UCRL 15535 VOL. 2

HAWAII ENERGY RESOURCE OVERVIEWS

volume 2

GEOTHERMAL

HYDROLOGY - GEOLOGY

C. FELDMAN & B. Z. SIEGEL

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THE IMPACT OF GEOTHERMAL DEVELOPMENT ON THE GEOLOGY AND HYDROLOGY OF THE HAWAIIAN ISLANDS

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GEOLOGIC SETTING OF THE HAWAIIAN ISLANDS

One of the best overall references on Hawaiian geology, hydrology, water resources, etc. is the textbook Volcanoes in the Sea (Macdonald and Abbott, 1970). This volume is the single most comprehensive reference available at the present time. It is the principal source of the information reported in this section, and is highly recommended as an introduction to the subject.

The Hawaiian archipelago is comprised of a chain of volcanic islands and seamounts trending northwest to southeast across more than 2000 km of the North Pacific Ocean. The chain has been formed by intraplate volcanism apparently generated by a mantle "hot spot" or convective plume which has remained relatively stationary in this region as the Pacific Plate passes over it in a northwesterly direction. The Island of Hawaii, at the southeastern end of the chain, is the youngest island and the current locus of volcanic activity. From Hawaii to the northwest, the islands become progressively older and less active, having moved away from the heat source. In the northwest, all that remains of formerly massive volcanoes are seamounts and a few small, jagged islets.

Individual island form as basaltic shield volcanoes which pass through various stages of development and deterioration. In the initial stage, the volcanic mountains are built up from the sea floor by countless thin flows of fluid lavas. Eventually, the mountain of volcanic material grows to heights well above sea level. At some depth beneath the volcano there is a magma chamber that supplies lava to the surface via numerous closely spaced conduits, which erosion may later expose as dense swarms of dikes. Eruptions occur at the summit of a Hawaiian volcano and along rift zones radiating from the summit. When a volcano reaches its "mature" stage of activity, a summit caldera has generally developed and will fill and collapse a number of times.

Differentiation within the magma chamber leads, with time, to compositional changes in the erupted lavas. Late-stage volcanism is characterized by more explosive eruptions that produce steeper--sided structures of more viscous material. The development of a cone of alkalic rocks on top of the caldera marks the end of the principal period of volcanism. From this time, the dominant processes are erosional, although renewed (post-erosional) volcanic activity has occurred on many islands. Intermittent eruptions with intervening periods of quiescence may continue for thousands of years. These late volcanics are compositionally different from the earlier basalts and vary in form from relatively fluid lava flows to steep--sided tuff cones and ash deposits.

Since volcanic rocks are by far the dominant geological materials in the Hawaiian Islands, it may be helpful at this point to describe the major volcanic rock types that occur. The following minerals are the primary constituents of Hawaiian volcanics and are used to classify the rock types:

I. FELDSPARS
   A. Alkalic feldpars: $(K, Na)AlSi_3O_8$
   B. Plagioclase feldspars
      1. Anorthite: $CaAl_2Si_3O_8$
      2. Albite: $NaAlSi_3O_8$
         (a) Oligoclase: a plagioclase containing 70 to 90 per cent albite

(b) Andesine: a plagioclase containing 50 to 70 per cent albite.

II. NEPHELINE: $NaAlSiO_4$

III. OLIVINE: $(Mg, Fe)_2SiO_4$

IV. PYROXENE

A. Pigeonite: $(Mg, Fe, Ca) (Mg, Fe)Si_2O_6$ Calcium and aluminum rich pyroxene.

V. QUARTZ: SiO_2

Rock Types: most Hawaiian volcanic rocks are types of basalt; i.e., they consist mainly of calcium-rich plagioclase feldspar and pyroxenes. There are two major groups or "series" of basalt, alkalic and tholeiitic, differing from each other in their content of SiO_2 and alkalic elements (Na and K). Within a series, rock types are gradational. The general scheme for the classification of basaltic rocks are given in Table 1.

TABLE I

Classification of Basaltic Rocks

ALKALIC SERIES (silica poor; Na & K rich; augite is major pyroxene)		THOLEIITIC SERIES (silica rich; Na & K poor; pigionite is major pyroxene)
ANKARAMITE	olivine-rich rocks sometimes grouped together as "picrite basalts"	OCEANITE
ALKALIC OLIVINE BASALT	$\geq$5% olivine	THOLEIITIC OLIVINE BASALT
ALKALIC BASALT		THOLEIITIC BASALT
HAWAIITE (andesine feldspar, pyroxene, and minor olivine)		
MUGEARITE (oligoclase feldspar)		
TRACHYTE (K-feldspar)		

Increasing Mg, Fe ↑

↓ Increasing Na, K

Two other important rock types do not fall within the above classification scheme. They are:

> NEPHELINITE (or nepheline basalts): resembles basalt but contains nepheline rather than feldspar.
>
> BASANITE: contains both nepheline and plagioclase; transitional between nephelinite and alkalic basalt.

Most of the basaltic rocks are erupted in lava flows of either the pahoehoe or aa type. Pahoehoe lavas move in thin, fluid streams which rapidly form a solid crust with smooth to ropy texture. Molten lava continues to flow beneath this crust, feeding into other lava streams and advancing in lobate protrusions or "toes". These natural conduits often become empty as the supply of lava diminishes and the remaining lava drains away by gravity. What remains are hollow tunnels or lava tubes that range in dimension from finger-size openings to caverns more than 1000 m long and 17 m in diameter (Howarth, 1973). While all tubes do not drain completely (many solidify when still entirely or partially full of lava), hollow ones are common in lava flows on many of the younger Hawaiian volcanoes (Kilauea, Mauna Loa, Hualalai, Mauna Kea, Haleakala). A bibliography on lava tubes has been compiled by Harter (1971). Erosion and sedimentation have destroyed lava-tube caves on most of the older volcanoes.

The aa type of lava flow is composed of material similar in composition to pahoehoe lavas, but differing in viscosity and gas content. Aa flows are more viscous, contain less gas, and are slower-moving than pahoehoe flows. The surface is very rough and jagged, composed of rubbly fragments of solidified lava known as "clinker". Beneath the clinkery surface, aa flows consist of a dense, sluggish liquid that carries the solid crust along, sometimes flowing over and engulfing fragments of clinker that fall from the top and sides. Extensive open conduits such as lava tubes rarely form in aa flows. However, many openings exist between the aa clinkers, and some empty channels do form in the interior portions of the flows as lava drains out.

Aside from lava flows, various types of cones are the principal volcanic manifestations in Hawaii. Fragments of volcanic ejecta falling around a vent produce cinder and spatter cones. If molten lava comes in contact with groundwater and/or seawater, more explosive eruptions occur due to the rapid heating of the water, producing broad cones of ash (unconsolidated, rapidly chilled fragments) and tuff (consolidated ash).

Minor amounts of sedimentary rock occur in Hawaii, mainly as products of mass wasting and stream deposition. Alluvial fill is thick in some valleys, and nonmarine alluvial deposits may grade into marine clays, sands, and gravels near valley mouths. Lualualei Valley on Oahu, an area under intensive geothermal investigation, contains nearly 400 meters of poorly lithified deposits of this type (Macdonald and Abbot, 1970).

Coral reefs are developed around most of the islands and are the source of calcareous material in beach sand, beachrock, and lithified dunes. Emerged fossil reefs are common on south-eastern Oahu, which is the only island with appreciable amounts of limestone.

Soil development is highly variable throughout the islands and is related to local geological and meterorological conditions. Geologically young areas, and locations with low rainfall and/or sparse vegetation, generally lack significant soil cover. On the other hand, prolonged exposure in wetter regions, aided by biological activity, has resulted in thick soil deposits (see Cline et al., 1955). Layers of soil and weathered material within a section of volcanic rock indicate prolonged pauses in volcanic activity.

Erosion has created some spectacular geomorphology in Hawaii, particularly on rainy windward slopes, where precipitous cliffs and deep gorges face the prevailing northeasterly trade winds. The combination of stream and wave erosion is capable of completely removing the above-sea-level portions of an island. The rate of erosion is affected by eustatic sea level changes, tectonically induced subsidence and emergence, and local meteorological conditions.

REGIONAL GEOLOGY OF THE MAJOR ISLANDS

HAWAII

Hawaii ("The Big Island") is the largest, youngest, and most active of the Hawaiian Islands. Five separate volcanic mountains are present on Hawaii today, and there is evidence that older volcanoes exist beneath the more recent lavas. In order of decreasing age, Hawaii's five volcanic systems are: Kohala, Mauna Kea, Hualalai, Mauna Loa, and Kilauea. All except Mauna Kea and Kohala have erupted in historic times.

Figure 1 is a generalized geologic map of the island of Hawaii.

Kohala Mountain (el. 1670 m), on the northern end of the Big Island, is composed of two series of volcanic rocks, separated by an erosional unconformity. The older rocks (Pololu Volcanic Series) consist of tholeiitic basalt, tholeiitic olivine basalt, and oceanite, grading upward into alkalic olivine basalt. The younger Hawi Series contains mainly mugearite with some trachyte. Available potassium-argon dates indicate ages of approximately 330,000 to 450,000 years for the Pololu Series and 25,000 to 60,000 years for Hawi rocks (McDougall and Swanson, 1972). The unconformity between the two series displays deep erosional valleys and up to 15 m of weathered rock and soil, confirming the considerable length of time between periods of volcanism. Kohala was built mainly around two rift zones that extend northwest and southeast from the summit. The windward (northeastern) side of Kohala has been deeply dissected by stream and wave erosion.

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

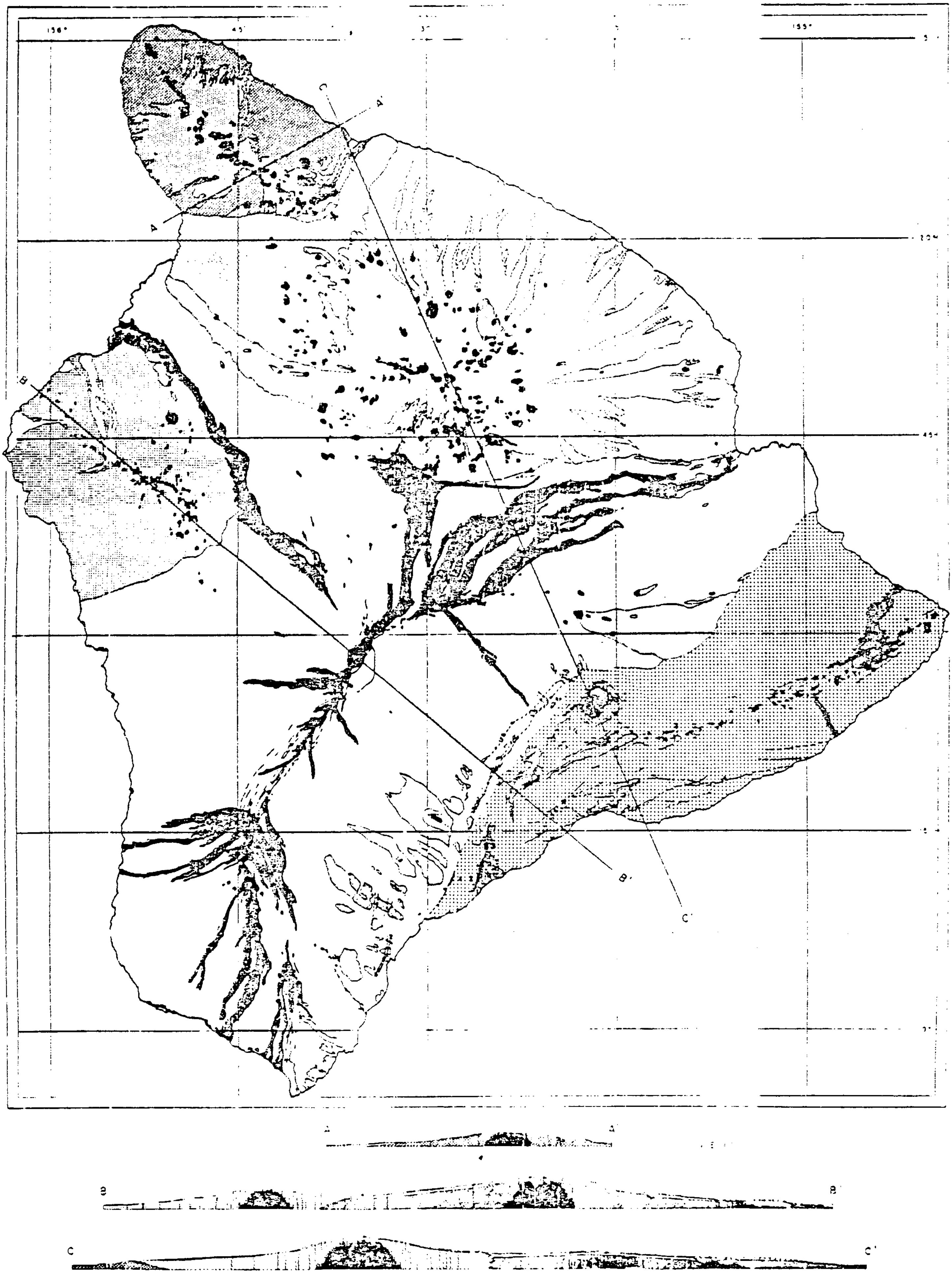
MAUNA KEA

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


A
A'
B
B'
C
C'

Although Kohala is the oldest of the five modern mountains of Hawaii Island, rocks older than the Pololu series are known from exposures on the southeast flank of Mauna Loa. These rocks, known as the Ninole Volcanic Series, are evidently the remains of an older shield volcano (the Niole Volcano) that developed at about the same time as the Kohala Volcano. With the excerption of a few tall ridges, however, the Ninole Volcano was buried by Mauna Loa eruptions. From the thin-bedded aa and pahoehoe lavas exposed in these ridges, ages up to 500,000 years have been determined for the Ninole Series (McDougall, 1964).

Mauna Kea (el. 4205 m) has a steep-sided cap of differentiated rocks typical of the late stage of Hawaiian volcanism. This summit cone is composed mainly of hawaiite, with some alkalic olivine basalt and ankaramite, all of which make up the Laupahoehoe Volcanic Series. Laupahoehoe eruptions characteristically built up numerous large cinder cones from which fans of lava issued. The last eruption on Mauna Kea occurred approximately 3600 years ago. Beneath its Laupahoehoe cap, Mauna Kea still displays the broad shield form of an earlier stage of activity. Rocks forming the shield are referred to as the Hamakua Volcanic Series, which is divided into a lower member of tholeiitic basalts, olivine basalts, and oceanites, and an upper member of alkalic olivine basalts, hasaiites, and ankaramites. The lower member is exposed only at a few localities, but the upper member can be seen along much of the Hamakua (northeast) coast. An extensive layer of altered ash, several meters thick in places, overlies the Hamakua Series. This unit, the Pahala ash, has been found on almost all of the volcanoes of the Big Island.

Mauna Kea probably had a caldera complex and radiating rift system, but these features have been obscured by Laupahoehoe eruptions. Some late-stage cinder cones are distributed in a linear manner, suggesting subsurface structural control. On the basis of these lineations, at least three principal rift zones may have been active, radiating from the summit towards the west, east, and south, with a subsidiary rift trending to the northeast.

