GROUND WATER IN KILAUEA VOLCANO AND ADJACENT AREAS OF MAUNA LOA VOLCANO, ISLAND OF HAWAII

By Kiyoshi J. Takasaki

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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per foot per day [(ft^3/ft)/d]	0.029290	cubic meter per meter per day
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the equation:

$$(1.8 \times {}^\circ C) + 32 = F^\circ$$

GROUND WATER IN KILAUEA VOLCANO AND ADJACENT AREAS OF MAUNA LOA VOLCANO, ISLAND OF HAWAII

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ABSTRACT

About 1,000 million gallons of water per day moves toward or into ground-water bodies of Kilauea Volcano from the lavas of Mauna Loa Volcano. This movement continues only to the northern boundaries of the east and southwest rift zones of Kilauea, where a substantial quantity of ground water is deflected downslope to other ground-water bodies or to the ocean. In the western part of Kilauea, the Kaoiki fault system, which parallels the southwest rift zone, may be the main barrier to ground-water movement. The diversion of the ground water is manifested in the western part of Kilauea by the presence of large springs at the shore end of the Kaoiki fault system, and in the eastern part by the apparently large flow of unheated basal ground water north of the east rift zone. Thus, recharge to ground water in the rift zones of Kilauea and to the areas to the south of the rift zones may be largely by local rainfall. Recharge from rainfall for all of Kilauea is about 1,250 million gallons per day.

Beneath the upper slopes of the Kilauea rift zones, ground-water levels are 2,000 feet or more above mean sea level, or more than 1,000 feet below land surface. Ground-water levels are at these high altitudes because numerous and closely spaced dikes at depth in the upper slopes impound the ground water. In the lower slopes, because the number of dikes decreases toward the surface, the presence of a sufficient number of dikes capable of impounding ground water at altitudes substantially above sea level is unlikely. In surrounding basal ground-water reservoirs, fresh basal ground water floats on seawater and, through a transition zone of mixed freshwater and seawater, discharges into the sea.

The hydraulic conductivity of the dike-free lavas ranges from about 3,000 to about 7,000 feet per day. The conductivity in the upper slopes of the rift ranges from about 5 to 30 feet per day and that of the lower slopes of the east rift zone was calculated at about 7,000 feet per day.

The occurrence of heated basal water south of the lower east rift zone of Kilauea indicates the movement of a large quantity of geothermally heated ground water southward from the rift zone. There is little indication of similar movement of water from the upper slopes of the east rift zone, and there is no obvious movement of heated water from the lower east rift to the north because of the absence of heated ground water north of the rift zone.

A broad range in temperature and chemical composition of geothermally modified ground water indicates several different sources. Four possible sources are (1) cold meteoric water, (2) cold seawater, (3) hydrothermal fluids of meteoric origin, and (4) hydrothermally modified seawater. The chloride-ion to magnesium-ion ratio of ground water indicates whether the water has been geothermally modified. A ratio greater than 15 to 1 generally denotes geothermally modified ground water.

1.0 INTRODUCTION

Occurrence and Movement of Ground Water in the Vicinity of Kilauea

A basic understanding of the occurrence and movement of ground water in Kilauea and Mauna Loa Volcanoes, and how this relates to the geologic setting of the volcanoes, will improve our general understanding of ground water-volcano interactions.

This report provides a basic description of the occurrence and movement of ground water in Kilauea Volcano and in the adjacent areas of Mauna Loa Volcano (fig. 1.0). Kilauea and Mauna Loa are among the world's most active volcanoes; on average, both volcanoes have erupted every 2 or 3 years for the last 200 years. Some of the effects on ground water caused by interaction with volcanic geothermal heat are also described in this report. An understanding of the occurrence and movement of ground water in Mauna Loa is essential in evaluating the ground-water resources of Kilauea, because a large volume of the ground water from Mauna Loa moves downgradient into some of the ground-water reservoirs of Kilauea. The principal factors that determine the occurrence, movement, and temperature of Kilauea's ground water are the rocks, geologic structures, and heat from the volcano's magma.

Early descriptions of the hydrogeology of the island of Hawaii and of the Kilauea area are those by Stearns and Clark (1930), Stearns and Macdonald (1946), and Davis and Yamanaga (1968). Later work, such as that by Druecker and Fan (1976) and Thomas (1987), has focused primarily on the physical and chemical state of the ground water contained in and transmitted by the rocks in the lower east rift of Kilauea. This report is a more general overview of the occurrence and movement of ground water as related to the geologic setting of Kilauea and Mauna Loa.

