source exists in this area as well. Further investigation of the area is required to determine whether the potential resource is a shallow, low-temperature reservoir or whether a high-temperature reservoir exists at a greater depth. No other obvious thermal anomalies were observed in this survey, probably because of incomplete coverage of the island. A more extensive survey of this type over Hawaii, and the other major islands, would provide useful data for future geothermal reconnaissance.

Meteorology and hydrology

The climatic conditions on Hawaii are largely a function of the topography and prevailing wind conditions. Both Mauna Loa and Mauna Kea reach above the trade wind inversion level and profoundly affect the air circulation patterns around the island. An isohyetal map of Hawaii is shown in Figure 13 (State of Hawaii, 1970). The mean annual rainfall on the windward slopes of Hawaii is over 760 cm in some places, whereas some areas on the leeward slopes receive less than 25 cm annually.

Temperature variations show similar topographic effects (Fig. 14); mean annual temperature on the lower windward slopes is approximately 22°C and decreases by approximately 6°C per thousand meter increase in elevation. The temperature gradient is somewhat higher on the leeward slopes, with a maximum mean annual temperature of approximately 24°C at the lower elevations (State of Hawaii, 1970).

The hydrology of Hawaii is strongly controlled by the geologic structure of the island and, as such, is significantly different for each volcanic system. Because Hawaii is an island environment, one would expect its hydrology to conform to the classical Ghyben-Herzberg lens model. To some extent this is the case, although the presence of dike systems, ash layering, and soil cover complicates the model to varying degrees. Figure 15 presents a summary of the hydrology for the island of Hawaii (Takasaki, 1978).

Kilauea volcano has very little soil cover and minimal ash interlayering; thus most rainfall percolates rapidly into the ground and down to the static water table (basal lens). There are no perennial streams on Kilauea, and the few ephemeral streams that are present are active only during periods of high rainfall. Spring discharge occurs only in coastal areas, and most discharges are brackish to saline. The static water level, as a general rule, increases in height by approximately 1/2 m/km inland, although extensive diking in the rift zones is thought to elevate the upslope water levels slightly. Tidal mixing occurs in many nearshore