There is also some geophysical evidence that a caldera and rift system exists beneath Mauna Kea's cap. The Big Island has been covered by aeromagnetic and gravity surveys, which have helped define subsurface features. Magnetic studies revealed numerous anomalies, and although many of these do not correspond to obvious surface features, they are believed to be related to structures at depth (Malahoff and Woollard, 1965). Gravity surveys indicate that the calderas of most volcanoes, with their contents of dense material, are fairly well defined by gravity highs (Kinoshita, 1965). Such a high beneath Mauna Kea provides reasonable evidence that a caldera complex is present.

Hualalai (el. 2521 m), on the western side of Hawaii, last erupted in 1801, producing lavas notable for their abundance of large olivine phenocrysts. Like Mauna Kea, Hualalai is capped by alkalic rocks (alkalic olivine basalts grading to hawaiites) which have obscurred the earlier shield form. One fairly well defined rift zone trends to the northwest across the summit, but other rifts are not especially obvious and are inferred mainly from lineations of spatter and cinder cones. Hualalai bears some highly differentiated rocks, notably the Puu Waawaa trachyte centered around the large pumice cone of the same name. Hualalai has no surface manifestation of a caldera complex; moreover, unlike the other volcanoes on the island, Hualalai has no well-defined gravity high in the region where a buried caldera might be expected (Kinoshita, 1965). It has been suggested that Hualalai's magma source was small and deep, which may explain both the highly differentiated nature of its rocks and the lack of a gravity high (Thomas, et al., 1979).

Mauna Loa (el. 4167 m) is a massive, broad mountain still in its shield building stage. As previously noted, Mauna Loa is built on top of the older Ninole Volcano, and it appears that still another volcano, the Kulani Shield, is buried beneath Mauna Loa as well. Rocks of the Kulani Shield are placed in the Kahuku Volcanic Series, which is exposed in a number of "kipukas" (islands of older rock that were not buried by subsequent lava flows) on the eastern and southern flanks of Mauna Loa, and along the Kahuku fault scarp in the southern part of the island. Consisting of tholeiitic basalts, the Kahuku Series overlies the Ninole Series.

Mauna Loa itself erupted as recently as 1975. Lavas have issued from the summit (Mokuaweoweo Caldera) but the major eruptions have occurred on the flanks, from southwest and northeast rift zones. Lavas produced by Mauna Loa belong to the Ka'u Volcanic Series. Mauna Loa has a number of fault systems, some of which have undergone considerable displacements in historic times. The Kealakekua and Kaoiki faults of Mauna Loa are among the more seismically active regions of the island.

Kilauea (el. 1231 m) is one of the world's most active volcanoes, and is experiencing a minor eruption even as this report is being written (November, 1979). A well defined summit caldera and two major rift zones (east and southwest) have produced lavas almost continously during historic times. The oldest Kilauea lavas, known as the Hilina Series, are only exposed on the island's southern coast, where fault scarps reveal about 300 m of thin flows of tholeiitic basalt, olivine basalt, and oceanite, overlain by about 10 meters of Pahala ash. The Hilina series may be contemporary with the Kahuku series of Mauna Loa. Above the Pahala ash are more tholeiitic basalts, olivine basalts, and oceanites of the Puna Series. The USGS-Hawaii Volcano Observatory is currently involved in intensive studies of Kilauea, including a project in which age determinations are being made for Kilauea lavas. Preliminary findings indicate that approximately 90 per cent of Kilauea's surface area is covered by lavas less than 1000 years old; 80 per cent of the surface may be less than 500 years old (T. Casadevall, USGS, pers. comm.).

Numerous faults are present on Kilauea, including several active zones along which seismic events are concentrated. The caldera is bounded by steep fault scarps formed by repeated collapsing of the caldera floor. Along the rift zones, distension of the ground surface has created numerous grabens, as well as single faults showing both vertical and lateral displacements. Several major fault systems of both Kilauea and Mauna Loa trend tangentially to the volcano slopes. Movement along faults of this type is primarily vertical. The ground downslope of a tangential fault is displaced downward relative to the upslope side of the fault so that these faults are marked by seaward-facing escarpments like the Hilina Pali, where more than 600 meters of vertical displacement has occurred. The Kealakekua and Kaoiki fault systems of Mauna Kea are also tangential faults. Whether these faults are caused by upward movement of the inland slope (forced upward by magmatic intrusion) or downward movement of the seaward side (by gravity sliding) is still unclear.

Earthquake swarms (hundreds of low-magnitude tremors per hour) along active fault systems frequently herald an imminent eruption and can be used to pinpoint the specific site of eruption before lava actually appears at the surface. Evidently such microseismic activity is associated with the movement of magma within the fault systems.

MAUI

Maui, the second largest Hawaiian island, is made up of two volcanic systems: West Maui and Haleakala. A geologic map of the island is shown in Figure 2.

West Maui (el. 1764 m) is the older of the two systems, and

MAUI

WEST MAUI ROCKS

RECENT and MIDDLE & LATE PLEISTOCENE	Picritic basalt, nepheline basanite	LAHAINA VOLCANIC SERIES
	Oligoclase andesite, soda trachyte	HONOLUA VOLCANIC SERIES
EARLY & MIDDLE PLEISTOCENE to PLIOCENE	Olivine basalt, basalt, picrite basalt	CALDERA COMPLEX & FLOWS — WAILUKU VOLCANIC SERIES
	Olivine basalt, basalt, picrite basalt	DIKE COMPLEX — WAILUKU VOLCANIC SERIES

EAST MAUI ROCKS

HISTORIC	Picrite basalt	VOLCANICS OF 1750
RECENT and MIDDLE & LATE PLEISTOCENE	Olivine basalt, basalt, picrite basalt, basaltic andesite, andesite	HANA VOLCANIC SERIES
EARLY & MIDDLE PLEISTOCENE to PLIOCENE	Basaltic andesite, andesitic & picrite basalt	KULA VOLCANIC SERIES
	Olivine basalt, basalt, picrite basalt	HONOMANU VOLCANIC SERIES

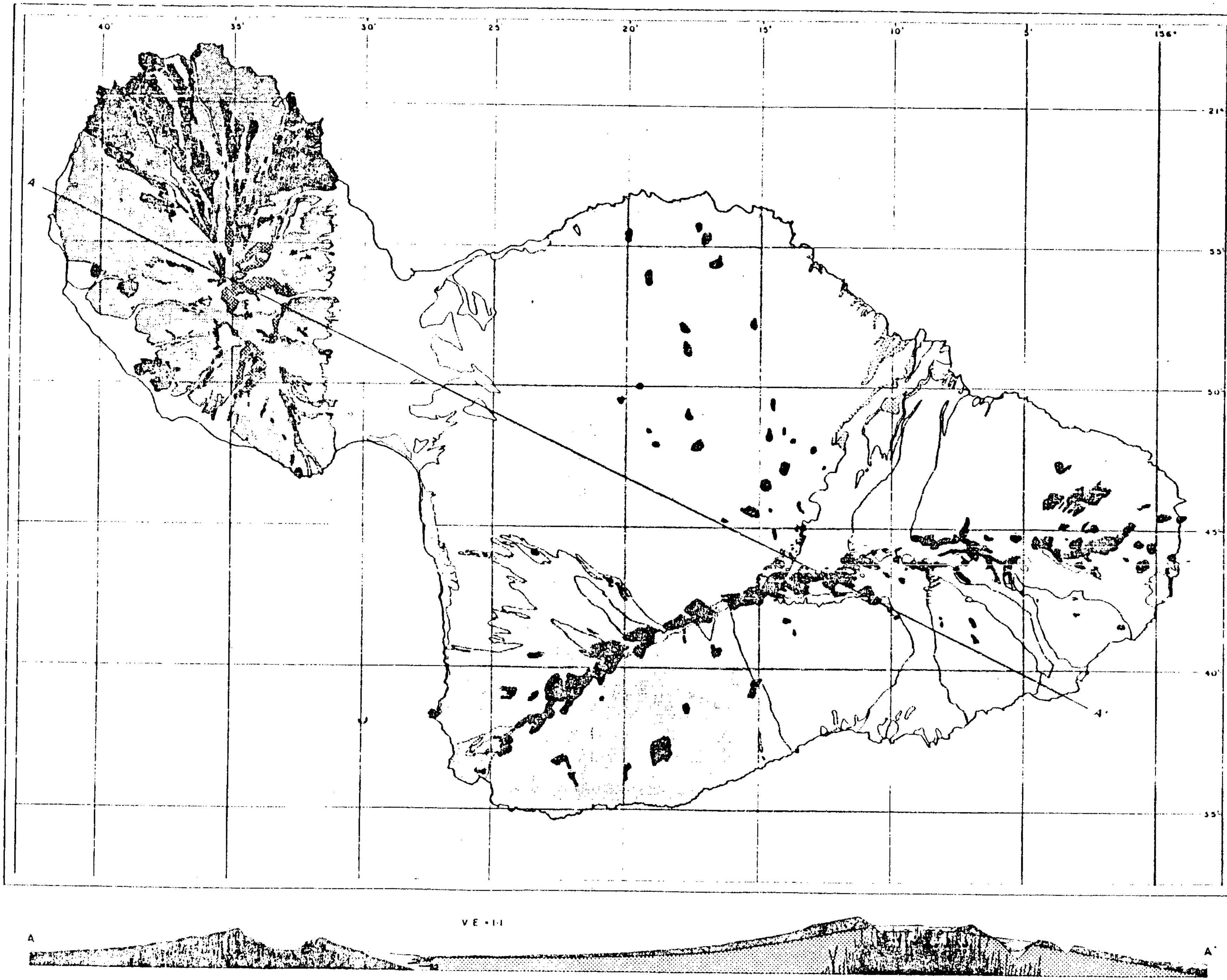
DOME

BOSS

CONE

DIKE

Figure 18 Surface geology of Maui


40'
35'
30'
25'
20'
15'
10'
5'
156°
21°
55'
50'
45'
40'
35'
A
A'
V.E.=1:1

has apparently completed all of the recognized phases of Hawaiian volcanic activity. No eruptions have occurred in historic times.

West Maui's shield building stage is represented by the Wailuku Volcanic Series, a sequence of tholeiites, olivine tholeiites, and oceanite, grading upward into alkalic olivine baslats. The original volcanic shield and summit caldera are visible today in the West Maui summit region where they ahve been exposed by erosion. Rift systems are poorly defined, although dike complexes appear to be slightly concentrated along two bands, one trending north-south, and the other extending north-eastward from the summit. Wailuku activity produced mainly thin, non-explosive lava flows with a few ash beds, and some intrusive rocks in the form of small gabbroic stocks.

The Wailuku Series is overlain in a few places by weathered material, but, in general, there appears to have been only a short period of quiescence before the next episode of volcanism. This phase was characterized by scattered eruptions of viscous alkalic lavas that only partially covered the existing shield. Rocks from this period belong to the Honolua Series and consist mainly of mugearite flows with some thicker flows and domes of trachyte. Rocks from both the Wailuku and the Honolua Series have been dated by potassium-argon and found to be slightly more than 1 million years old, or of Pliocene age (McDougall, 1964).

The post-Honolua history of West Maui has essentially been dominated by erosion, except for one brief episode of renewed activity that produced the cinder cones and small flows of the Lahaina

Volcanic Series. These rocks, found on the western slope of West Maui, are mainly picrite basalts, although nepheline-bearing basanite was erupted from a small cone on the bank of Olowalu Stream (Macdonald and Abbott, 1970).

West Maui has been deeply dissected by stream erosion. Much of the original caldera-filling material has been removed, leaving only a few isolated remnants such as the Io Needle. Alteration of caldera rocks by rising gases presumably increased their susceptibility to erosion. The original boundaries of the caldera are now marked by sheer cliffs. The northeastern flank of the mountain is cut by deep canyons, separated by broad areas that are capped by resistant Honolua lavas. Where this Honolua cover is absent, erosion is more advanced, and dissection has been more complete. Many of the canyons contain thick alluvium, probably deposited during a high stand of the sea. Extensive alluvial fands occur on the eastern and southwestern sides of West Maui. Other notable geologic features of West Maui are the large lithified sand dunes near the north coast. They are composed of calcareous beach sand that was transported inland by wind, and some dunes are as high as 60 meters.

Haleakala (el. 3055 m), the massive volcano of East Maui, last erupted around 1790. Haleakala was constructed in three main stages. The primary shield volcano, built by the Honomanu Volcanic Series, was composed of tholeiite, tholeiitic olivine basalt, oceanite, and minor pyroclastics, which were almost entirely buried by subsequent eruptions. Honomanu lavas appear to be transitional with the overlying Kula Series. Consisting mainly of hawaiite with some alkalic basalt and ankaramite, the Kula Series was generated during a more explosive phase of activity that produced large cinder cones and ash beds as well as blocky aa flows.

Three well-defined rift zones are present on Haleakala, trending southwest, east-northeast, and north-northwest from the summit. They are all marked by chains of cinder cones and dike swarms.

Volcanic activity became less frequent during the latter part of the Kula stage, allowing extensive stream erosion to occur. Haleakala's famous "crater" is actually an erosional feature formed during this period by the coalescence of two large stream-carved valleys. When volcanism resumed, these valleys were repeatedly inundated with new lava flows of the Hana Series, composed of silica-poor alkalic olivine basalts and hawaiites. Abundant Hana lavas issued from the summit region and over-flowed through the channels provided by stream-carved valleys. Numerous cinder cones were also produced inside the crater and along the rift zones. Molokini Islet, located about 5 km off Maui's southwest coast, is a tuff cone formed during this stage by an eruption on the seaward extension of Haleakala's southwest rift zone.

The 1790 eruption also took place along the southwest rift. Lava emerged from two vents and flowed into La Perouse Bay, where a small peninsula was constructed. In light of this eruption within historic times, Haleakala is considered a dormant volcano, and renewed activity in the future is not improbable.

The volcanic landscape of East Maui is mantled by surface deposits of alluvium, sand dunes, and talus in various states of consolidation.

KAHOOLAWE, LANAI, AND MOLOKAI

Maui is separated from its 3 immediate neighbors by relatively shallow channels. All four islands were probably exposed as a single landmass during lower stands of the sea.

Kahoolawe (Max. el. 450 m) is a presently uninhabited island used by the U.S. Navy as a bombing target. Structurally, windswept Kahoolawe is a typical Hawaiian volcano--a dome-shaped shield with a caldera, capped by post-caldera volcanics and late-stage (post erosional) cinder deposits. Apparently situated on a projection of Haleakala's southwest rift, Kahoolawe may be genetically related to East Maui.

Lanai (max. el. 1027 m) is one of the best examples of a Hawaiian shield volcano. Because it lies in the rain shadow of West Maui and East Molokai, Lanai is quite dry, and therefore, has not been subjected to severe stream erosion. Although a few canyons have been cut into Lanai's northeast slope (the region of maximum rainfall), the original shield form is generally well preserved.