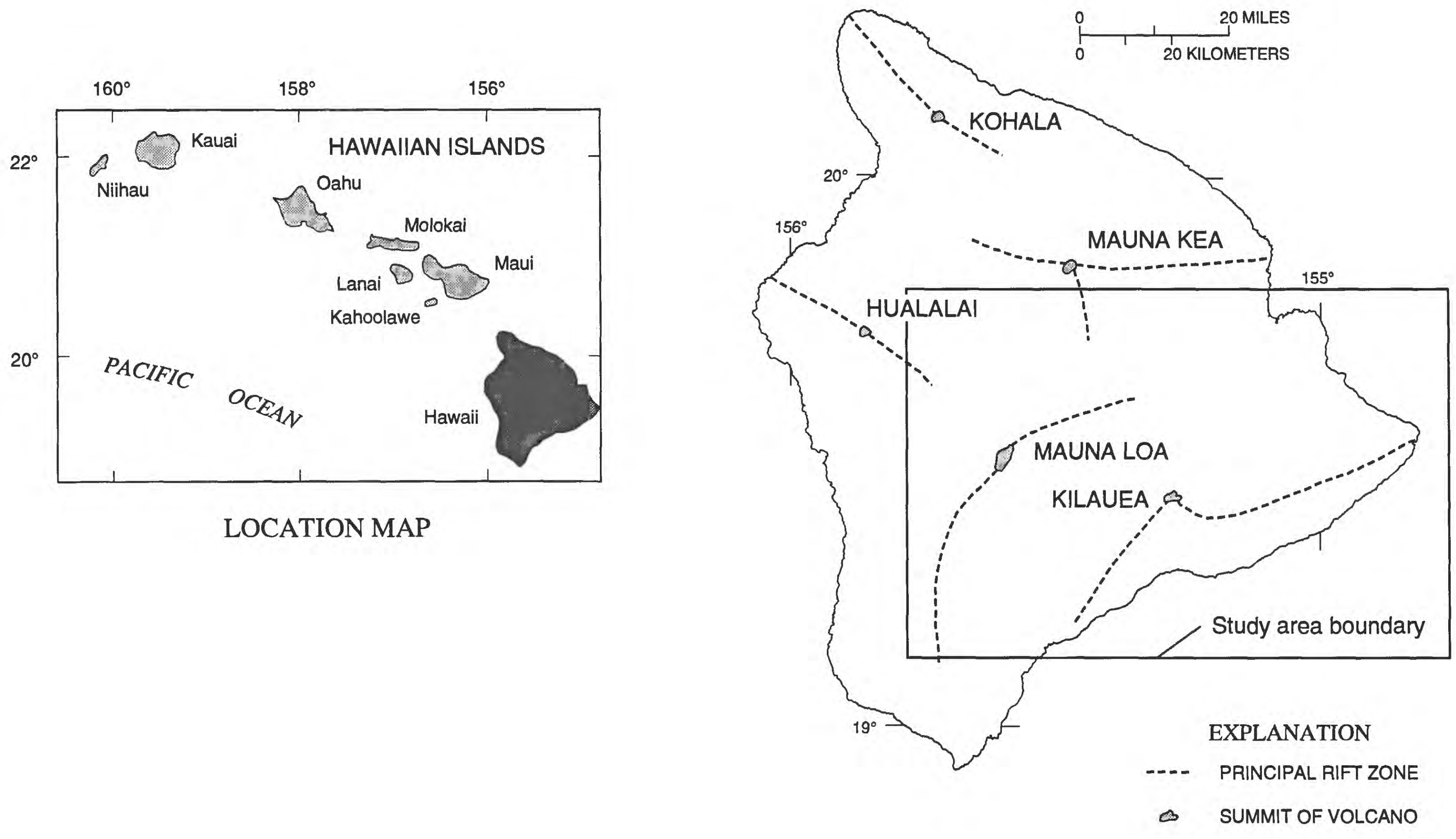


Figure 1.0. Location of the study area, the island of Hawaii, its volcanoes, and their principal rift zones.

2.0 GEOLOGIC SETTING

Kilauea Volcano Forming on Southeast Flank of Mauna Loa

Kilauea Volcano, its summit at 4,087 feet above mean sea level, is forming on the southeast flank of the 13,679-foot Mauna Loa Volcano. Most volcanic activity occurs at the summit and along the rift zones of Kilauea.

Kilauea, the youngest of the volcanoes that make up the island of Hawaii, is forming on the southeast flank of the older Mauna Loa Volcano (fig. 2.0-1). Of the five volcanoes that form the island of Hawaii, only Mauna Loa and Kilauea are currently active. These two volcanoes occupy the central and southeastern parts of the island, respectively, and their lava flows cover nearly two-thirds of the island's land surface (fig. 2.0-2).

Kilauea first erupted from a magma column that rose through and onto the southeast flank of Mauna Loa. Subsequent lava flows have erupted from the central vent and from the two principal rift zones of Kilauea (fig. 2.0-3).