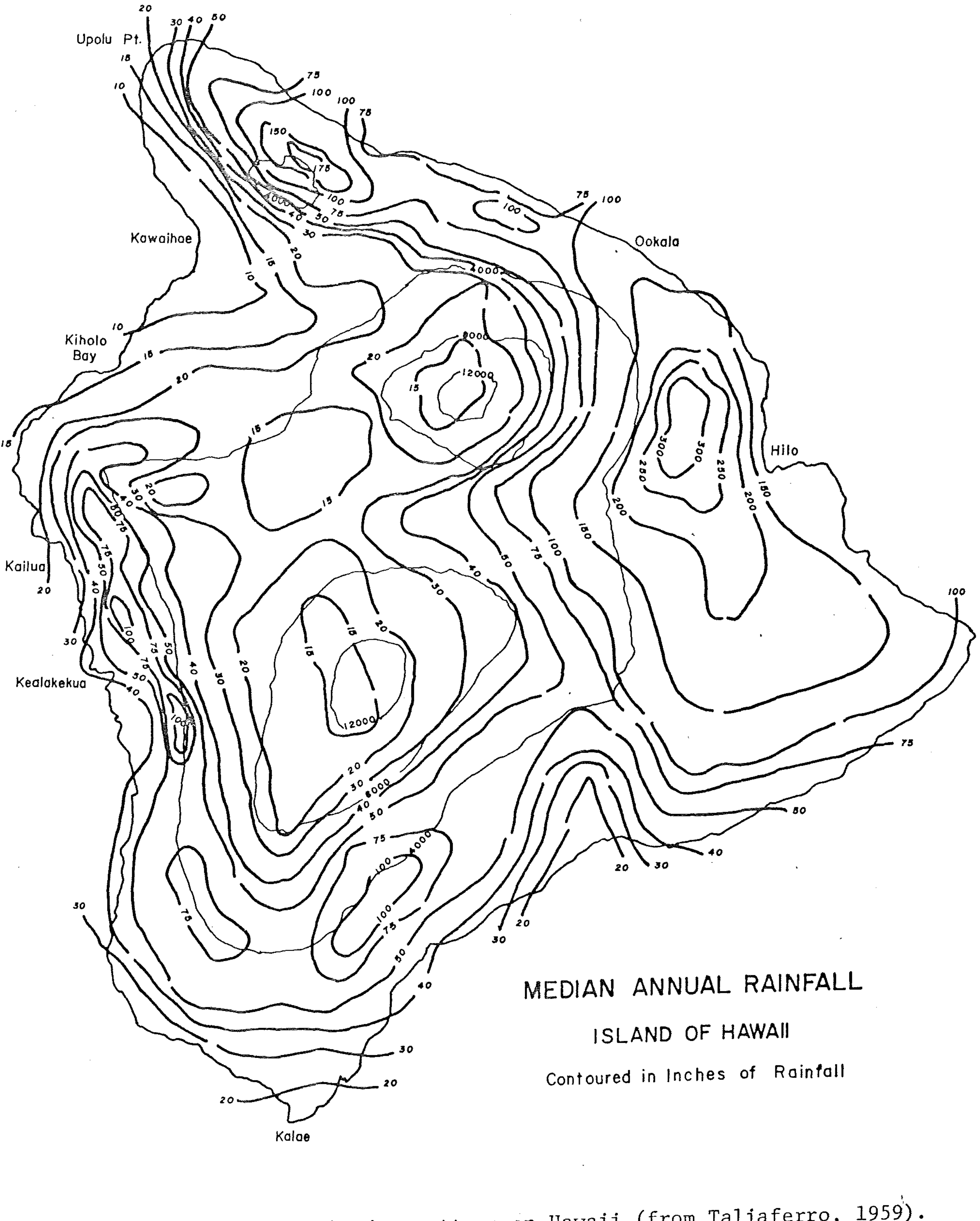


Fig. 13. Rainfall distribution pattern on Hawaii (from Taliaferro, 1959).

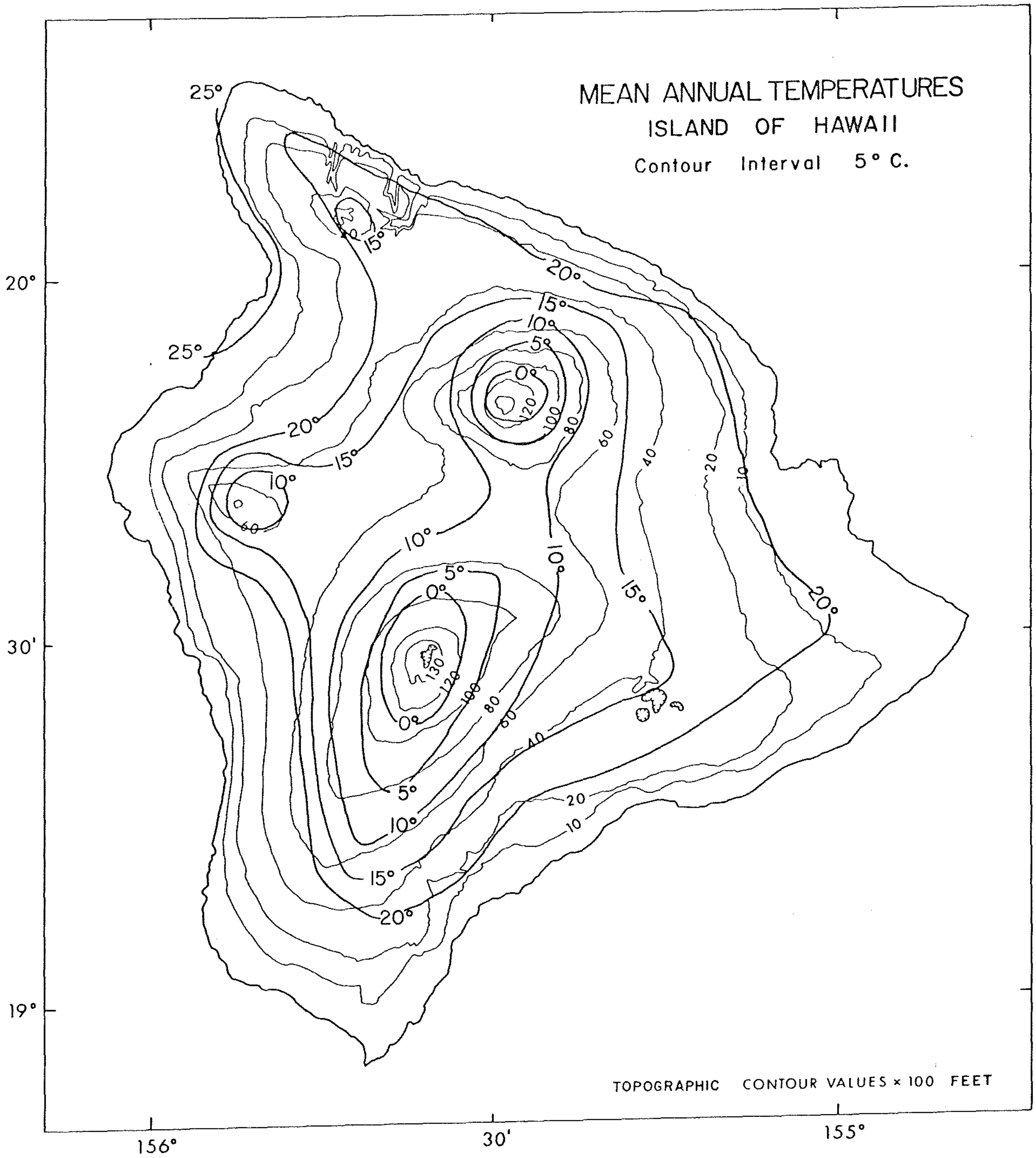


Fig. 14. Temperature distribution on Hawaii (from State of Hawaii, DOWALD Report R34, 1970).