Lanai is essentially composed of a single series of tholeiitic basalts (the Lanai Volcanic Series) that were erupted from the summit and three rift zones (Figure 3). Palawai Basin, in south--central Lanai, is a remnant of the summit caldera that is now bordered by fault scarps. Palawai Basin extends into a large graben to

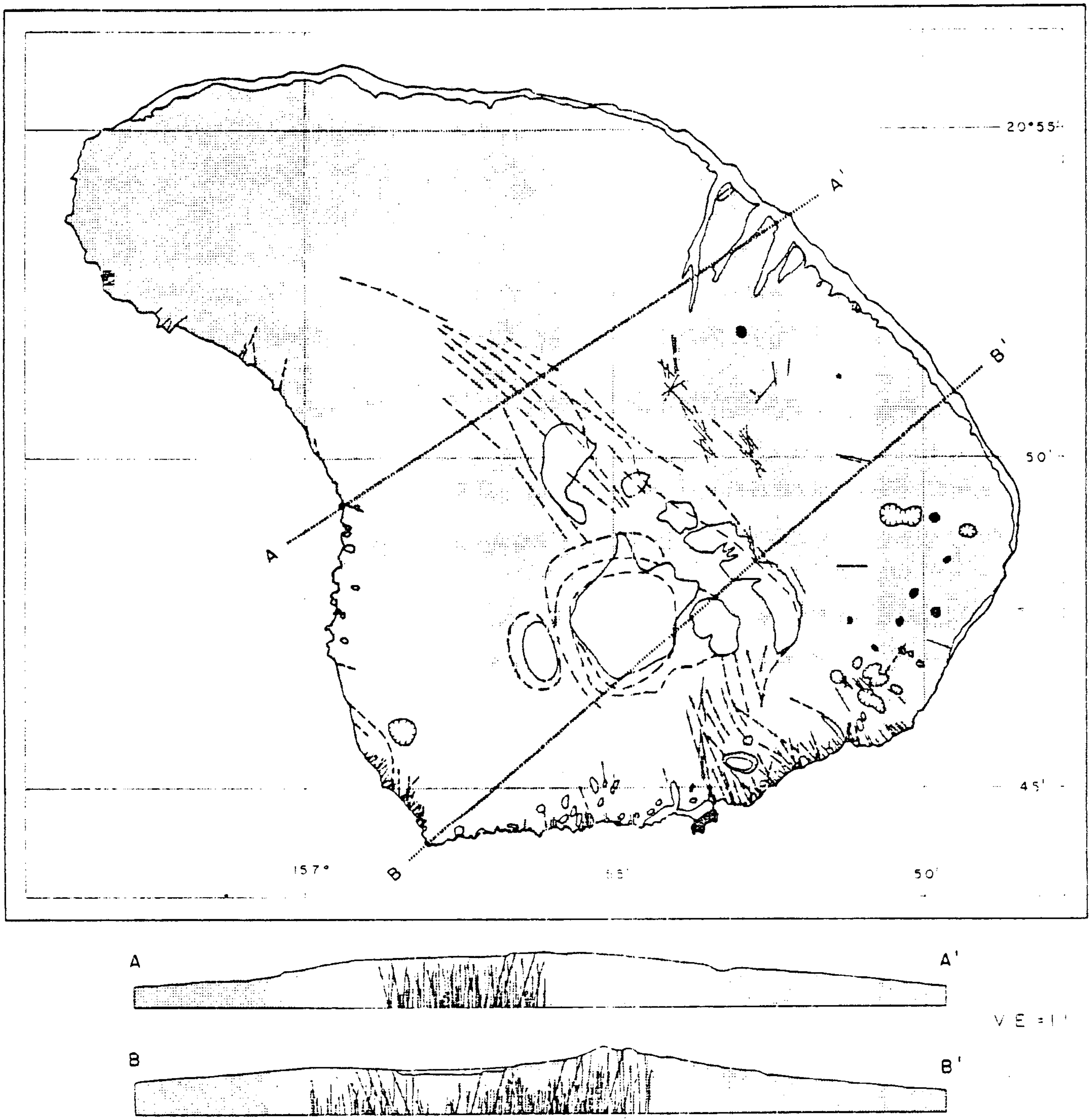
LANAI

? EARLY PLEISTOCENE and PLIOCENE		Olivine basalt, basalt, picrite basalt	LANAI VOLCANIC SERIES

CRATER

CONE

DIKE

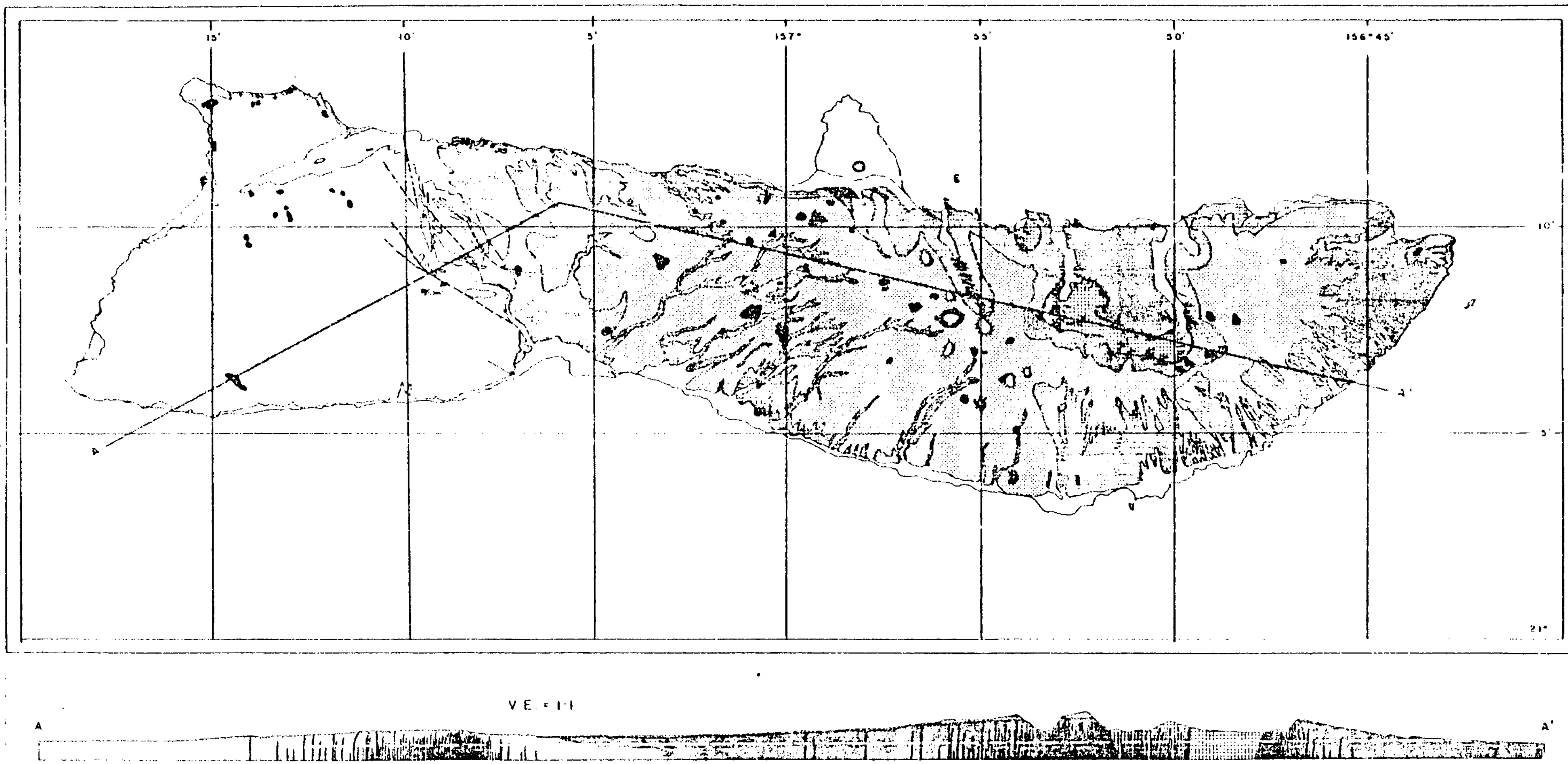

20°55'
A'
B'
50'
A
45'
157°
B
55'
50'
A
A'
V E = 1
B
B'

the southwest, the Manele Graben. The coastal terminus of the graben displays many nearly vertical dikes which suggest that the structure lies along one rift zone. Lanai's primary rift trends to the northwest, as shown by the obvious elongation of the island in that direction, and also by numerous northwest-striking dikes. A southwest rift zone is also marked by a multitude of dikes with related fausts (Stearns, 1940).

The leeward (southwest) coast of Lanai is exposed to strong waves generated by southwesterly storms, while the windward side is protected from such storm waves by Maui and Molokai. High sea cliffs and sea stacks are numerous on the leeward shore, whereas alluvial fans and beaches characterize the windward coast. In spite of its relatively sheltered position, Lanai is still subjected to wind erosion which has been effective in removing a considerable amount of soil cover from the island. Like Maui, Lanai has numerous calcareous sand dunes, some well lithified, as well as dunes composed of wind-blown soil.

Molokai is composed of two principal volcanic massifs. As on Maui, the younger volcano forms the eastern part of the island and partially overlaps an older volcano on the island's western end. A generalized geologic map of Molokai is shown in Fig. 4.

West Molokai (el. 421 m) is a flat shield volcano composed mainly of tholeiitic basalts, covered by thin patches of alkalic olivine basalt and hawaiite. Cinder and spatter cones mark a northwest rift zone, and several related dikes are exposed in sea cliffs on the north coast. On the opposite side of the summit, other northwest-trending dikes occur. Another rift zone is indicated by the wide structural arch that extends east-north-eastward from the summit.


15'
10'
5'
157°
55'
50'
156°45'
10'
5'
21°
A
A'
V.E. = 1:1
A
A'

MOLOKAI

WEST MOLOKAI ROCKS

PLIOCENE — Olivine basalt, basalt, picrite basalt — WEST MOLOKAI VOLCANIC SERIES

EAST MOLOKAI ROCKS

PLEISTOCENE — Olivine basalt — KALAUPAPA BASALT

Andesite, trachyte — UPPER MEMBER

PLIOCENE — Olivine basalt, basalt, picrite basalt — CALDERA / LAVA FLOWS — LOWER MEMBER

(UPPER MEMBER and LOWER MEMBER: EAST MOLOKAI VOLCANIC SERIES)

DOME

PIT CRATER

CONE

DIKE

Figure 27 Surface geology of Molokai

Dikes related to this rift zone are exposed near the summit, at the head of Waiahewahewa Gulch.

The main rift zone of West Molokai trends southwestward and continues offshore into Penguin Banks, a broad, flat shelf presumably truncated by wave erosion during a lower stand of the sea.

Evidence of a caldera is lacking on West Molokai. Northeast of the summit a number of northwest-southeast trending faults are present, and rocks adjacent to the fault scarps show considerable hydrothermal alteration. Presumably volcanic activity was centered in this faulted region (Thomas, et al., 1979). A distinct gravity high is present in this area (Moore and Krivoy, 1965). The northwest and southwest rift systems are also well defined by gravity anomalies.

West Molokai lies in the rain shadow of East Molokai; therefore, stream erosion is not well advanced. A thick (up to 15 m) layer of lateritic soil has developed reflecting both a long period of exposure and the absence of effective erosion. Along the north coast of West Molokai, wind erosion has produced numerous calcareous sand dunes, some of which are well lithified, while others are still active and mobile. Both sand and calcareous beachrock are abundant on West Molokai and have been utilized by the construction industry.

East Molokai (el. 1515 m) is another shield volcano, with two principal rift zones and a caldera. Rocks of East Molokai belong to the East Molokai Volcanic Series, which is devided into two members. The lower member contains tholeiitic basalt, tholeiitic olivine basalt, and oceanite. Towards the top of the lower member, more alkalic rocks are found. The upper member of the East Molokai

Series is primarily mugearite with some hawaiite and trachyte. The two members are separated by a thin layer of soil, but apparently the interval between eruptive periods was brief. Numerous cinder cones and domes were formed during Upper East Molokai eruptions. These more viscous lavas did not form a continuous cover over the older rocks, but where the upper member is present, it has served as a resistant cap rock.

Caldera-filling lavas, where not removed by erosion, are hydrothermally altered and intruded by some small stocks of gabroic composition.

A long period of erosion followed the eruption of the Upper East Molokai Series. Wave and stream erosion produced an extremely rugged coastline on the windward side, where sea cliffs rising nearly 1000 meters are intermixed with large stream-carved canyons.

Renewed volcanic activity following the development of the windward cliffs and valleys built the peninsula of Kalaupapa and the tuff-cone islet off the east end of Molokai. Kalaupapa is actually a small shield volcano in itself, composed of alkalic olivine basalts of late Pleistocene age (Stearns and Macdonald, 1947).

Molokai bears numerous relics of changing sea level, including emerged coral reefs, thick alluvial deposits, and submerged coastal sand dunes.

OAHU

Like Maui and Molokai, Oahu is composed of two separate volcanoes, with the older one forming the western part of the island, and the younger one on the east. Oahu's original volcanic shape has been drastically modified by prolonged erosion, so that the two volcanic shields have been reduced to narrow, dissected ridges separated by a broad plateau. Figure 5 shows the general geology of Oahu.

The Waianae Range (max. el. 1227 m) of western Oahu represents the eastern flank of the Waianae Volcano. Most of the western slope has been eroded away. There are three members in the Waianae Volcanic Series, representing the shield building stage, the caldera stage, and a post-caldera stage of activity. Tholeiitic rocks comprise the lower Waianae member and most of the middle member, which grades upwards into alkalic basalts and hawaiites in the upper member. Rocks from the Waianae Volcanic series range from 3.6 to 2.2 million years in age (Doell and Dalrymple, 1973). At least one episode of post-erosional volcanism occurred, forming a few cinder and spatter cones, with some lava flows, in the southeastern part of the Waianaes.

Thick dike swarms have become exposed in the Waianae volcano, revealing major rift systems that trend northwestward and south-southeastward, and a minor northeast-trending rift zone. The caldera was filled by thick lava flows which eventually spilled over its rim. Both aeromagnetic and gravity surveys of the Waianae Range show anomalies that correspond well with the known rift systems and the caldera (Malahoff and Woollard, 1965; Strange, Machesky, and Woollard, 1967). Recent geologic mapping in the Waianaes has better defined the boundaries of the caldera (Cox, et al., 1979) in terms of surface geology.

The western side of the Waianae Range is carved into large valleys that contain very thick deposits of alluvium (over 300 m in

OAHU

Age	Rock type	Formation	Series
RECENT and MIDDLE & LATE PLEISTOCENE	Nepheline-melilite basalt	TANTALUS and SUGAR LOAF VOLCANICS	HONOLULU VOLCANIC SERIES
	Fire fountain deposits		
	Vitric-crystal lithic tuff	KOKO VOLCANICS	
	Basalt flows		
	Olivine nephelinite, nephelinite-melilite basalt		
	Vitric lithic crystal tuff		
EARLY PLEISTOCENE and TERTIARY	Basalts, olivine basalts, picrite basalts	RIFT ZONE THROAT BRECCIA LAVA FLOWS	KOOLAU VOLCANIC SERIES
	Basalts, olivine basalts, picrite basalts and andesites	TUFF BRECCIA RIFT ZONE FLOWS	WAIANAE VOLCANIC SERIES

CRATER

CONE

DIKE


21°40'
35'
30'
25'
21°20'
158°15'
10'
5'
158°
55'
50'
45'
157°40'
A
A'
B
B'
V.E. = 1:1

some valleys). Such tremendous accumulations of alluvial material are attributed to a rise in base level, due to rising sea level and/or subsidence of the island, which reduced the carrying capacities of streams. Wave erosion has truncated the northwestern edge of the range, while the northern and eastern slopes have experienced relatively little dissection.