Rift zones are elongate areas of fissures caused by regional stresses as a shield volcano grows, as well as by the gravitational stress imposed by any preexisting volcanic edifice that affects the growth of the newer volcano (Fiske and Jackson, 1972). Magma that consolidates within the fissures of a rift zone forms dikes. Typically, dike rock is more dense than the rock through which it intrudes because the dike rock formed at depth, and under pressure, and the intruded rock formed as accumulations of surface lava flows. The upslope, or northwest, side of the Kilauea lava pile abuts the flank of Mauna Loa; however, the downslope, or southeast side, is unbuttressed and has little resistance to downslope movement during repeated swellings of the magma chamber and as magma intrudes into the rift zones. Numerous fault scarps on the downslope side are surface manifestations of the downslope, slumping movement of the Kilauea lava pile (fig. 2.0-3).

Both Kilauea and Mauna Loa are in the shield-building stage of growth of shield-type volcanoes, a stage that has been divided into three substages (Peterson and Moore, 1987): (1) a submarine substage, during which lava builds moderate slopes on the submarine volcano; (2) a sea-level substage that is characterized by vigorous interaction between molten lava and seawater; and (3) a subaerial substage, during which pahoehoe and aa lava flows build a gently sloping shield volcano.

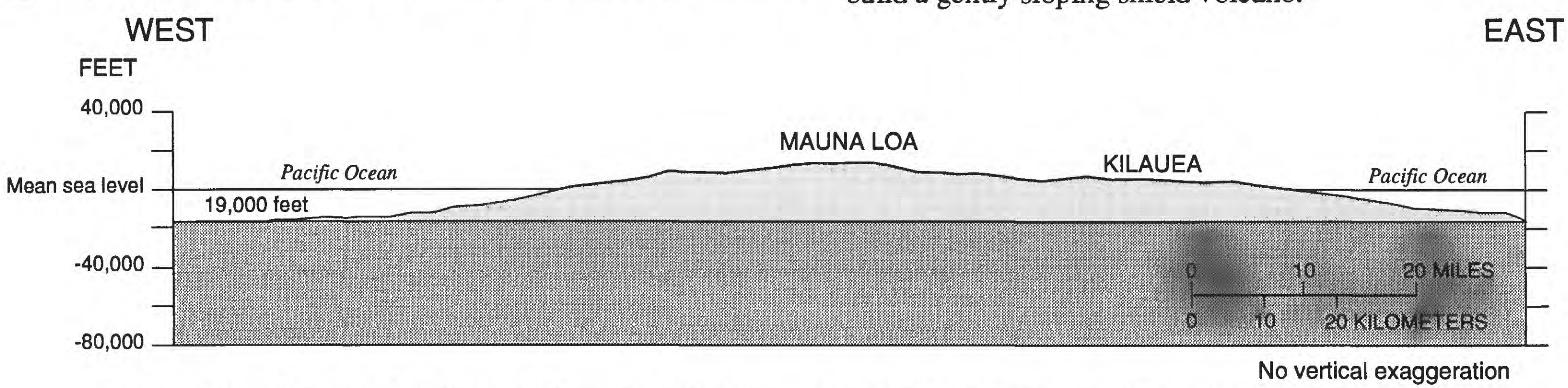


Figure 2.0-1. Section of Kilauea and Mauna Loa Volcanoes (modified from Tilling and others, 1987).