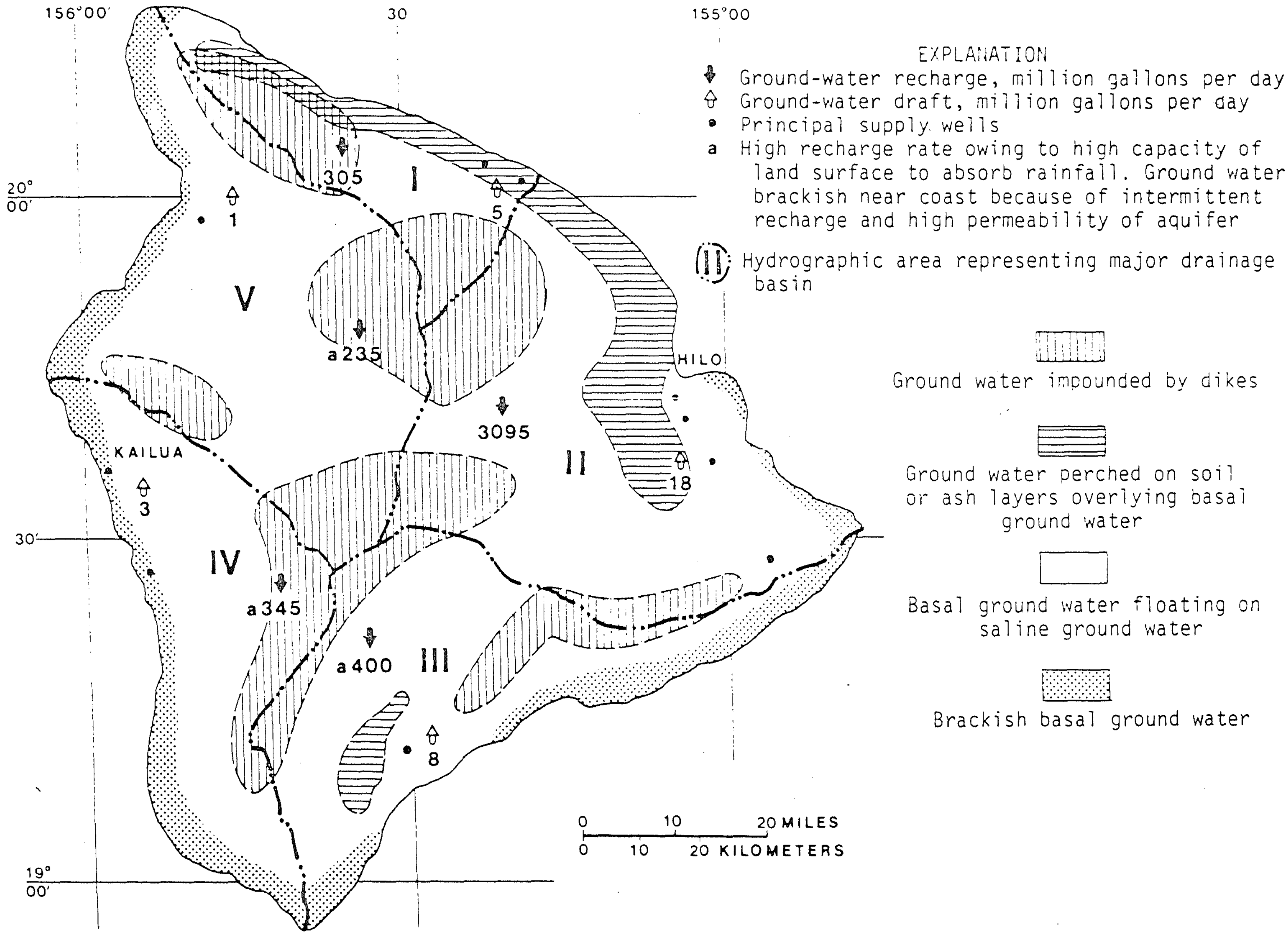


Fig. 15. Hydrologic summary of Hawaii (from Takasaki, 1978).

wells and, under conditions of heavy drawdown, some wells farther inland have become increasingly saline (Stearns and Macdonald, 1946). Some of the warm water wells in Puna have also been found to be brackish as a result of thermal density inversions: i.e., warmer saline waters float above colder meteoric waters.

The leeward slope of Kilauea (Ka'u) receives little rain and has even less soil cover than the windward slope. Although the hydrology in this area is relatively unexplored, one nearshore basal spring in the Ka'u district is reported to have warm water. No data exist at present for the temperature and water chemistry of this spring and, as discussed in the geophysics section above, there are probably several other nearshore warm water seeps, but the inaccessibility of this area has made it impossible to confirm their existence.

Although the northeastern (windward) slopes of Mauna Loa receive a moderately high annual rainfall, the absence of significant soil cover results in minimal surface discharge. There are few, if any, perennial springs or streams on Mauna Loa and, of those that are present, nearly all lose their flow during extended periods of low rainfall. Dike-impounded water is thought to exist on the upper Mauna Loa slopes, although at the lower elevations the dikes associated with the rift zone have no observable effect on the local hydrology.