The Koolau Range (max. el. 960 m) represents the remains of another volcano which was built up after activity on the Waianae Volcano had ceased. Koolau lavas overlie and bank against eroded surfaces of the Waianae Shield, forming a broad central plateau (the Schofield Plain) between the two massifs. Much of the northeastern flank of the Koolau Volcano has been removed by erosion, so that only the southwestern portion of the volcano and remnants of the caldera exist above sea level today.

Lavas of the Koolau Volcanic Series, consisting predominantly of tholeiitic basalts and olivine basalts, were erupted mainly along a prominent northwest-trending rift zone. The rift system is defined by dense swarms of dikes, which are well exposed along the windward (northeast) side of the Koolau Range, and by magnetic and gravity anomalies (Malahoff and Woollard, 1965; Strange, Machesky, and Woollard, 1965). A secondary rift zone apparently trends to the southeast, and another rift system is indicated by south-southwest trending dikes on the southern flank of the mountain range.

The approximate boundaries of the Koolau summit caldera are known, and described by Macdonald and Abbott (1970). Caldera-filling rocks, strongly altered by hot water and volcanic gases, are still exposed in remnant hills and peaks between the main mountain range and Oahu's northeast shoreline. Various geophysical studies have identified a dense mass, believed to be the former Koolau magma chamber, at 1.5 to 2 km beneath the surface (Thomas, et al., 1979).

Rocks from the Koolau Volcanic Series have been found by potassium-argon dating to range between 2.2 and 2.6 million years old (Macdonald and Abbott, 1970). More than two million years of quiescence followed the primary Koolau activity, allowing extensive erosion to occur. During this time the spectacular line of cliffs on windward Oahu was formed, principally by stream erosion. Large stream-cut valleys developed as well, and accumulated thick alluvial deposits.

Less than one million years ago volcanism resumed and continued intermittently until about 30,000 years ago (Thomas, et al., 1979). The resulting assortment of tuff and cinder cones, as well as lava flows, constitutes the post-erosional Honolulu Volcanic Series. Scattered throughout southeastern Oahu, rocks of this series include nephelinites, basanites, and alkalic olivine basalts, all silica poor and Mg-Fe rich. Many of the prominent landmarks of south-eastern Oahu, including Diamond Head, Hanauma Bay, Tantalus, and Rabbit Island, are products of this late period of volcanism. The length of time since Oahu's last activity is geologically short, and additional eruptions may be possible.

Some important non-volcanic events took place during Oahu's geologic history. Numerous sea level changes occurred before and throughout the Pleistocene (Stearns, 1966) and, in conjunction with local tectonic events (mainly subsidence) these changes influenced erosional and depositional processes as well as coral reff development. The emerged reef that underlies much of southern Oahu represents a higher stand of the sea. This limestone border has important effects on the Island's hydrology, as discussed in a later section of this report.

KAUAI

Northernmost of the major islands, Kauai (max. el. 1548 m) is also the oldest. The single large shield volcano that formed this island has been extensively dissected and modified by erosion, collapse, and faulting.

The original shield volcano of Kauai was built between 5.6 and 3.3 million years ago (Thomas, et al., 1979) by lavas of the Waimea Canyon Volcanic Series. Figure 6 illustrates the general geology of Kauai. Tholeiitic basalt, olivine basalt, and oceanite lavas constitute the main mass of the shield and are known as the Napali Formation. These lavas were apparently erupted from many vents on the flank of the volcano, as shown by the dikes which radiate from the summit in all directions. However, a west-southwest trending rift zone is evident from a concentration of dikes and from aeromagnetic and gravity surveys (Malahoff and Woollard, 1965; Krivoy, et al., 1965). Other rift zones are not as well developed. Although another set of dikes suggest a northeastward-trending rift system, geophysical studies do not reveal any particular anomalies in that area and indicate rather an east-southeast rift (Thomas, et al., 1979).

In addition to a large central caldera (16 to 20 km in diameter), the Kauai Shield developed some secondary collapse features, including

Figure 45 Surface geology of Kauai.

KAUAI

PLEISTOCENE

PLIOCENE

Nepheline basalt, olivine basalt, and basanite — KOLOA VOLCANIC SERIES

Olivine basalt, picrite basalt, basalt, basaltic andesite — MAKAWELI FORMATION, OLOKELE FORMATION, HAUPU FORMATION

Olivine basalt, picrite basalt, basalt — NAPALI FORMATION

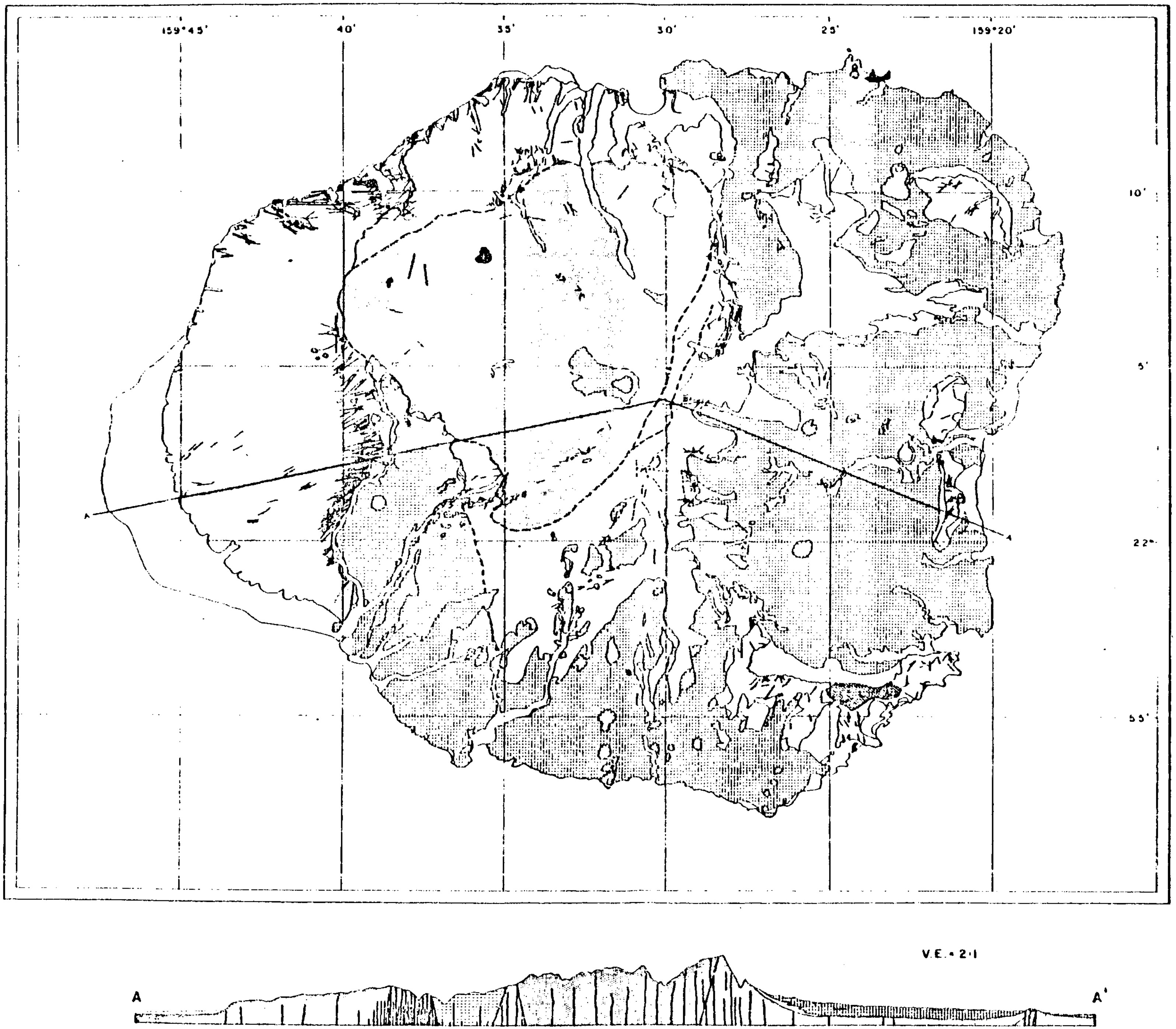
WAIMEA CANYON VOLCANIC SERIES

BOSS

VENT

CONE

DIKE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V.E. = 2:1

two flank calderas and a wide graben. The main caldera was filled by thick layers of tholeiitic basalt grading upwards into alkalic olivine basalt and hawaiite (the Olokele Formation). A smaller caldera, the Haupu cladera, developed on the southeastern flank of the volcano and filled with lavas of the Haupu Formation. These rocks were more resistant to erosion than the surrounding shield lavas and presently stand out as topographic highs.

On the southern flank of the volcano, the fault-bounded Makaweli Graben collapsed at about the same time as the Haupu caldera. Lavas of the Makaweli Formation are essentially the same as those in the Olokele Formation, since tha graben evidently was filled by overflowing caldera lavas. Within the graben, however, lavas are interbedded with cinder and ash as well as stream-deposited conglomerate and talus breccia.

The Lihue Basin is another collapse feature on the southeastern flank of the shield volcano. It is presently exposed as a nearly circular depression, containing lavas from a later stage of volcanic activity.

After its initial shield building phase, the Kauai Volcano remained inactive for over 1.5 million years (Macdonald and Abbott, 1970). Volcanism resumed after this erosional period, with widespread eruptions of the Koloa Volcanic Series. Composed of alkalic olivine basalt, basanite, and nephelinite, the Koloa lavas erupted from scattered vents to form spatter and cinder cones and extensive lava flows. Like the Honolulu Series volcanics on Oahu, Koloa eruptions were intermittent, but they occurred over hundreds of thousands of years. Koloa lavas filled the Lihue Basin as well as many of the valleys on the island.

Sedimentary deposits are abundant on Kauai and include calcareous beach and dune sand, lagoon marls, and alluvium. Soil development is well advanced.

Additional References:

Macdonald, Davis, and Cox, 1960; Macdonald and Kyselka, 1967; Stearns, 1939; 1946; Stearns and Macdonald, 1942; 1946.

GEOHYDROLOGY OF THE HAWAIIAN ISLANDS

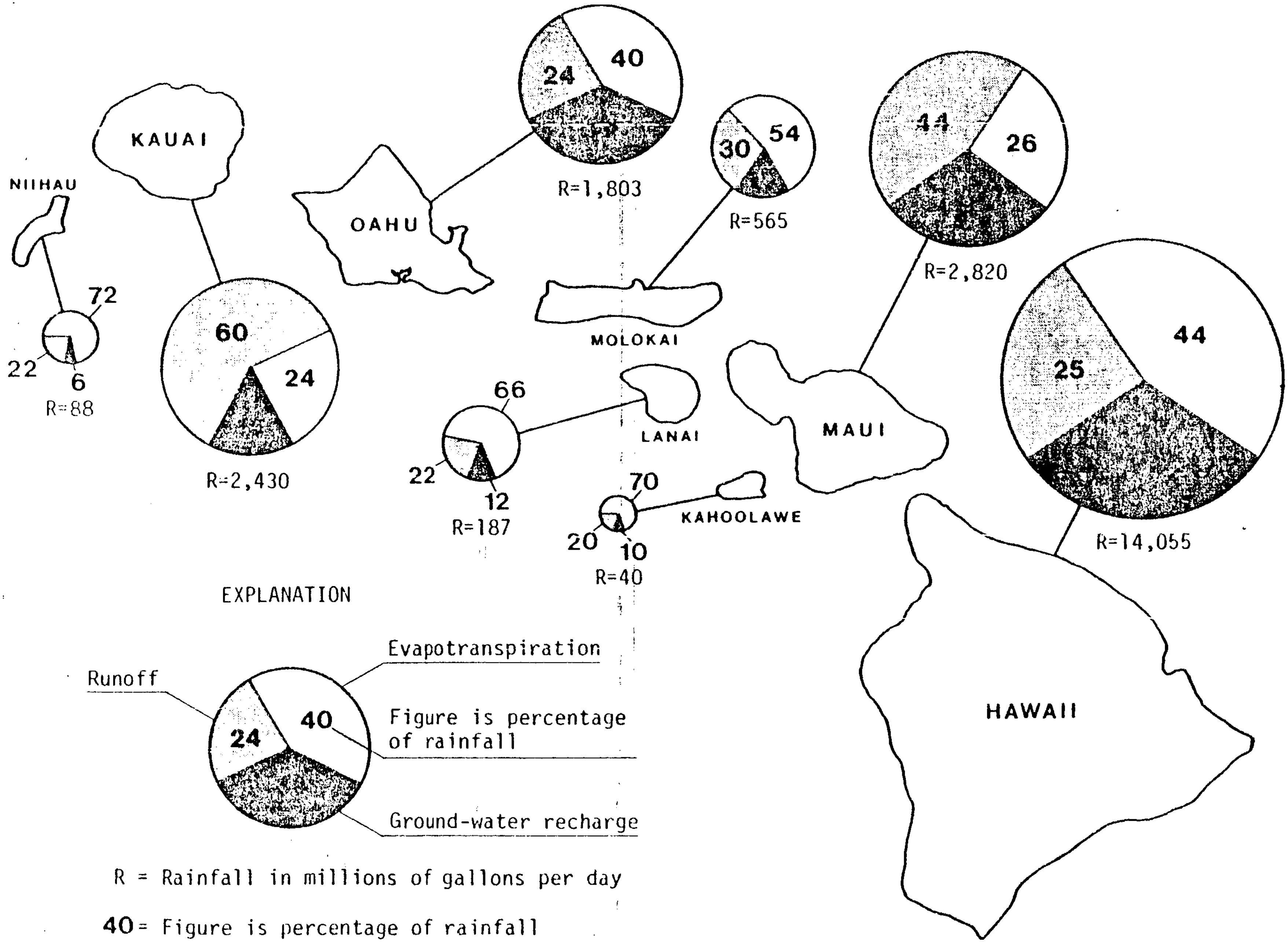
Geothermal development in Hawaii is likely to focus on hot water/steam resources. Therefore, the availability of a geothermal resource in the State is dependent on suitable hydrologic conditions. Conversely, the quality of hydrologic systems may be affected by geothermal development, which makes it necessary to consider the general hydrology of the islands in the Overview Report. Review of Hawaiian hydrology and numerous references on specific localities may be found in the publications by Takasaki (1978) and Thomas, et al. (1979).