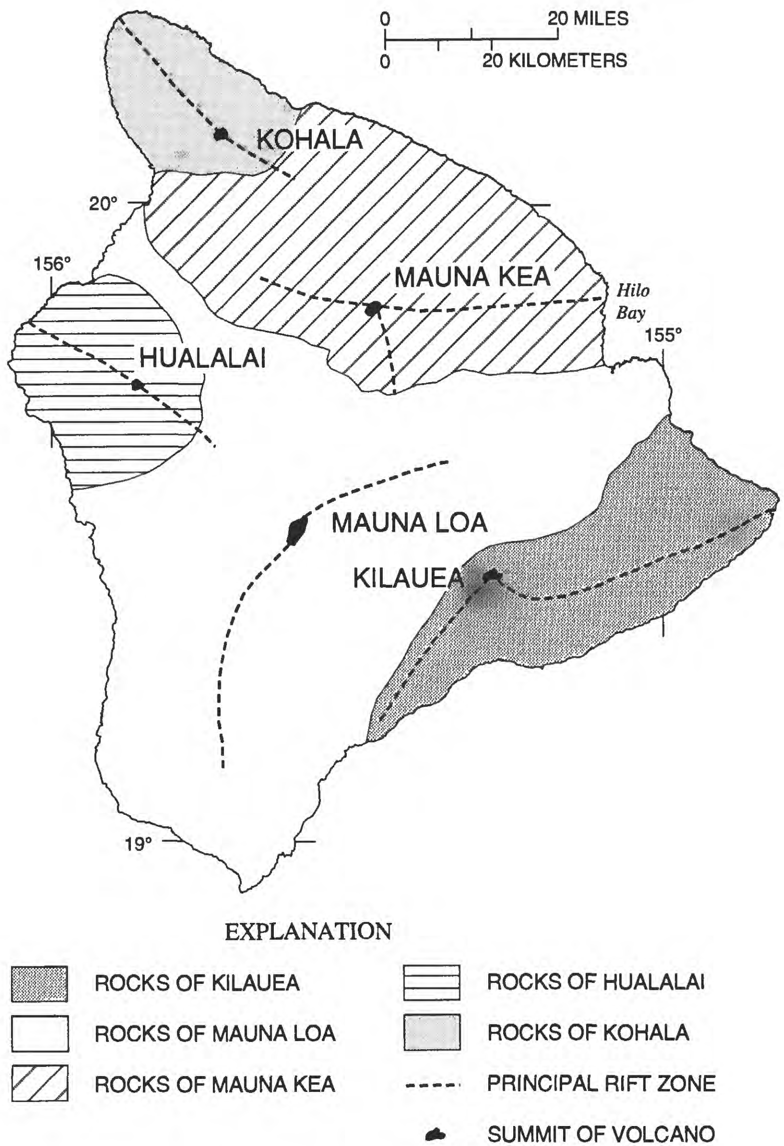


Figure 2.0-2. Distribution of rocks from the volcanoes that form the island of Hawaii.

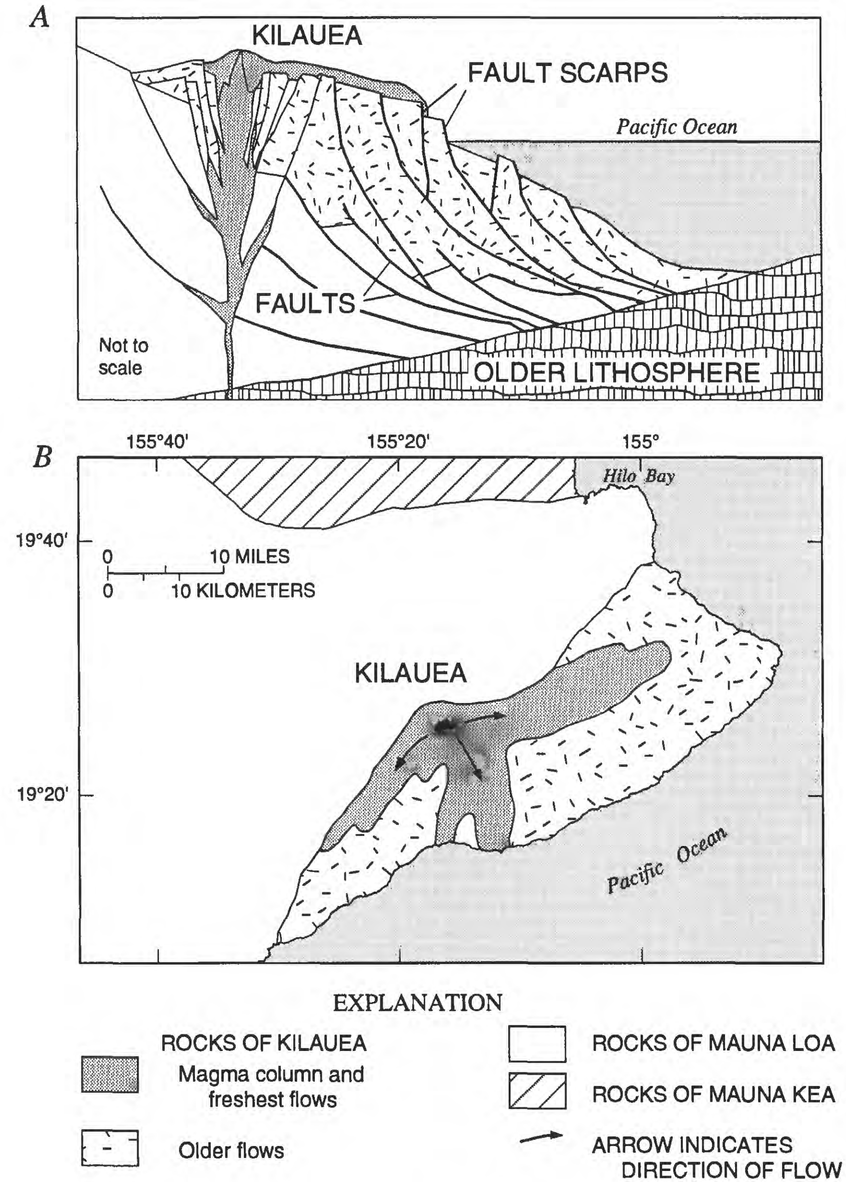


Figure 2.0-3. *A*, Magma column and slumped fault scarps. *B*, Surface lava flows during typical summit eruption of Kilauea (modified from Holcomb, 1987).