The southeastern slopes of Mauna Loa receive a moderate amount of rainfall from the trade winds funneled through the saddle between Mauna Loa and Kilauea. The hydrology of this particular area is controlled to some extent by ash deposits on the upper flanks of Mauna Loa; high-level water has been obtained from tunnels placed along the tops of impermeable ash and tuff beds buried under a few hundred meters of permeable lava flow (Stearns and Macdonald, 1946). Coastal springs in this area discharge considerable cold brackish water; the discharge temperatures indicate that the ultimate source of the water is well inland and at a relatively high elevation. The south rift of Mauna Loa, which extends nearly to the northern end of the island, appears to have a minimal impact on the hydrology of the Pahala and Ka'u districts.

The southern tip of the island (South Point) along the south rift zone of Mauna Loa receives relatively little rainfall. There is little cultural activity in the area and, as a result, hydrologic investigations of South Point have been minimal.

Although the leeward side of Mauna Loa (Kona) is cut off from the normal trade wind patterns, the lower slopes still receive a moderate amount of rainfall due to the diurnal coastal breezes. Nonetheless, basal groundwater is limited and many nearshore springs, and wells are brackish either due to tidal mixing or possible thermal disruption of the Ghyben-Herzberg lens. Although there are small amounts of ash-bed perched water on the upper slopes, there has not been enough to develop groundwater sources similar to those in the Pahala district.

The windward slopes of Mauna Kea receive higher annual rainfall than any other part of the island. Considerable depths of ash and soil cover are present at the surface as well as interlayered with the earlier lavas of Mauna Kea. There are several intermittent high-level springs on the intermediate slopes of Mauna Kea but only a few perennial streams. Most of the high-level water observed is the result of meteoric waters perched on impermeable ash beds rather than dike-fed spring systems.

Large volumes of basal water are withdrawn from nearshore wells and tunnels at the base of the Mauna Kea shield. The minimal drawdown resulting from the rapid withdrawal of water from these aquifers indicates a large storage capacity in this area. The east rift of Mauna Kea underlies the windward slope of the mountain, although, to date, its impact on the local hydrology has not been observed.

The leeward slope of Mauna Kea and the northern Hualalai flank (Kawaihae) receive less rainfall than any of the other low-lying areas of the island. Soil cover is minimal and shallow groundwater is virtually nonexistent. The few nearshore wells and springs that are present usually have brackish waters. Recent deep drilling at the mid-level elevations on Hualalai encountered a water table elevated several feet above the expected basal lens. This deep source water remained fresh to a depth of approximately 1000 m below sea level, and heavy withdrawal from the aquifers resulted in a negligible drawdown. The well was emplaced upslope of the north rift of Hualalai and, at present, it is believed that the dike system in the rift area has disrupted the seaward flow of basal waters, resulting in an elevated water table above the rift and a depressed level in the coastal areas. There are no known thermal springs or wells on the lower slopes, although the brackishness of most water supplies has led to relatively little groundwater exploration.

The hydrology of the Kohala district is substantially different from that in any other area of Hawaii: the basal water lens is very thin and quite often brackish even at a considerable distance from the shoreline. Extensive weathering and dissection of the original shield have exposed the rift zone dike systems. Most freshwater sources in this district are the result of leakage from the dike-confined water. Moderately high rainfall in this region provides sufficient recharge to maintain these high-level water sources throughout the year. None of the high-level water sources have been reported to be above ambient temperatures.

Geochemistry

Geochemical data for the island of Hawaii are presented in the Appendix, Table 1, listing all water sources on the island having elevated silica concentrations. The wells are listed according to well numbers (assigned on the basis of latitude-longitude coordinates of the well); the most recent available water chemistry and temperature data for each well are also included. The location of each well identified is shown in computer-generated maps of the well locations in Figure 16; for comparison, the locations of all wells on the island are plotted in Figure 17. (Large scale maps of the well locations are available upon request from Hawaii Institute of Geophysics.)

One point that should be immediately apparent from Figure 17 is that groundwater development is not evenly distributed over the island and, as a result, the available data are biased toward areas with high population densities and of intensive groundwater withdrawal. These locations are largely restricted to the coastal areas.

In some respects, this is not a particular disadvantage; it is presently believed that Hawaii's thermal reservoirs are restricted to depths of at least several hundred meters below sea level where formation permeability is considerably lower than that in the subaerially erupted basalts. If this is the case, the exploitation of thermal reservoirs from higher elevation areas would be much more difficult than exploitation in the lower elevation, nearshore, areas. The primary disadvantage inherent in the uneven distribution of water sources is that there are no geochemical data available for a large portion of the island.