Groundwater in Hawaii, the carrier of geothermal energy, is derived primarily from rainfall. Much of the precipitation in the islands results from orographic lifting of moist air masses. Because northeasterly trade winds dominate through most of the year, the islands tend to experience higher mean annual rainfall on their northeastern (windward) sides, although local deviations are common. The trade winds are confined to a layer between sea level and about 2000 meters, which means that the taller mountains (Haleakala, Mauna Loa, Mauna Kea) rise above the trades and develop their own wind and weather patterns. In general, mean annual rainfall in the islands ranges from less than 35 inches (890 mm) in dry, leeward areas to over 100 inches (2530 mm) in some mountainous locations.

Rainfall is "consumed" by processes of evapotranspiration, surface runoff, and groundwater recharge. The proportions of rainfall used in each of these processes are illustrated in Figure 7. Permanent Hawaiian streams are best developed in areas with abundant year-round rainfall, as in interior mountain regions. Elsewhere, many streams are ephemeral and, because of the highly permeable nature of the volcanic rocks in Hawaii, overland flow is possible only during heavy storms.

Rainwater infiltrates through a variety of natural pathways, a major one being the spaces between aa clinkers, which develop on the surface of many Hawaiian lava flows. Lava tubes, fractures, and intragranular spaces in sediments provide other conduits for the migration of groundwaters. Seawater infiltrates laterally to saturate the rocks at the base of an island. This saturated zone acts as a lower barrier to ground water movement and causes the fresh water to float on top of it in a lens-shaped body, the Ghyben-Herzberg Lens, which is typical of oceanic islands. Generally, the upper surface of the lens (known as the basal water table) slopes towards the sea, i.e., rises inland, at the rate of a few feet per mile. The water table slopes less in highly permeable rocks than in tight formations, and dry areas have less sloped water tables than regions with high rainfall.

The bottom part of the fresh water lens (basal water) tends to migrate outwards towards the edges of an island where, if the flow is unobstructed, it may "escape" in so-called basal springs. However, this seaward flow may be blocked by dikes, or by impermeable sedimentary deposits on the seaward slopes of older islands. Dike impoundment is common in rift zones and caldera regions. Groundwaters in such areas tend to "pile up" on the upslope side of a dike barrier, creating a locally elevated water table, and a locally depressed water table downslope of the dike.



R = Rainfall in millions of gallons per day

40 = Figure is percentage of rainfall

Note: Map of islands not drawn to scale nor in proper position (for pictorial presentation only).

Distribution of rainfall by islands.

Groundwaters may also be held by impermeable layers of soil or sediment near the surface, or they can become "perched" on ash beds at depth.

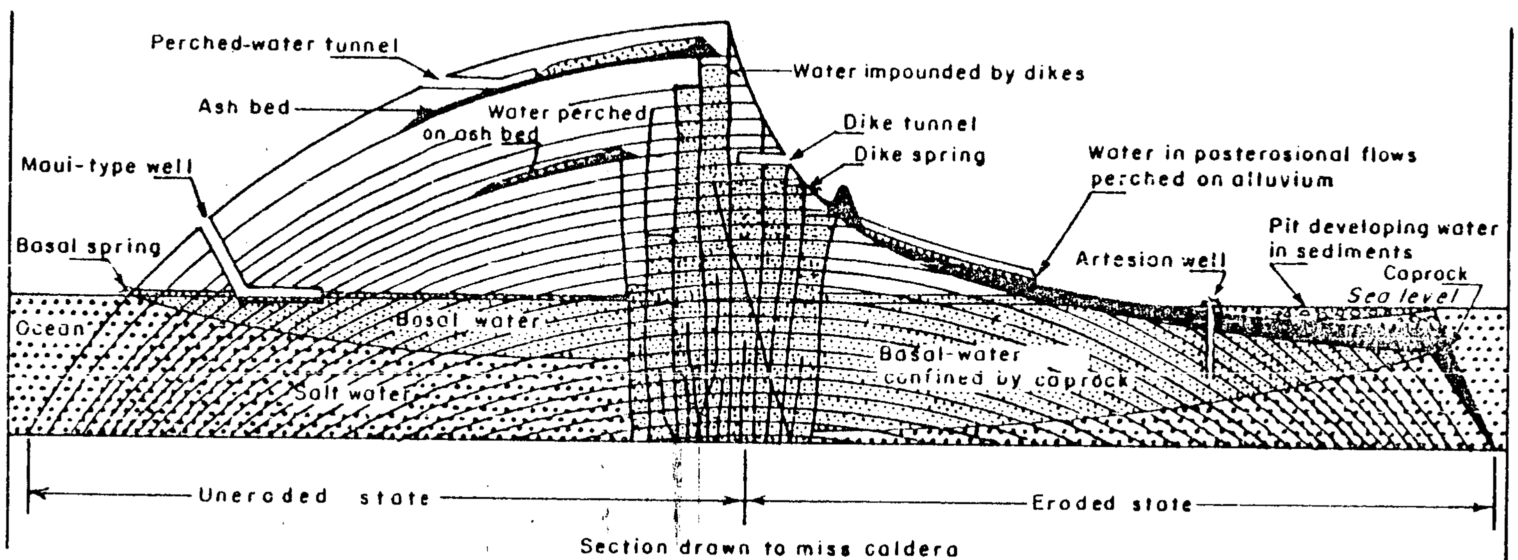
The various types of Hawaiian groundwater systems are illustrated in Figure 8.

REGIONAL HYDROLOGY OF THE MAJOR ISLANDS

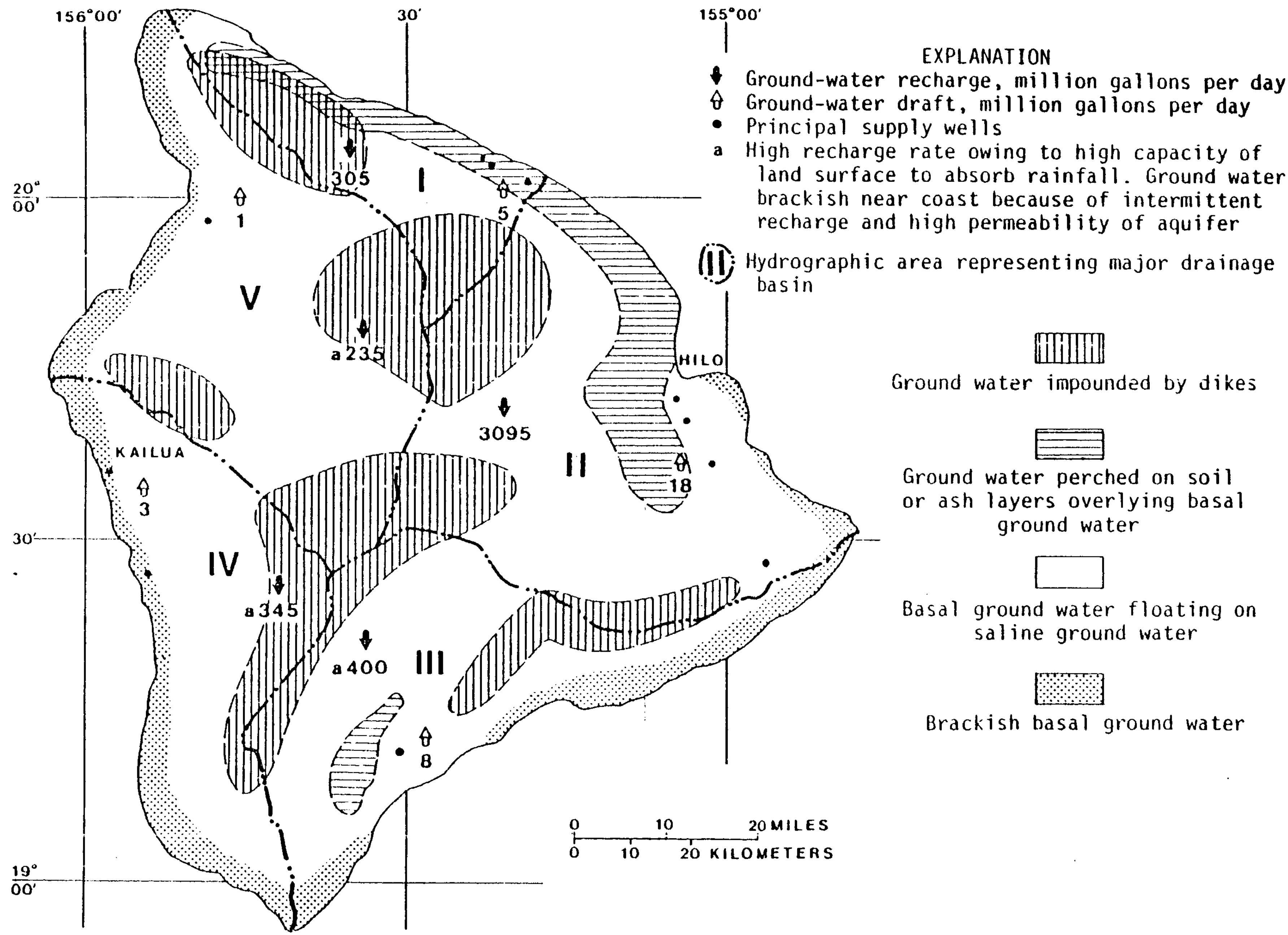
HAWAII (Figure 9)

The Island of Hawaii, with its five different volcanic systems, has a variety of hydrologic conditions which are influenced by local meteorology and geology. Although the Ghyben-Herzberg lens model is generally applicable to this island, it is complicated by these local factors. Hydrologic investigations have been concentrated in the more developed, culturally active regions, where most wells (primary sources of information) are located. Little is known about conditions in the sparsely inhabited and/or inaccessible regions of the island, such as South Point and Ka'u, both on the rugged southern coast.

The youngest volcanic mountain, Kilauea, has minimal soil cover and few interlayered ash beds. Therefore, rainwater can percolate rapidly into the ground. There are no permanent surface streams. Basal springs discharging along the coast are usually brackish or saline due to tidal mixing. Many water wells near the coast also contain brackish water, and during periods of heavy water usage, saline waters migrate further inland. Warm water occurs in some wells in Puna, and has also been detected in some coastal springs by infrared surveys (Fischer, et al., 1966). In some warm water wells on Kilauea, warm brackish water has been



Occurrence and development of ground water in an idealized Hawaiian volcanic dome (from Cox, 1954).



Map of island of Hawaii showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Modified from Davis and Yamanaga, 1973.)

encountered on top of colder fresh water, a condition known as a thermal density inversion.

Mauna Loa also lacks significant soil cover and, consequently, has negligible surface discharge. Some groundwater reserves of Mauna Loa are perched on impermeable ash and tuff beds on the upper flanks of the mountain. This water is withdrawn through roughly horizontal tunnels on the southeastern slope. Some dike impounded water may also be present. Along the coastal rim of Mauna Loa, cold brackish water is discharged by many basal springs. Although temperatures of the springs reflect an inland source at high elevation, tidal mixing has resulted in their brackish properties. Disruption of the Ghyben-Herzberg Lens by thermal activity may also contribute to the salinity of near-shore springs and wells.

Mauna Kea has relatively abundant groundwater reserves due to a combination of high rainfall (especially on the windward slopes) and deep soil and ash cover on the surface as well as at depth (interlayered with older lavas). Although there are only a few perennial streams on Mauna Kea, many intermittent springs issue at intermediate and high levels on the mountain, and large quantities of basal water are obtained from near-shore wells and tunnels on the lower slopes.

Hualalai, and the leeward slope of Mauna Kea, receive little rainfall and have sparse soil cover, resulting in a near absence of shallow groundwater. A deep source of fresh water was recently discovered by drilling upslope of the North Rift of Hualalai. Presumably, this water (which is fresh down to about 1000 m below sea level) is impounded by dikes in the rift area (Thomas, et al., 19 79). Downslope of the rift, the water table is depressed, resulting in minimal groundwater reserves in the coastal areas. The springs and wells that do exist contain primarily brackish water.

Kohala Mountain has undergone a considerably longer period of weathering and erosion than the other, younger mountains on the island. As a result, the dike systems of the Kohala shield have been exposed and dissected, allowing dike-impounded waters to escape. Fresh water leaking from the "breached" dikes, recharged by moderately high rainfall in the region, provides a year-round water resource on Kohala. Only a thin, generally brackish basal water lens exists in the region, however.

The hydrology of Hawaii Island is illustrated in Fugure 9.

MAUI (Figure 10)

The windward slopes of West Maui recieve the majority fo the rainfall in this part of the island. Dike impounded waters at high elevations feed several perennial streams on the windward side. In contrast, the drier leeward slopes support few permanent streams. A relatively thin lens of basal water provides a fresh water source in near-shore areas of West Maui, although some saltwater intrusion affects the quality of this resource when groundwater withdrawal is excessive.

Haleakala is underlain by a basal fresh water lens which is tapped in near-shore areas by means of inclined shafts. At higher levels, fresh water is retained on interlayered ash beds. On rainy windward slopes of Haleakala, erosion has exposed these perched aquifers, allowing them to provide water to numerous perennial streams.

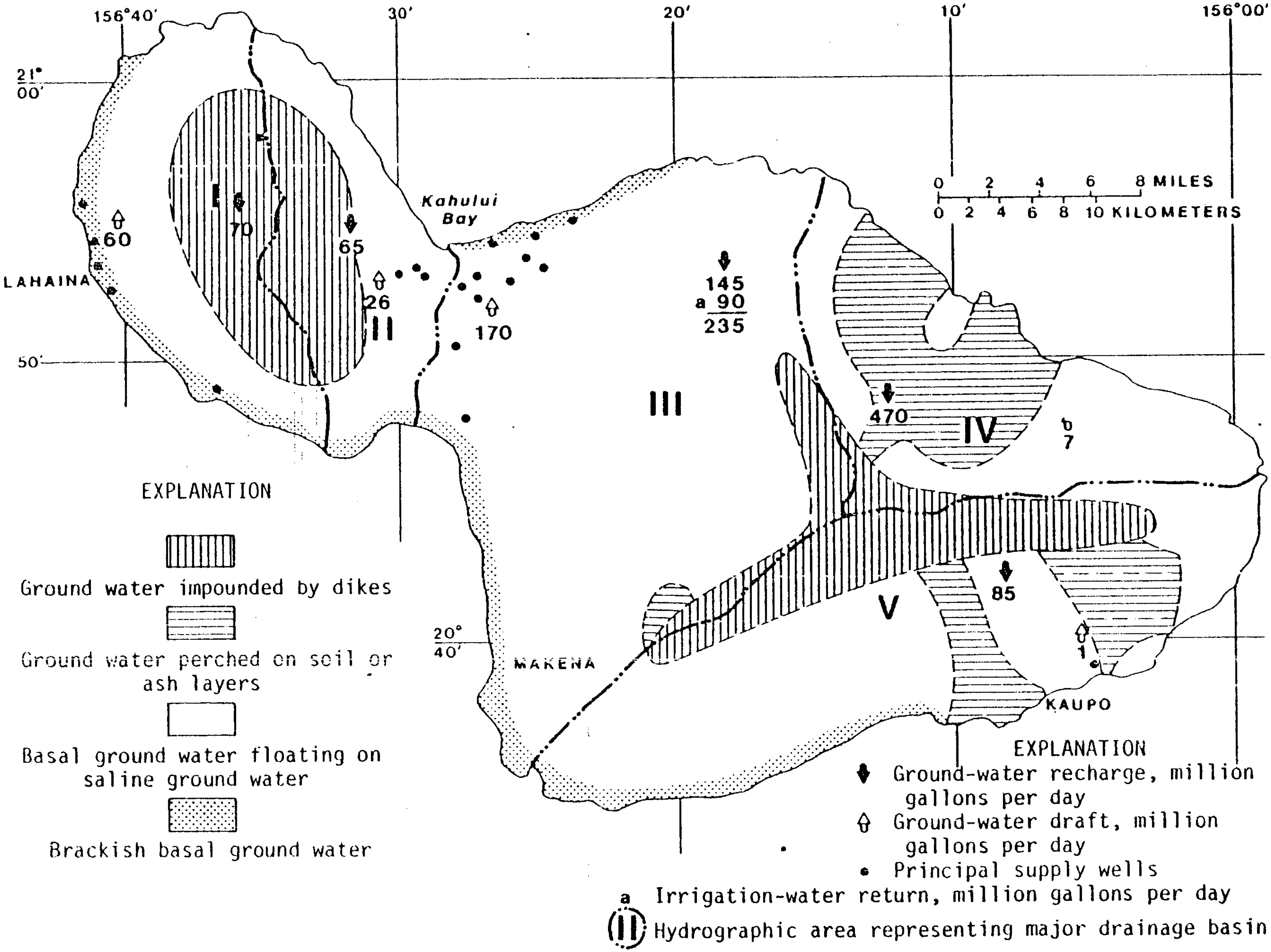


FIGURE 10.—Map of island of Maui showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Modified from Stearns and Macdonald, 1942.)