3.0 CLIMATE

Climate is Dominated by Northeast Trade Winds

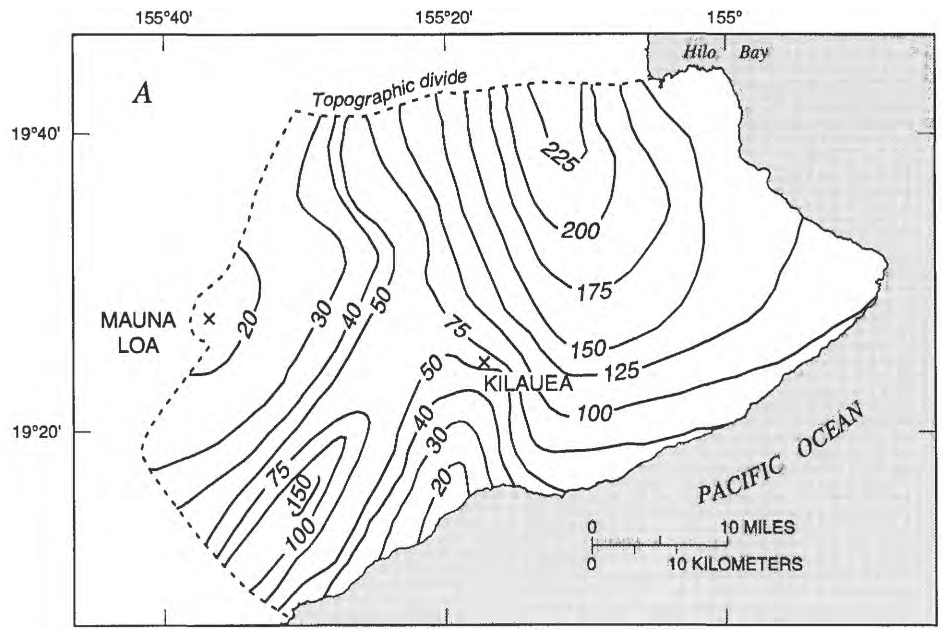
Orographic lifting of moisture-laden northeast trade winds results in high rainfall, cloudiness, and relatively cool temperatures on the windward slopes of Kilauea and Mauna Loa.

Climate is dominated by the northeast trade winds blowing against the slopes of Kilauea and Mauna Loa. Orographic rainfall, caused by lifting and cooling of moisture-laden air masses, is highest in a north-south trending zone on the eastern slope of Mauna Loa between altitudes of 2,000 and 4,000 ft. Rainfall decreases sharply above and below this zone and in the area southwest of the summit of Kilauea. Mean annual rainfall ranges from less than 20 in. at the summit area of Mauna Loa and near sea level southwest of the Kilauea summit to more than 225 in. on the eastern slopes of Mauna Loa (fig. 3.0-*A*).

Cloudiness persists more than 70 percent of the time in the zone of high rainfall. However, skies are normally clear at the summit of Mauna Loa, because during normal trade-wind conditions, a temperature inversion, which usually exists between 5,000 and 7,000 ft, prevents cloud development at higher altitudes (Blumenstock and Price, 1967). Skies are also usually clear in the area southwest of the summit of Kilauea on the leeward, or sheltered, side of the volcano. The lowest temperatures, which average about 10°C, occur at the summit of Mauna Loa; and the highest temperatures, which average about 24°C, occur southwest of the Kilauea summit. The average decrease in mean annual temperature is about 1°C per 1,000 ft of increased altitude. The mean annual temperature range at any location usually is less than 3°C, except at the summit of Mauna Loa, where the range exceeds 4°C.