Nearly all the wells in the Puna district are included in the data compilation. This is to be expected since Puna has a proven thermal reservoir and many of the wells in the area have temperatures well above ambient. The Cl/Mg ratios encountered in this district range from 57.8 down to 2.4; in general, the higher ratios are found downslope of the rift zone whereas the lower ratios are found above the rift. Although the extent of the high-temperature reservoir is not known at present, the fact that many wells in the area exhibit both silica and chloride/magnesium ion anomalies indicates

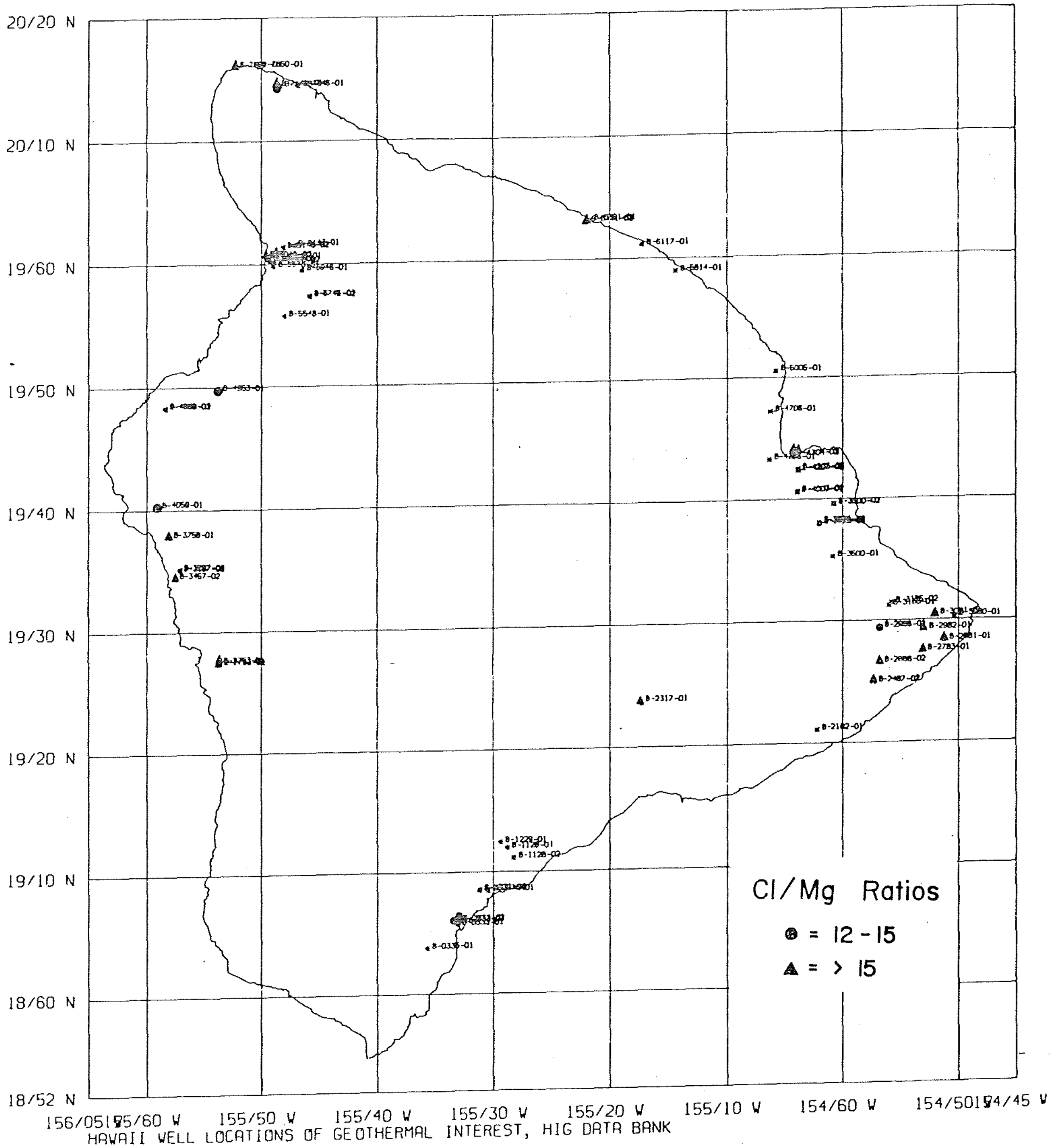


Fig. 16. Silica and chloride/magnesium ion anomalies on Hawaii. All wells shown have elevated silica (>30 ppm).