MOLOKAI (Figure 11)

Most of the precipitation on Molokai falls on the windward and higher sections of East Molokai, where a thick basal water lens supplies substantial quantities of fresh water for public use. High level reserves also exist on dense layers of alkalic lavas.

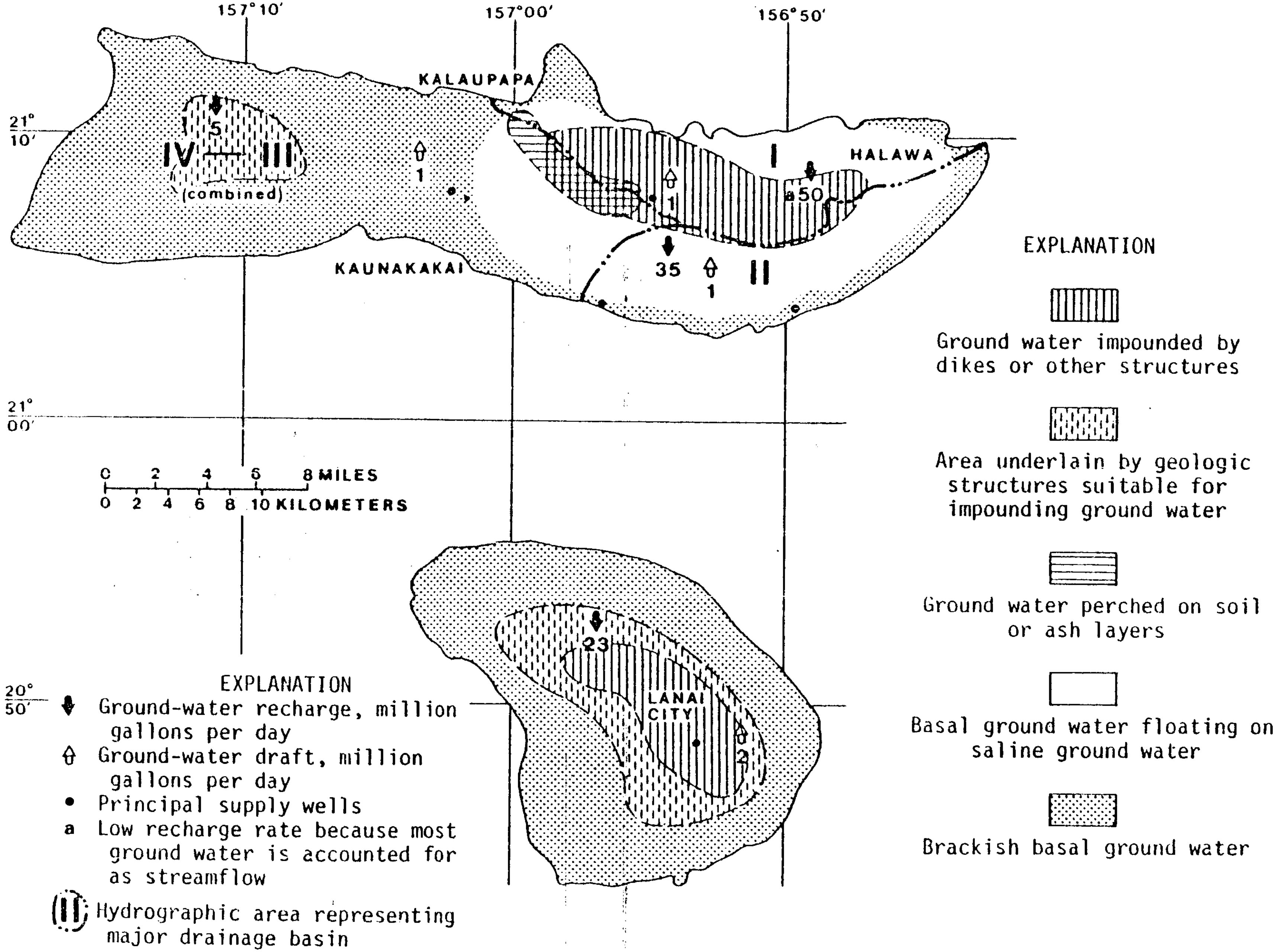
In contrast, West Molokai receives insufficient rainfall to maintain a fresh water basal lens, perennial streams, or springs, and no dike-impounded water bodies are known despite the presence of a well-developed dike system in the central part of West Molokai.

OAHU (Figure 12)

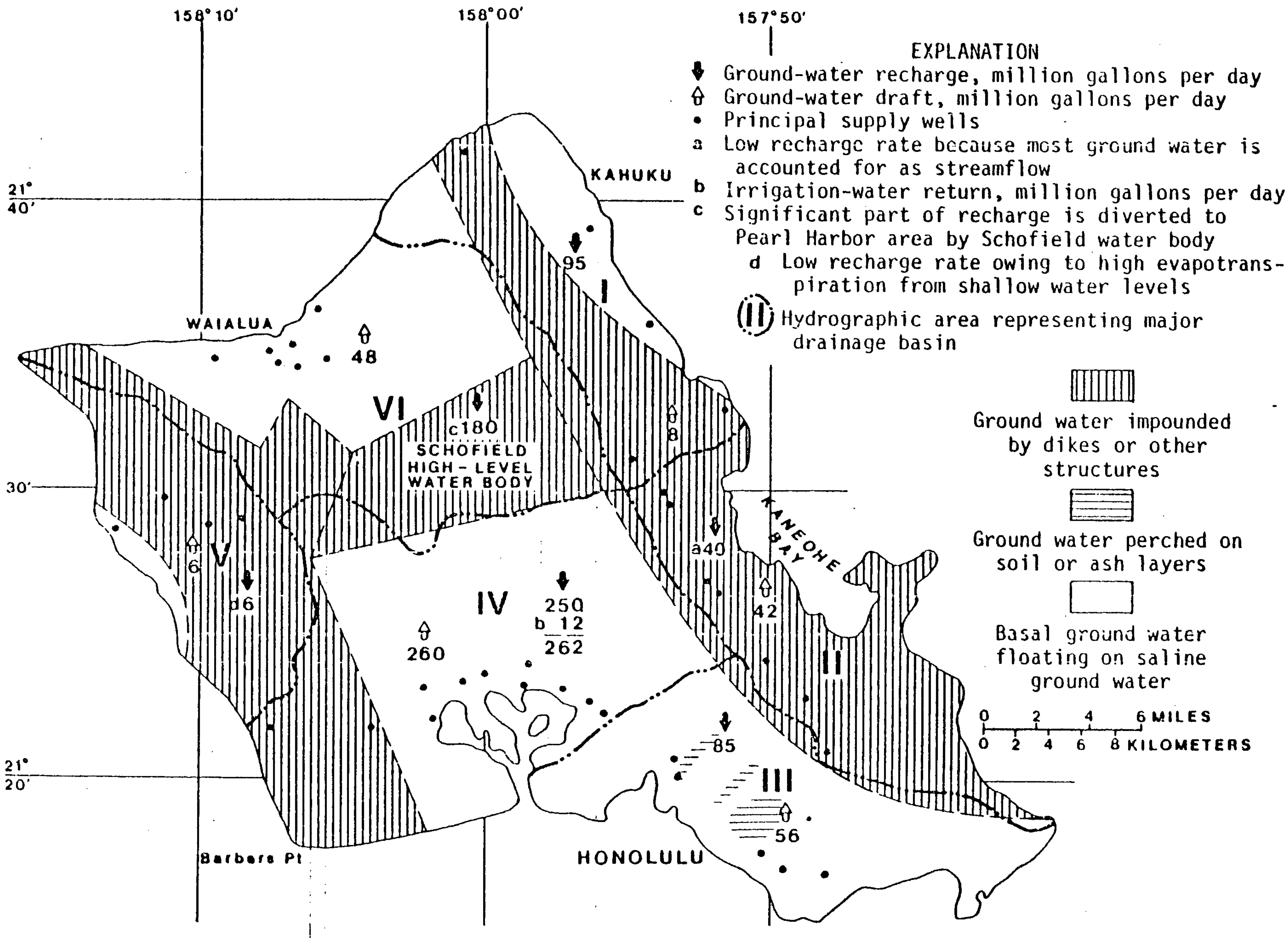
The hydrology of Oahu is unique among the Hawaiian Islands because of the existence of the impermeable layer of limestone around the perimeter of the island. As discussed previously in the section on regional geology, this limestone is the result of a period of multiple sea level changes, during which many layers of fringing coral reefs formed around Oahu (and subsequently silted over). Basal groundwater beneath Oahu is unable to escape in coastal springs due to the limestone barrier. Therefore, the basal water lens is unusually thick, and water tables are elevated. Additional fresh water reserves are impounded by high rainfall in the Koolaus, many permanent dike-fed springs issue from higher elevations of this mountain range, whereas only intermittent spring discharge occurs in the drier Waianaes.

KAUAI (Figure 13)

Abundant fresh groundwater supplies are present beneath Kauai in the extensive basal lens, as well as in dike-impounded and ash bed-perched reservoirs at higher elevations. These high level



Map of islands of Molokai and Lanai showing ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins. (Molokai: modified from Stearns and Macdonald, 1947; Lanai: from S.P. Bowles, unpublished data, in 1973.)

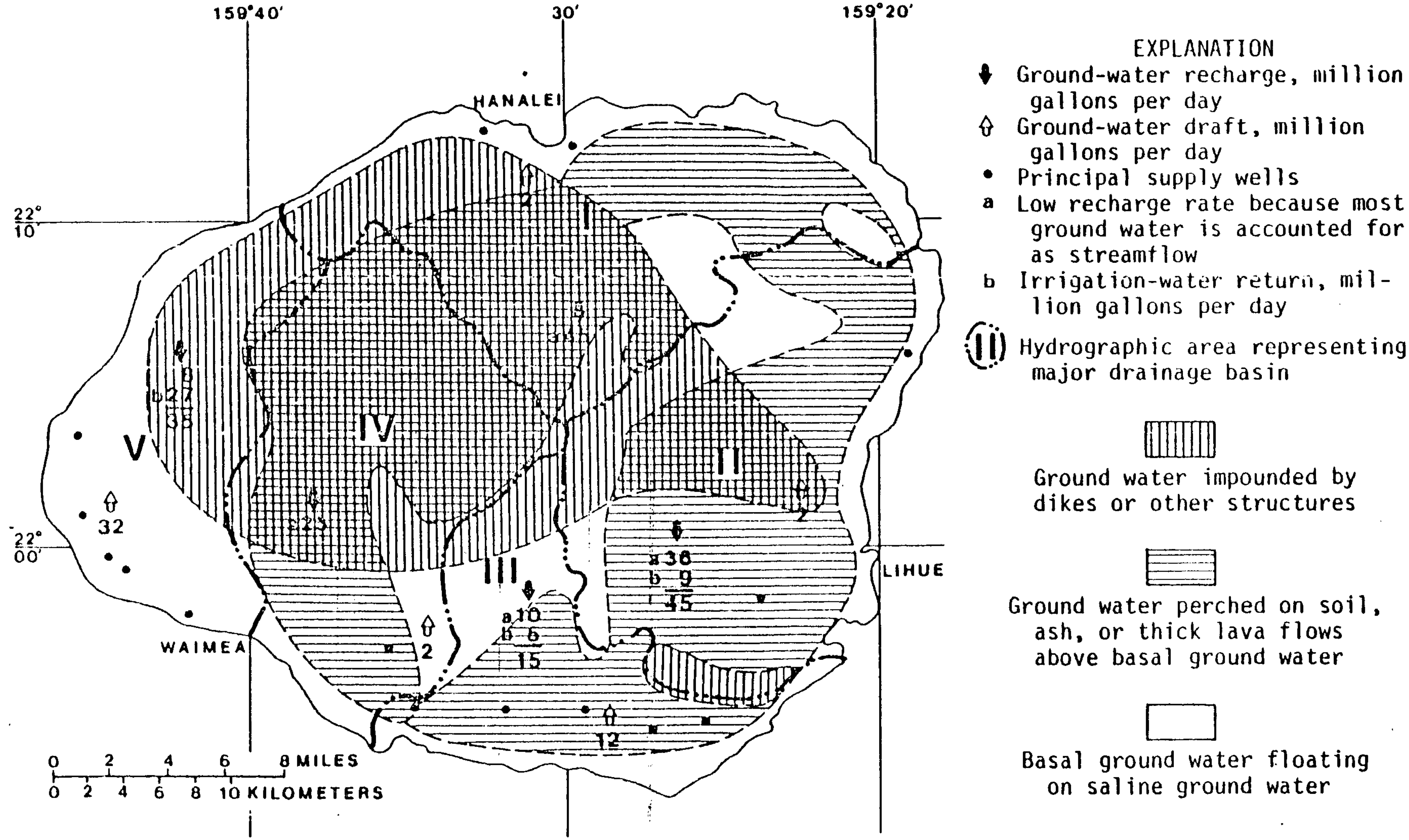


Map of island of Oahu showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins.

sources feed numerous springs and support many perennial streams on Kauai, particularly on the northeastern (windward) side of the island.

Additional References:

Palmer, 1967; Macdonald, Davis, and Cox, 1960; Stearns and Macdonald, 1942; 1946; 1947; Stearns and Vaksvik, 1935; Wentworth, 1951.



Map of island of Kauai showing approximate outline of ground-water reservoirs, recharge, 1975 draft, and principal supply wells by hydrographic areas representing major drainage basins.