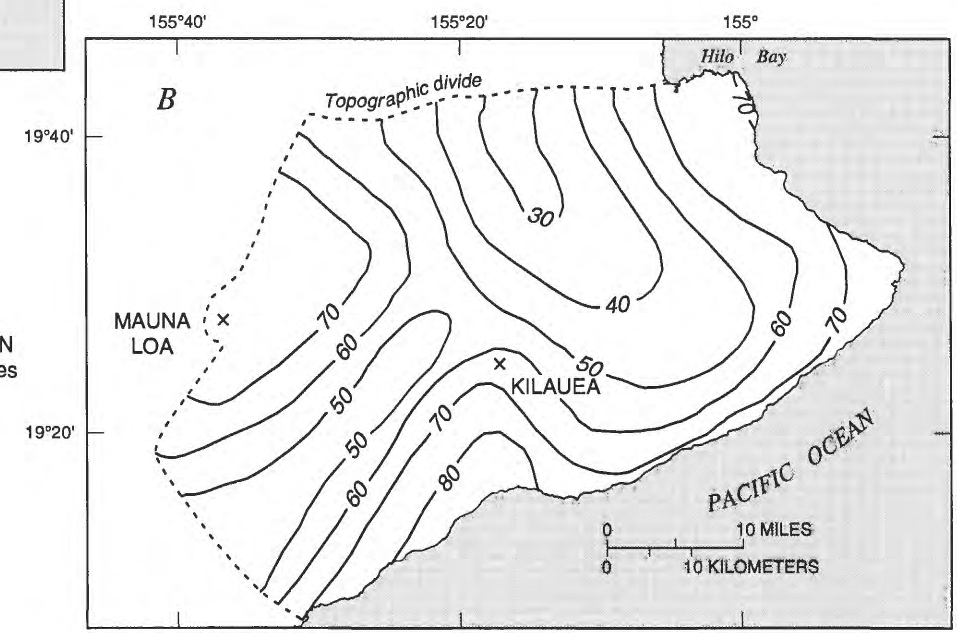
In contrast to the distribution of rainfall, the evaporation potential, measured by pan evaporation, is lowest on the eastern slopes of Mauna Loa and is highest southwest of the Kilauea summit. This reverse correlation between the rates of pan evaporation and rainfall is common in the Hawaiian islands, where rainfall and cloudiness are predominantly orographically controlled. Mean annual pan evaporation ranges from less than 30 in. to more than 80 in. The distribution of mean annual pan evaporation is shown in figure 3.0-*B* (Ekern and Chang, 1985).

Rainfall, solar radiation, and temperature are the climatic factors that have the greatest effect on the hydrology of the study area. Rainfall is significant because it is the primary source of recharge to ground water. Solar radiation and temperature determine evaporation, and thus affect the net ground-water recharge.



EXPLANATION

—225— LINE OF EQUAL MEAN ANNUAL RAINFALL -- Interval is 10 and 25 inches



EXPLANATION

—60— LINE OF EQUAL MEAN ANNUAL PAN EVAPORATION--Interval is 10 inches

Figure 3.0. *A*, Mean annual rainfall (modified from Giambelluca and others, 1986). *B*, Mean annual pan evaporation (from Ekern and Chang, 1985).

4.0 GROUND WATER

4.1 Recharge

Ground-Water Reservoirs are Recharged by More Than 3,550 Million Gallons of Rainfall Per Day

About 1,250 Mgal/d of rainfall recharges ground-water reservoirs in the lavas of Kilauea; about 2,300 Mgal/d recharges the lavas in the adjacent areas of Mauna Loa.

Annual ground-water recharge was calculated for the study area as the residual of mean annual rainfall after mean annual evapotranspiration and surface runoff were subtracted. In the calculation, annual surface runoff was set equal to zero because there are no perennial streams on the volcanic slopes, thereby indicating low or nonexistent runoff. Data from Ekern and Chang (1985) and Takasaki and others (1969) show that 60 in. of mean annual rainfall approximately coincides with 60 in. of mean annual pan evaporation. Areas with greater than 60 in. of rainfall generally have less than 60 in. of pan evaporation, and areas with less than 60 in. of rainfall have more than 60 in. of pan evaporation.

In areas where mean annual rainfall exceeds about 60 in., mean annual pan evaporation was assumed to be equal to mean annual evapotranspiration because at high rates of rainfall, moisture for evaporation and transpiration is always available within the plants' root zone in the soil. In these areas, therefore, the annual ground-water recharge was set equal to the annual rainfall minus the annual pan evaporation.

In areas where annual rainfall is less than 60 in., the calculation is modified because a negative value for recharge would result from subtracting pan evaporation from rainfall; likewise, to assume that recharge is zero for areas with less than 60 in. of rainfall is not realistic. In areas with less than 60 in. of mean annual rainfall, moisture is not always available for evaporation and transpiration in the root zone. Therefore, pan evaporation overestimates evapotranspiration. To estimate evapotranspiration in the low rainfall areas, a comparison is made with the rainfall-recharge relation of the island of Oahu, Hawaii. In the driest areas on Oahu, where rainfall averages only 20 in/yr, 10 to 20 percent of the rainfall infiltrates into the underlying aquifer (Eyre and others, 1986; Giambelluca, 1986). Assuming similar rates for the Kilauea and Mauna Loa area results in the following estimates of recharge:

Annual rainfall, in inches	Annual recharge, in inches
51 to 60	10
41 to 50	8
31 to 40	5
21 to 30	2
16 to 20	1
0 to 15	0

Recharge values thus calculated may be low for two reasons. First, mean annual values were used for both rainfall and pan evaporation; the use of values of shorter duration can result in the calculation of larger recharge values (Giambelluca and Oki, 1987). Second, even in areas of high rainfall, between about 60 and 150 in/yr, rainfall is seasonal and the soil is not saturated throughout the year so that pan evaporation probably overestimates evapotranspiration.