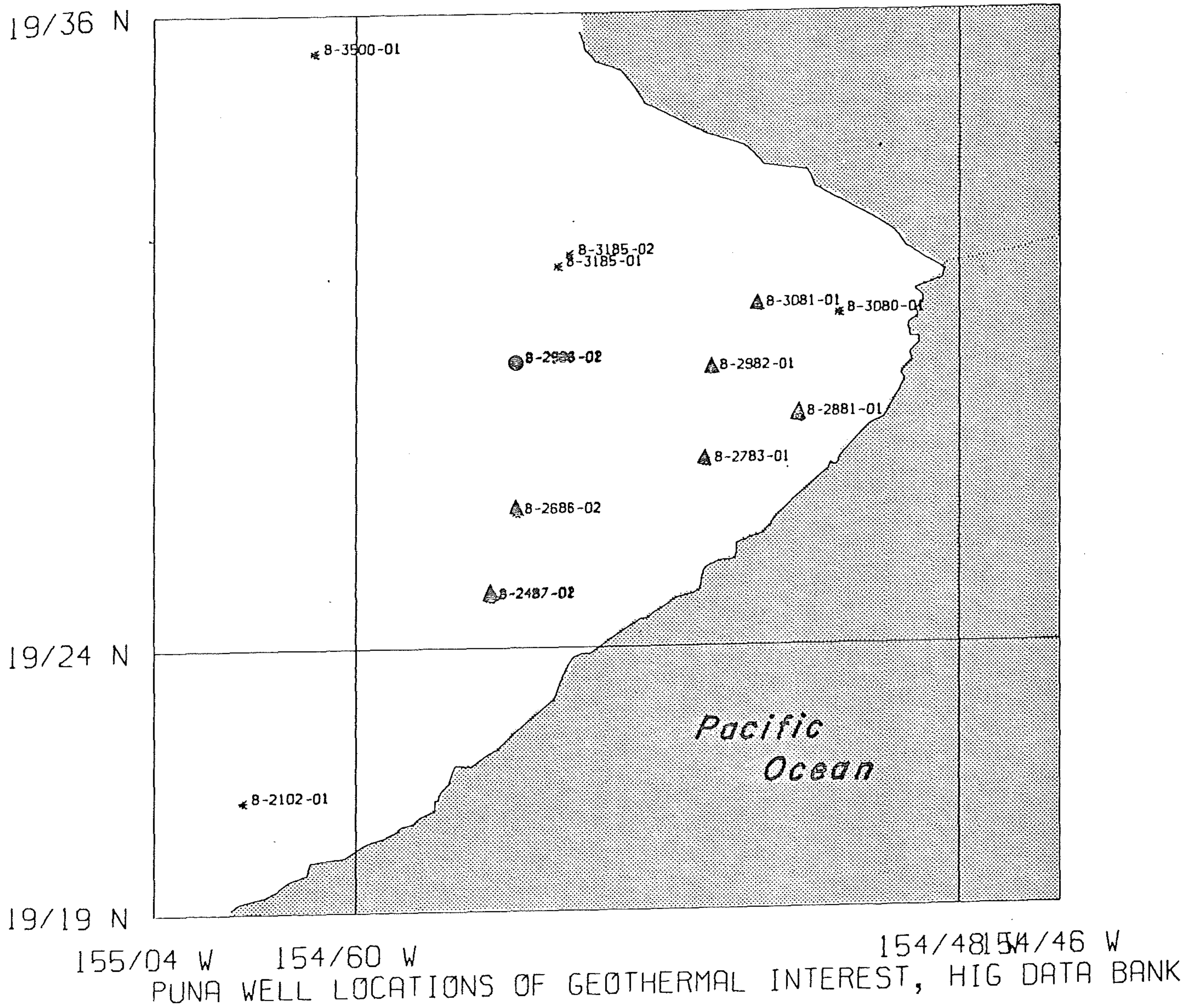
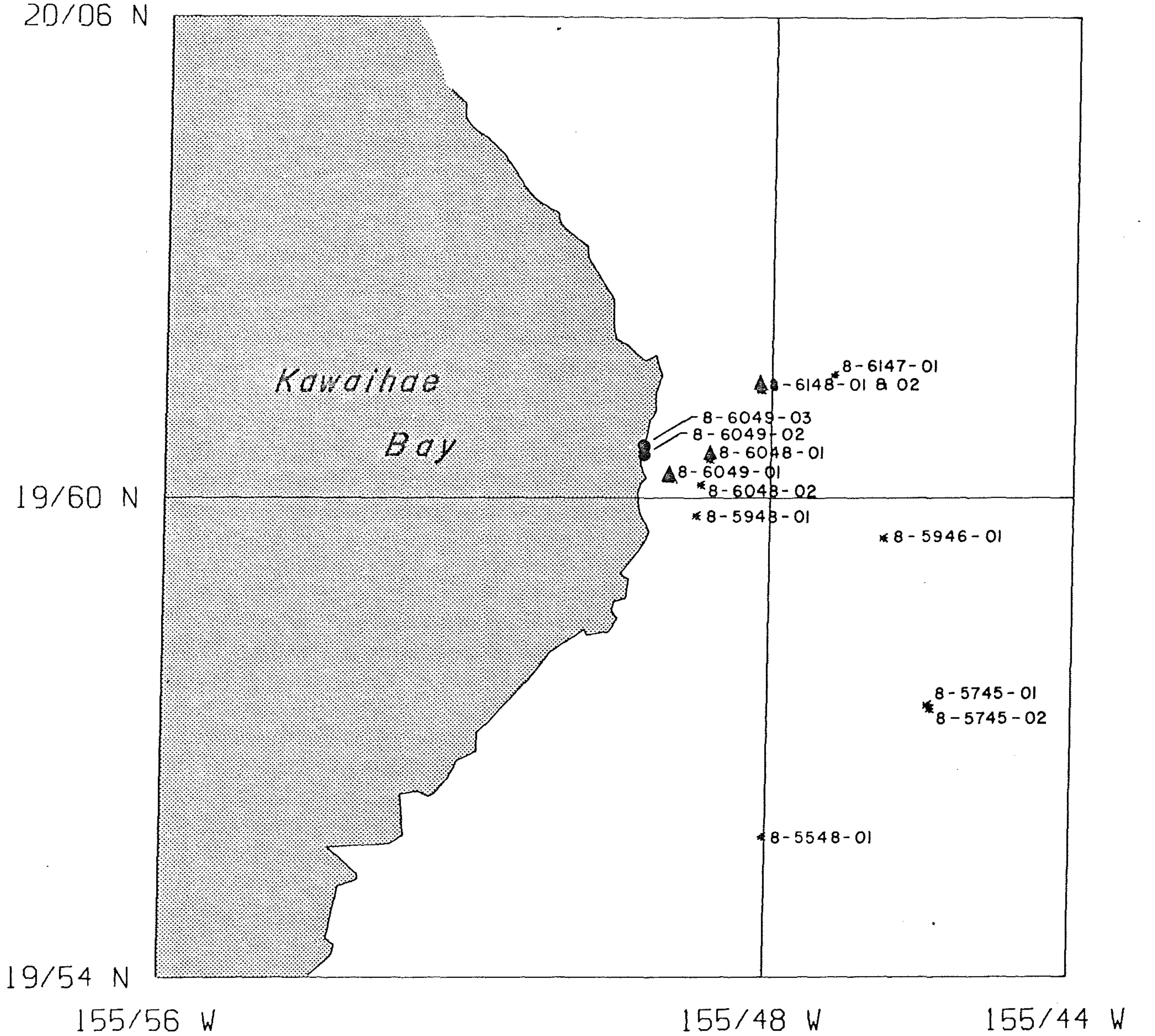