HAWAII'S GEOTHERMAL RESOURCES

Introduction:

All of the world's developed geothermal resources have the same essential properties:

- A source of heat, either hot rock or magma.
- A carrier (groundwater) that is heated by the thermal source.
- A "cap" of relatively impermeable rock that holds the hot water in place and forms a reservoir. (This reservoir must be at a depth that is accessible and economical with present drilling techniques).

The combination of all three conditions is rare in the world. The first requirement, a source of heat, generally limits geothermal areas to certain tectonic provinces of the world where the earth's heat is relatively close to the surface. Subduction zones, where one lithosperic plate slides beneath another, are marked by belts of volcanic activity produced by the melting of rocks in the overridden plate. The geothermal areas of Japan, New Zealand, Indonesia, the Philippines, Chile and Ecuador are in regions of this type. Spreading zones, where fluid mantle material rises into extensive crustal rifts and solidifies to form new crust, are also provinces with enhanced thermal properties. Examples of spreading-zone geothermal areas are Iceland (which is directly astride the Mid-Atlantic Rift), and Mexico, California, and Nevada (presumably above the East Pacific Rise, where is has been overridden by the North American Plate).

Hawaii's volcanoes are situated neither in a subduction zone nor a spreading zone. Mid-plate volcanism is unusual, and Hawaii's potential geothermal resource is unique in its tectonic setting.

The groundwater supplies in the Islands have been described in another section of this report. While some research on direct use of hot rock or magma (without a groundwater carrier) is in progress, economical exploitation of such a resource is unlikely in the foreseeable future. Even at Kilauea, where molten pools of lava may accumulate at the very surface, the rate of cooling and solidification of the lava is too rapid for exploitation. The thickness of the surface "crust" on such lava lakes has been found to increase exponentially with time (Peck, 1974).

Hawaii's basaltic rocks are generally rather permeable; however, relatively impermeable layers of weathered ash, hydrothermally altered basalt, dense dikes, and limited amounts of sedimentary rock serve as "caprock" for groundwater aquifers. Structural traps such as faults may also occur. While the effectiveness of these barriers in retaining hot, possibly pressurized geothermal fluids may be somewhat less than their ability to restrain cool meteoric waters, caprock does indeed exist in Hawaii; thus all the requirements for a geothermal resource is met.

Hawaii has the fundamental necessities of a geothermal area, but only one actual site of proven capacity (the HGP-A well) has been located to date. The events leading to the identification of this reservoir, and the selection of the actual drill site, are described by Furumoto et al. (1977).

Geology of the Hawaii Geothermal Well, HGP-A

The Hawaii Geothermal Project's successful well, HGP-A, is located on the lower East Rift of Kilauea volcano. From the surface (at about 600 ft. elevation) to approximately 1700 feet downhole, the well was drilled into basaltic rocks similar to the thinly bedded aa and pahoehoe flows found on the surface. Below 1700 feet, the rocks encountered were evidently pillow basalts (formed during the mountain's submarine phase of growth) that have been highly fractured, with fractures locally filled by secondary minerals. From 4200 feet to the bottom of the well at 6450 feet (5850 ft. below sea level) the pillow basalts are intensely altered, with considerable amounts of actinolite, chlorite, and pyrite.

Microearthquakes are frequently detected in the vicinity of the well, with hypocenters concentrated in a zone between 3000 and 10,000 feet below the surface. The depth at which this microseismic activity ensues appears to coincide with the start of a sharp thermal gradient in the well itself. This has led to the suggestion that microearthquakes are related to the geothermal fluids (Helsley, 1977) much as earthquake swarms elsewhere on Kilauea are related to the presence of moving magma. The areal distribution of this earthquake zone may help define the boundaries of the reservoir.

Other Potential Geothermal Areas

The ongoing Hawaii Geothermal Resource Assessment Program at the Hawaii Institute of Geophysics is an effort to identify other potential sources of geothermal energy in the islands. The two reports released so far (Thomas et al., 1979; Cox et al., 1979) are probably the best available sources of information on possible geothermal areas in the State. Only a brief summary of these reports is attempted here.

The resource assessment program has been largely concerned with compiling existing data on groundwater geochemistry, geology, and geophysical properties of the Hawaiian Islands. Areas having geothermal properties of the Hawaiian Islands. Areas having geothermal potential were identified on the basis of the following criteria (Thomas et al., 1979):

(1) Surface geology: Young, recently active volcanoes are obvious targets for geothermal exploration. Older volcanoes may still bear residual head deep within magma chambers. Identification of rift zones and caldera complexes by surface mapping would assist in locating these magma chambers.

(2) Infrared studies: Although coverage is presently limited to the Island of Hawaii (Fischer et al., 1964; 1966; Abbott, 1974) infrared imagery can reveal

above-ambient ground temperatures and warm spring discharges into near-shore ocean waters. This information is especially useful in exploring remote, inaccessible areas.

(3) Geophysics:

(a) Seismicity studies. Both active and passive seismic studies provide potentially useful information about possible geothermal resources. Refraction studies on Oahu (Adams and Furumoto, 1965) have been used to locate the ancient magma chamber beneath the Koolaus. Passive earthquake monitoring may reveal subsurface activity caused by movement of fluids at depth, although the only extensive monitoring of this sort has taken.place on the Island of Hawaii (see Hawaii Volcano Observatory reports).

(b) Magnetic and gravity surveys. Information from aeromagnetic and gravity studies has been used to locate buried rift-zones and calderas which, again, are the areas most likely to have residual heat in older volcanic systems.

(4) Groundwater temperature: Above-ambient temperatures in wells and other near-surface water sources may by strong evidence of geothermal resources in the

area, although other factors may be responsible for local temperature variations. Moreover, available well-temperature data are not always reliable.

(5) Groundwater geochemistry: Reactions that occur between rock and groundwater at elevated temperatures can result in anomalous chemical properties in near-surface waters. A number of chemical parameters are used to identify possible thermal sources:

(a) Elevated silica (SiO_2) concentration in groundwater can be produced by the leaching of silica from rocks, which is a temperature-dependent reaction. High silica concentration have been found in numerous Hawaiian groundwater samples, but many of these anomalies reflect cultural/agricultural activities rather than thermal effects.

(b) Ratios of certain elements, such as Na-K-Ca and Cl-Mg, are also influenced by thermally enchanced water-rock interactions. The Na-K-Ca "geothermometer" has been found to be of little use in Hawaii because of the large amounts of these elements brought into the system by seawater intrusion (McMurtry, Fan, and Coplen, 1977). The Cl/Mg relationship is a better geothermal

> indicator in Hawaii. At elevated temperatures, magnesium is lost from groundwaters by reaction with clay minerals. Chloride ion concentration is increased by the incorporation of magmatic volatiles. The Cl/Mg ratio can be used to distinguish between thermally altered water and fresh water that has simply intermixed with seawater.

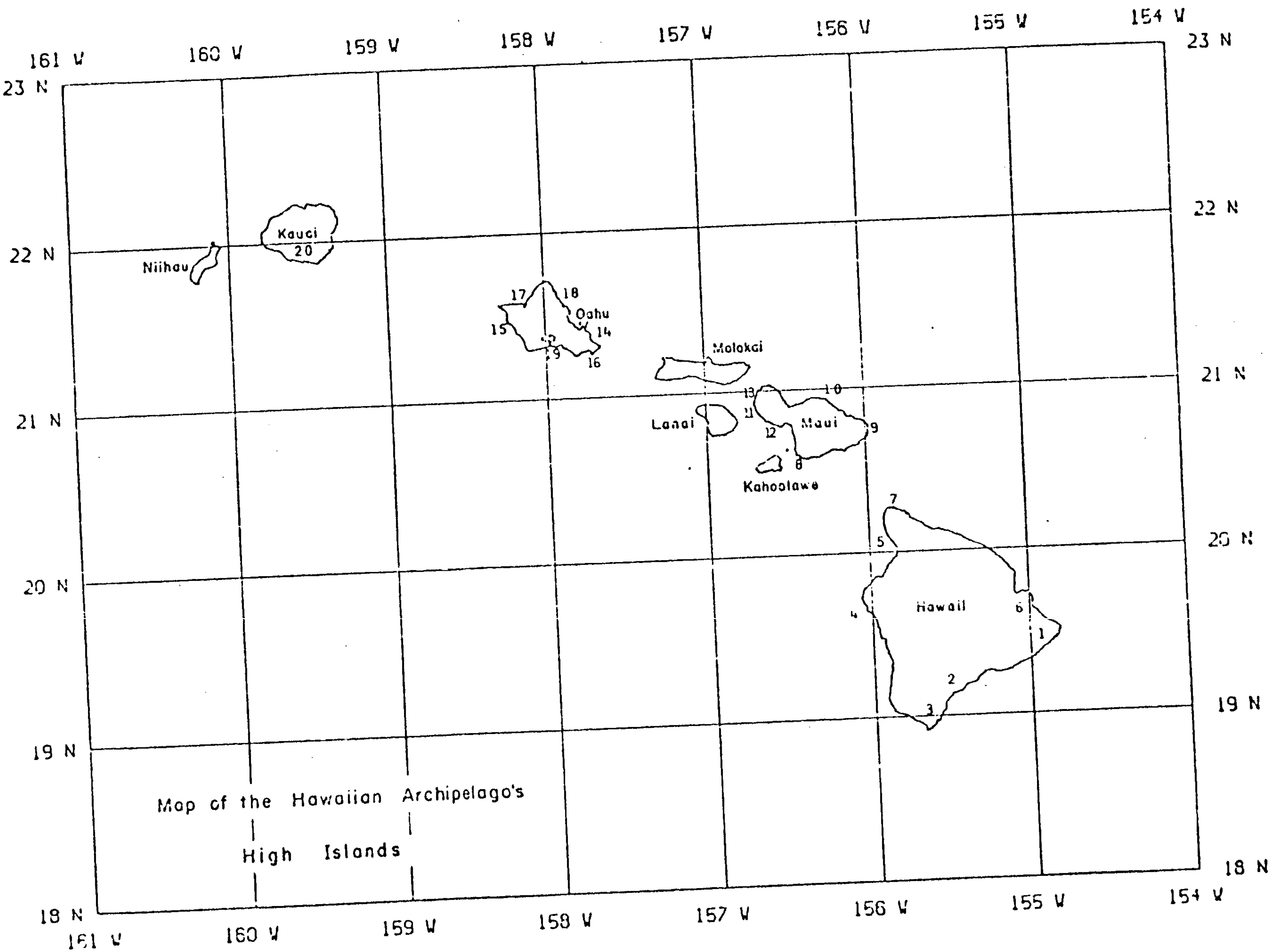
While no single property can be used to pinpoint a drilling site, the presence of multiple anomalies in an area indicates unusual conditions that may warrant further investigation.

On the basis of the above criteria, several anomalous and interesting areas have been identified in Hawaii. Summarized in Table I, these areas have been ranked according to their likelihood of having a resource as well as the probability that development of the resource would take place in the near future. The likelihood of development is assessed on the basis of the state of drilling and development technology, existence of a market for the energy produced, and the availability of the land in question. Areas ranked "10" have the lowest. Figure 14 shows the approximate locations of these areas. Only one, Lualualei Valley in the Waianae Range of Oahu, has actually been explored to date.

TABLE 1

Ranking is on a scale of 1 to 10: 1 having the highest potential, 10 the lowest. Although other areas in the state undoubtedly have thermal resources, their probability for development in the near future (1980-2000) is so small as to not justify their inclusion in the present assessment.

Location	High Temp. Resource	Low Temp. Resource	Probability for Development
Hawaii			
1. Puna	1	1	3
2. Ka'u	2	1	7
3. South Point	3	2	3
4. Hualalai - North Kona	5	3	1
5. Kawaihae	5	3	1
6. Keaau	6	4	1
7. Kohala	7	5	8
Maui			
8. Haleakala - Southwest Rift	3	2	5
9. Haleakala - East Rift	3	2	6
10. Pauwela	4	3	3
11. Lahaina	3	1	1
12. Olowalu - Ukumehame	3	1	2
13. Honokawai	5	4	2
Oahu			
14. Waimanalo	7	5	1
15. Lualualei	8	6	1
16. Honolulu Volcanic Series	8	7	2
17. Haleiwa	9	7	3
18. Laie	9	7	3
19. Pearl Harbor	10	9	1
Kauai			
20. Post erosional Volcanic Series	10	8	5


Map of the Hawaiian Archipelago's High Islands
161 W
160 W
159 W
158 W
157 W
156 W
155 W
154 W
23 N
22 N
21 N
20 N
19 N
18 N
Niihau
Kauai
20
Oahu
17
18
15
14
16
Molokai
Lanai
Maui
13
10
11
12
9
8
Kahoolawe
Hawaii
7
5
4
6
1
2
3

POTENTIAL GEOLOGICAL/HYDROLOGICAL PROBLEMS ASSOCIATED WITH GEOTHERMAL DEVELOPMENT

During the course of interviews, workshops, and other Overview activities, the following key geologic/hydrologic issues were identified.

- Increased seismicity due to geothermal activity
- Subsidence
  - (a) due to removal of geothermal fluids
  - (b) due to collapse of lava tubes
- Changes in eruptive character of volcanoes
  - (a) increase in frequency and/or magnitude of eruptions
  - (b) decrease in frequency and/or magnitude
- Accidents--malfunctions of geothermal facility due to earthquakes or lava flows
- Groundwater contamination by geothermal effluents (spent fluids)
- Effects of lava tubes and other subsurface pathways on the movement of effluents during percolation or reinjection of wastes.

While some of these problems have been encountered in other geothermal areas, <u>many are particularly "Hawaiian" concerns due to the unusual geological and hydrological conditions in this island environment</u>. Most of the questions raised were addressed to the existing geothermal well in Puna (HGP-A) which is likely to be the "proving ground" for geothermal development in the State. The same physical conditions that make Puna an area of good geothermal potential also make this area unusual in its natural geological, geophysical, and geochemical properties. Seismicity, ground deformation, volcanic eruptions—all are common occurences in the vicinity of the well, and the additional effects caused by the geothermal facility may be difficult to distinguish from the natural "state of geological affairs". However, future developments in other, less active regions in Hawaii may have a noticeable effect on the existing environment, and, therefore, these questions must be raised.

Discussion of Key Issues

(1) Increased seismicity. In the vicinity of some producing geothermal fields (notable the Geysers Field in Northern California) an increase in earthquake activity has been detected. However, the magnitude of these seismic events is so small that they are indetectable by humans and have caused no damage. Usually attributed to reinjection of spent geothermal fluids, microseismic activity at the Geysers may actually reflect readjestments of the earth as the geothermal reservoir cools (L. Anspaugh, 1979 Hilo Workshop).

At HGP-A, disposal of spent fluids will be effected by surface percolation rather than reinjection, so that enhanced seismicity due to forced injection of fluids will not be a factor. However, reinjection may become the practice if the Puna reservoir is developed into a large producing field with many wells.