The spatial distribution of annual rainfall, annual pan evaporation, and hydrogeologic boundaries were superimposed using a geographic information system (GIS) to produce maps of ground-water recharge (fig. 4.1). Total recharge in the study area was calculated to be more than 3,550 Mgal/d: about 1,250 Mgal/d in the Kilauea area and about 2,300 Mgal/d in the adjacent areas of Mauna Loa.

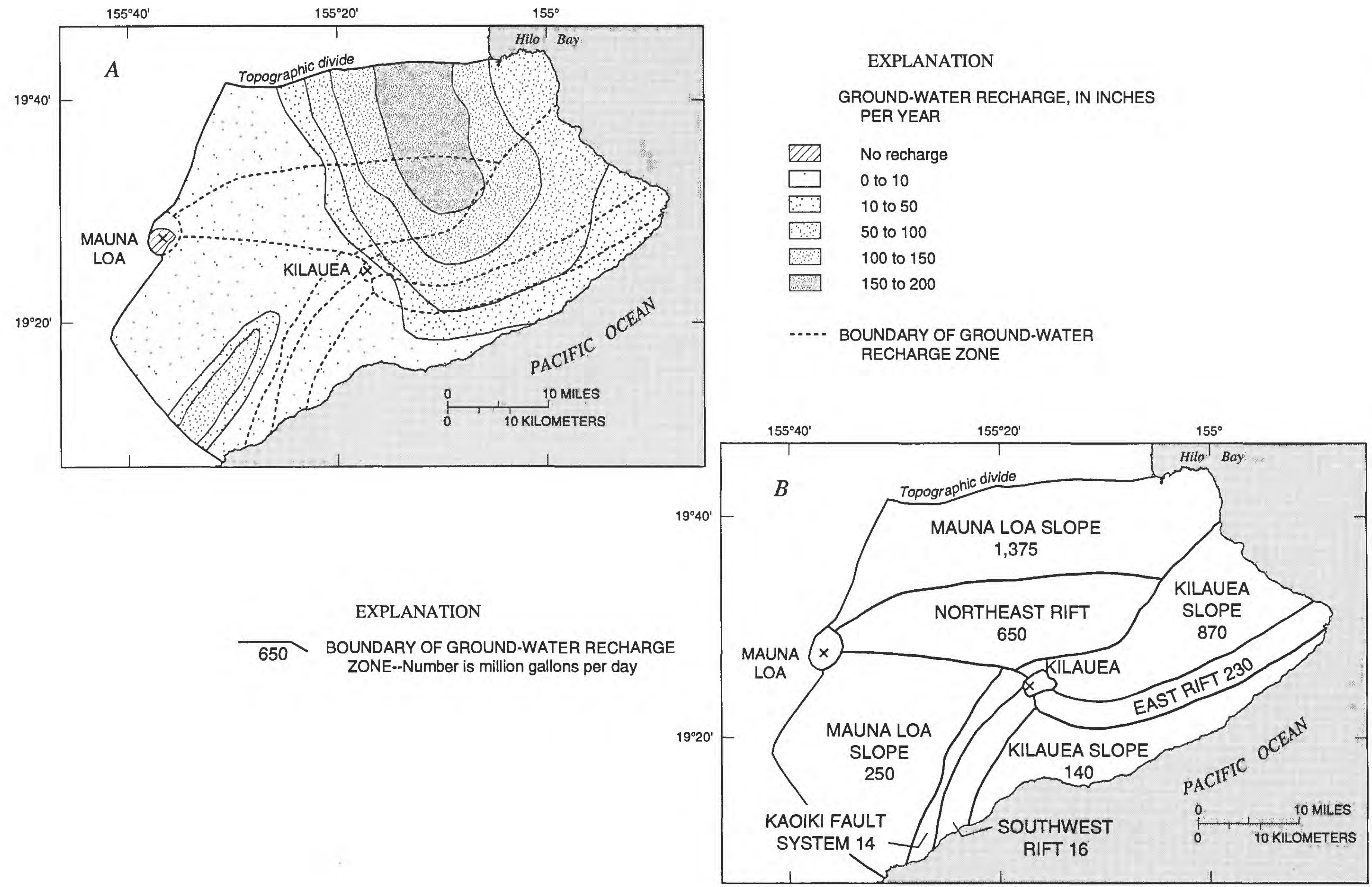


Figure 4.1. Ground-water recharge *A*, in inches per year, and *B*, in million gallons per day.