Fig. 16 (continued).



KAWAIHAE WELL LOCATIONS OF GEOTHERMAL INTEREST, HIG DATA

Fig. 16 (continued).

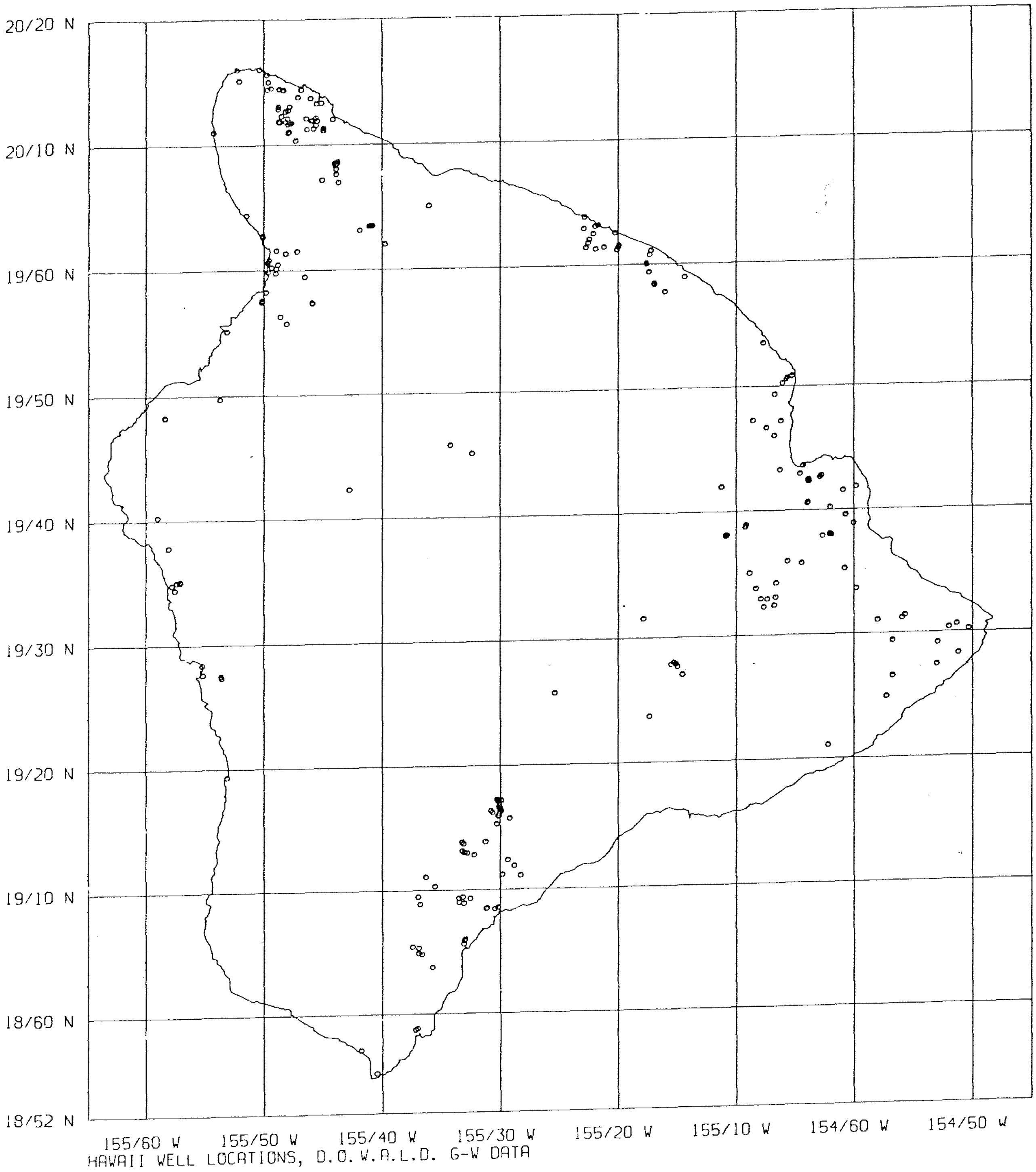


Fig. 17. Locations for all water sources on Hawaii.

that low-temperature (50°C to 150°C) resources are probably extensive.