The seismicity of the Puna area is well documented both before and after completion of the geothermal well. Both passive monitoring and seismic refraction profiling were carried out by the Hawaii Institute of Geophysics (Suyenaga et al., 1978) as part of the wellsite selection process. Other records are kept by the Hawaii Volcano Observatoary (see list of publications). While microearthquakes in the Kilauea region have usually been attributed to the movement of magma (or geothermal fluids) at depth, scientists at the Hawaiian Volcano Observatory have recently proposed that earthquake activity in the HGP-A region may be due to movement along a fault that crosses the lower east rift in this area (D. Jackson, 1979 Hilo Workshop). If this is the case, geothermal development may still have some effect on seismicity, perhaps by inducing fault movement.

Natural seismicity at other potential geothermal sites is relatively unknown, although a few limited studies have been performed in the Lualualei Valley of Oahu (see Cox et al., 1979). Prior to any serious exploration (i.e. drilling) in these other regions, microearthquake monitoring should be initiated.

(2) Subsidence. The problem of surface subsidence is pronounced in New Zealand, where more than three meters of subsidence has been measured in the Wairekei field. A smaller degree of sinking (on the order of a few centimeters) has occurred in California. Withdrawal of geothermal fluids can decrease the pore pressure in reservoir rocks, allowing weak or poorly consolidated formations to become compressed by the weight of overlying rocks. This

compaction at depth may be manifested by sinking and collapse of the ground surface above.

At HGP-A, the subsurface geology is known from drilled cores and has been described else where in hte present report. Of relevance to the subsidence question is the fact that below 1700 feet in the well, the rocks are dense pillow basalts. Flow tests to date have indicated that the producing depths in this well are near the bottom of the hole and at approximately 4300 feet (Yuen et al., 1978), well within the pillow basalt layer. Moreover, the producing formation has been classified as "tight", and porosity of the rocks at the bottom of the well ranges from 3 to 18 per cent (B. Chen, 1979 Hilo Workshop). It seems likely, therefore, that the rocks in the region of fluid withdrawal are self-supporting (not dependent upon pore fluids for compressive strength) and will not be very susceptible to collapse due to removal of pore waters.

Another mitigating factor is the abundant natural recharge of groundwaters in the Puna District. More than 100 inches of rain falls per year in the area, and the rate of recharge is roughly 3000 gal/min/mi^2 (L.S. Lau, Water Resources Research Center, pers. comm.). Compared to this rate of recharge, the rate of fluid production by HGP-A is small (approximately 150 gallons per minute). Continual renewal of the deep reservoir should further minimize the effect of fluid withdrawal, although more wells and higher production in the Puna field may begin to change the balance.

Subsurface geological and structural features must be understood in any potential geothermal "field", so that the susceptibility to subsidence due to fluid withdrawal can be assessed. Rock cores, refraction profiling, and other geophysical techniques should provide this information at other geothermal sites.

Another type of subsidence that is of some concern is related to the collapse of lava tubes. Construction in Hawaii routinely involves the drilling of pilot holes to assure a solid base, partly because lava tubes are so common in the younger volcanic regions. Tubes are generally most abundant near the subsurface, as they are destroyed by pressure and time, and heavy construction equipment has been known to break through the roofs of tubes and fall down several feet. In drilling HGP-A, numerous cavities were encountered. The drill bit, after working through a section of very hard rock, frequently was observed to drop several feet, presumable upon encountering a lava tube (D. Thomas, 1979 Hilo Workshop). Further evidence of an extensive lava tube network beneath the well site was in the poor circulation of drilling mud. Enormous volumes of mud were lost in subsurface voids.

Although many people in Hawaii have informally explored lava tubes, the locations of these features are generally not documented and can only be obtained by talking to local people. Aside from the works of Howarth (1973), an entomologist specializing in cave-dwelling fauna, few scientific studies or mapping programs have been undertaken on lava tubes, and no extensive survey has been performed. A method of mapping subsurface tubes by electromagnetic techniques has been tested (von Seggern and Adams, 1967), but has evidently not gone beyond the experimental stage. This methods requires that one person be inside the tube with a transmitting device, while a second person traces the transmissions along the ground surface. It is, therefore, not useful in locating unknown tubes, or tracing those which have no accessible termini through which a person could enter them.

The presence of lava tubes beneath a wellsite would, or course, be an engineering concern, and would be recognized early in the drilling process. Puna residents have homes that sit atop lava tubes, and these people are concerned about possible microearthquakes or small degrees of subsidence that might collapse the tubes beneath their houses. Whether geothermal development could produce such earthquakes and ground deformation is an unanswered question, and, again, it would be difficult to distinguish geothermally-induced effects from naturally occurring phenomena in this active region.

Greeley et al., (1976) used aerial photographs to map the distribution of lava tubes on Mauna Loa volcano. Based on analysis of about 15% of the volcano surface, they found evidence of lava tubes and channels on at least 82% of the surface. Only collapsed or partly collapsed tubes can be recognized in the photographs. Similar photogeologic studies are in progress in other volcanic provinces and have been used in the study of the Moon and other planets.

Lava tubes are not as abundant on the older islands, and would be of less concern in geothermal development. However, their presence should be considered, especially in light of the absence of lava tube "maps" or surveys in the Hawaiian Islands.

(3) Changes in eruptive character of volcanoes. Many of the world's geothermal fields are located near or on active volcanoes. In Iceland, a large geothermal power plant operates within the very caldera of Krafla volcano, directly astride a fissure that has erupted in historic times. Iceland's location on the Mid-Atlantic Ridge, an active spreading center, makes it susceptible to continual episodes of rifting, volcanism, and intrusive events. Shortly after the Krafla facility went into operation, the volcano entered a new phase of activity marked by subsurface seismic events and intrusions as well as surface eruptions. One eruption actually took place through a geothermal well bore (T. Casadevall, 1979 Hilo Workshop). Although the cause and effect relationship is unclear and precedents are non-existent, many nearby residents believe that the geothermal development caused the renewed activity of Krafla Volcano.

As mentioned previously, HGP-A is located on the active lower east rift of Kilauea Volcano. The wellsite itself is just off the edge of a 1955 lava flow, and the lower east rift has erupted as recently as 1960. Therefore, renewed activity somewhere in the vicinity of HGP-A is entirely possible and, indeed highly probable. It would be extremely difficult, however, to prove a relationship between the geothermal well and an eruption in this area.

Effects on the activity of Kilauea within the boundaries of Hawaii Volcanoes National Park are difficult to predict, but the probability of any such effects seems quite remote. Volcanic activity at Kilauea characteristically originates in the summit region and migrates down the rift zones. Reverse movement would be highly unusual, although the most recent eruption (Nov. 1979) was marked by a puzzling occurrence of microearthquakes uprift of the eruption site. Whether this phenomenon was caused by uprift migration of magma is unknown.

(4) Accidents. Geological effects on the geothermal facility are much more likely than the reverse situation. The possibility of eruption and lava inundation was carefully considered in the design of the HGP-A electrical generating facility. Much of the equipment is designed to be mobile and can be removed from the path of an imminent lava flow. Permanent structures, including the wellhead itself, will be protected by barriers, and can evidently be insulated from a lava flow by a protective layer of cinders. The danger of a blowout or malfunction due to the destruction of wellhead materials by volcanic heat is, evidently, minor in light of the safety features designed into the facility.

(5) Groundwater contamination by geothermal effluents. The

chemical and physical properties of geothermal effluents from HGP-A are described in other volumes of this Overview report. Available data suggest that the fluids produced by this well so far have been relatively benign, actually quite "clean" when compared to geothermal fluids in other parts of the world. There is no reason to expect that fluid composition will remain the same after a period of time, however. Moreover, inhomogeneities in the reservoir (in the fluid itself as well as the rocks through which it passes) may result in wide chemical variations between one well and another. In Iceland, the chemical characteristics of the geothermal fluids changed markedly with the onset of volcanic activity. For these reasons, the possibility of future groundwater contamination should be considered.

Persons familiar with the geothermal system in Puna tend to anticipate minimal effects of the effluent on water supplies. The initial disposal method of percolation has been approved by the State Board of Health not only because the effluent is clean, but also because the groundwater in the immediate area is normally brackish and not used for public consumption. Most drinking water in the area is obtained by catchment rather than water wells. There are no surface streams in this region. Furthermore, the high rate of recharge (high rainfall) is expected to dilute effluents beyond recognition.

Nevertheless, diligent monitoring of local groundwaters will be part of the operational procedures at this particular well. In view of the likelihood that effluents will change with time and location, monitoring is essential. Other geothermal areas will have completely different subsurface hydrologic systems, and contamination must be considered separately at each potential site. Reinjection plans must be based on such factors as the depth and configuration of groundwater reservoirs. Such information is known in a general sense on most of the major Islands, but will have to be understood in greater detail at specific geothermal sites.

(6) Effects of lava tubes and other subsurface pathways on the movement of effluents. This issue was one of the most frequently raised, and it is a difficult issue to address. Not only are lava tubes ubiquitous (on Hawaii Island, at least) and uncharted; evidently no experimental work has been reported on the behavior of lava tubes as groundwater conduits. Some sort of "tracer" experiment would be useful.

One of the most commonly expressed concerns is that lava tubes may channel effluents all the way to the sea, where they may have adverse impacts on coastal organisms. However, the subterranean path to the ocean may be long and complex, and whether any lava tubes are that continuous is unknown. The permeability of lava tube walls may allow fluids to seep out fairly quickly, or permit effluents to disperse gradually along the length of the conduit. Again, dilution by existing groundwaters may mask geothermal wastes.

If geothermal fluids can be channelled by lava tubes, then ordinary groundwaters are likely to behave in the same manner.

Other subsurface features that may be capable of altering the flow of effluents would include fractures and permeable layers of buried ash (conduits) or dikes and impermeable strata (barriers).

The frequency with which the lava tube question is raised, and the scarcity of relevant information, reveals one of the major data gaps. This is a problem that is rather unique to Hawaii, and other geothermal areas provide few clues. While Iceland's geothermal field is also located in basaltic terrain, the tectonic and structural differences between Iceland and Hawaii make comparison difficult.

SOURCES OF INFORMATION ON THE GEOLOGY OF HAWAII

Hawaii has no State Geological Survey and, consequently, there is no centralized source of geological information. However, numerous agencies and institutions are involved in geological and hydrological research in the State. While no comprehensive Index of Hawaiian Geology has been published to date, most of the individual agencies maintain their own bibliographies and lists of publications, which are generally available upon request.

The primary sources of information are described in this section, and their addresses are listed at the section's end.

The United States Geological Survey has two principal offices in Hawaii: (1) The Water Resources Division, which is concerned with hydrology, water supply, water quality, and acquisition of various types of hydrological data; (2) the Hawaiian Volcano Observatory, located on the active volcano Kilauea. HVO performs research on volcanism, petrology, geophysics, field geology. Both USGS offices in Hawaii maintain lists of publications.

A complete list of USGS reports and maps dealing with Hawaiian geology and mineral and water resources is contained in the pamphlet "Geologic and Water-Supply Reports and Maps--Hawaii", which is available from the USGS in Reston, Virginia. A fairly recent index of geologic maps in Hawaii has been prepared by the USGS (McIntosh and Eister, 1977).

Other USGS publications include Bulletins, Professional Papers, Water-Supply Papers, Circulars, Hydrologic Investigations, Atlases, and Maps, all of which may contain specific information on Hawaiian topics. The Bibliography of North American Geology, another USGS publication, is a helpful guide to geologic literature in general, and contains numerous references to Hawaiian subjects.

At the State level, the two principal sources of information are the State Department of Land and Natural Resources and the University of Hawaii, with its many affiliated Institutes and research groups. The Department of Land and Natural Resources, particularly the Division of Water and Land Development, has sponsored many geo-hydrologic investigations in the state. This office was formerly known as the Hawaii Division of Hydrography, and many of the pioneering works on Hawaiian geology and water resources were prepared under the auspices of this Division during the 1930's and 1940's. A complete list of publications is available from DLNR.

At the University of Hawaii in Honolulu, the primary facility involved in geological research is the Hawaii Institute of Geophysics (HIG), which maintains its own staff of research personnel. The University also has publications from the Departments of Geology, Oceanography, Geochemistry, Geodesy, and Soils. Scientific papers from all of these departments are released as university publications and are generally available upon request from the HIG Publications Office. An updated list of HIG publications is prepared each year. Those papers which are no longer available for distribution may be examined in the HIG library, located on the campus of the University of Hawaii.

A bibliography of Theses and Dissertations dealing with Hawaiian geology and geophysics (1909-1977) is also available from HIG. This publication (Rowell, 1978) contains references to graduate studies at many Universities besides the University of Hawaii, although most are locally prepared works by UH students.

Information on Hawaii's geothermal resources is scattered throughout the sources described above. The two leading organizations in the State with regard to geothermal research are both associated with the University. The Hawaii Geothermal Project (HGP) has been the principal agency involved in development and research on the geothermal well in the Puna District of Hawaii Island. HGP includes participants from the University, and from local, State, and Federal agencies, as well as some private companies. In conjunction with developing an operating geothermally-powered electrical generating facility, the HGP has performed a variety of engineering, technical, geological, environmental, and socioeconomic studies, and a large body of HGP reports exists. A current list of these reports is available from the HGP office.

The Hawaii Institute of Geophysics has been responsible for the Hawaii Geothermal Resource Assessment Program, which is part of a larger, federally funded project known as the "Western States Cooperative Direct Heat Resource Assessment Program." An overall assessment of geothermal potential throughout the State is contained in the Phase I Final Report (Thomas _et al_, 1979), and a second detailed report deals with a possible low-temperature resource on the Island of Oahu (Cox, et al., 1979). Both publications contain a great deal of information and numerous pertinent references, and both provide good summaries of current knowledge on the subject.

Data on water quality in Hawaii are available from the USGS Water Resources Division and the State Dept. of Land and Natural Resources, as well as agencies such as the State Board of Public Health, and Boards of Water Supply in individual counties. At the University of Hawaii, the Water Resources Research Center (WRRC) is involved in a variety of projects dealing with Hawaii's water supply, including practical research on hydrogeology, irrigation, pollution, flooding, coastal hydrology, as well as numerous theoretical problems. A current list of WRRC publications may be obtained from the address listed below.

Individual references on the subjects of geology and hydrology are far too numerous to list here and are best obtained from the bibliographies and lists of publications described above. However, a list of selected references, dealing particularly with geothermally-related subjects, is included at the end of the present report.

Addresses of Agencies Described

Information and lists of publications may generally be obtained from the following offices:

Water Resources Division
U.S. Geological Survey
P.O. Box 50166
Honolulu, HI 96850

Hawaiian Volcano Observatory
U.S. Geological Survey
Hawaii National Park, HI 96718

U.S. Geological Survey
420 National Center
Reston, VA 22092

Division of Water and Land Development
Hawaii State Department of Land and Natural Resources
P.O. Box 373
Honolulu, HI 96809

Hawaii Institute of Geophysics
Publications, Room 262
University of Hawaii
2525 Correa Rd.
Honolulu, HI 96822

Hawaii Geothermal Project
University of Hawaii
Holmes Hall, Room 206
2540 Dole St.
Honolulu, HI 96822

Water Resources Research Center
University of Hawaii
Holmes Hall, Room 283
2540 Dele St.
Honolulu, HI 96822

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