The identified anomaly in the Kilauea summit area is a research well drilled to a depth of approximately 1200 meters. Although a thermal anomaly was encountered (94°C) at 600 m, the bottom hole temperature was only 137°C at a depth of 1262 m (Zablocki *et al.*, 1974). It is unlikely that exploitation of geothermal resources in this area will be economically feasible in the near future. In addition, extensive land holdings of the U.S. National Park Service at the Kilauea summit would severely restrict the type and extent of exploitation in this area.

The lower Ka'u and Pahala districts have few wells with silica anomalies and of these, fewer still have elevated Cl/Mg ratios. The source of the anomalous water is thought to be the Kilauea south rift, although the scarcity of groundwater data from near the rift zone makes it difficult to give a realistic assessment of this area. The similarity between the Puna and Ka'u rifts, as well as the reported infrared anomalies along Ka'u coastline, indicate that there are potential resources in this area and that further exploration should be conducted.

Although very few geochemical data exist for the south rift of Mauna Loa, it seems unlikely that a rift system as young and recently active (last erupted in 1868 at an elevation of 900 m [Macdonald and Abbott, 1970]) could be completely without thermal potential.

The leeward side of Hawaii, from South Point to Hualalai, has a sparse distribution of shallow groundwater sources, and as a result the interpretation of the geochemical anomalies observed is very tentative. Most sources in the North Kona-Hualalai area have been identified as anomalous both in silica concentrations and in Cl/Mg ion ratios. Although it is possible that the unusual chemistry observed is the result of meteorological and hydrological conditions in the Kona district, the identification of thermal springs along the coastline and the presence of seismic and gravity anomalies in this area strongly imply that some structural features exist with which a thermal reservoir may be associated. Whether this structural feature is simply a fracture system associated with the Kealakekua Fault or whether it is an intrusive body will not be known until more extensive site-specific surveys have been conducted. In light of the planned future population expansion in this area, and consequent increased power requirements, this area should receive detailed investigation in the near future.

Several wells clustered in the Kawaihae Bay area have both silica and chloride/magnesium anomalies. Shallow groundwater temperatures are generally elevated as well. Kawaihae may be at, or near, the junction of the major or minor rift systems of Hualalai, Kohala, and Mauna Kea and, as such, could derive a substantial amount of heat from any of these systems. The relatively high temperatures of the groundwaters in this district seem to indicate that anomalous subsurface temperatures exist at a relatively shallow depth, and for this reason we have targeted the Kawaihae district for intensive investigation.

Groundwater sources in the North Kohala district also have silica and chloride magnesium ion anomalies. Although this is one of the oldest areas of the island, it is still quite possible that a significant amount of residual heat remains within the old caldera-rift complex. Nonetheless, the inaccessibility of the area as well as its low population density makes it less suitable for geothermal investigation in the near future.

There are a few weak silica anomalies along the windward coast of Hawaii to the north of Hilo; most have neither significant chloride/magnesium ion nor temperature anomalies. The only well that does exhibit a magnesium ion depletion has a near neighbor with normal ion ratios, thus indicating a possible analytical error in the former data set. Nonetheless, the fact that the Mauna Kea rift zone passes through this area increases the likelihood that a thermal reservoir exists, and a more complete investigation of this district is warranted.

The district of South Hilo has a number of silica anomalies but, again, only one has a significant chloride/magnesium ion anomaly. Although local groundwater temperatures are not significantly above ambient, recent volcanism (2000 years B.P.) (Macdonald and Abbott, 1970) has taken place in this district near Waiakea; thus there is a possibility that a thermal resource is present. The proximity of South Hilo to a deep water port (Hilo Harbor) as well as to industrial consumers of energy such as sugar-processing plants makes this area suitable for rapid commercial development of any resource that may be found. For these reasons, the Keaau area has also been target for intensive investigation.

Summary geothermal assessment

The island of Hawaii has several areas in which there is moderate to strong evidence for the existence of a thermal reservoir. Table 1, below, presents a preliminary estimate of the potential for a high-temperature and a low-temperature reservoir and the probability for development of each of the areas discussed above. The appraisal of each site has been based on all geophysical and geochemical data presently available. The ranking is in descending order: 1= highest potential (Puna, KGRA), 10 = lowest potential.

Table 1. Summary geothermal assessment for Hawaii Island

Area	High-Temp. Resource	Low-Temp. Resource	Probability for Development
Puna	1	1	2
Ka'u	2	1	7
South Point	3	2	5
Hualalai-North Kona	5	3	1
Kawaihae	5	3	1
Kohala	7	5	8
South Hilo-Keaau	6	4	1