4.0 GROUND WATER

4.2 Occurrence

Large Quantities of Water are Stored In the Lava Flows of Mauna Loa and Kilauea Volcanoes

Large quantities of ground water are present as fresh basal water floating on seawater, separated by a mixed zone of saline water; as dike-impounded water in the rift zones; or as perched water overlying beds of weathered ash. The principal aquifers are lava flows.

Water in lava-flow aquifers on the island of Hawaii occurs as basal water, as dike-impounded water, and as perched water (fig. 4.2). Water in dike-free rocks outside the rift zones occurs as basal water, the fresher part forming a lens-shaped body floating on saline ground water. Dike-impounded ground-water bodies occur in dike-intruded lavas in the rift zones. Perched ground-water bodies in lava flows that overlie dike-impounded and basal water bodies are also found. Weathered volcanic ash is the principal perching material.

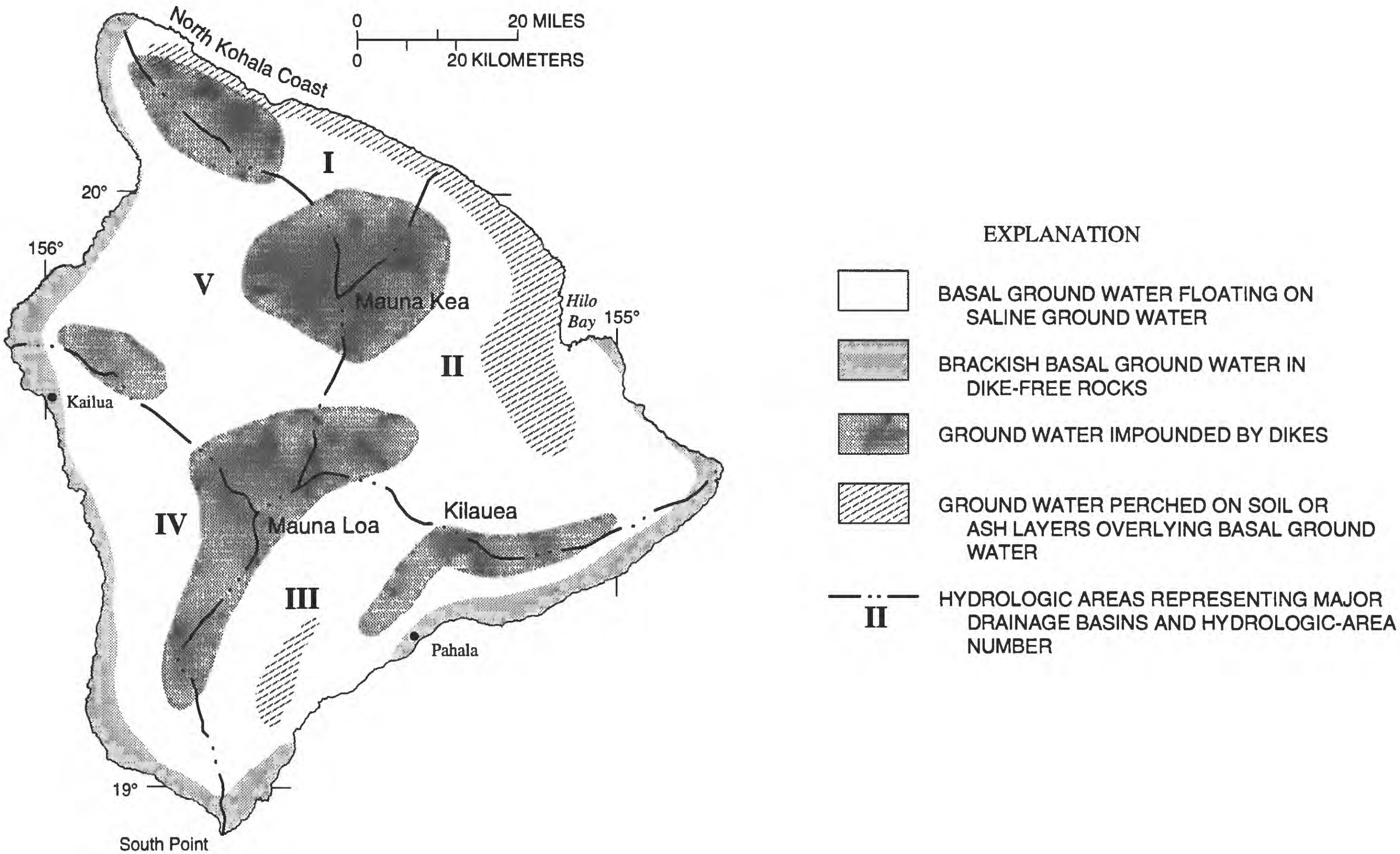


Figure 4.2. Ground-water occurrence and major drainage basins, island of Hawaii (modified from Takasaki, 1978).

4.0 GROUND WATER

4.2 Occurrence

4.2.1 Basal ground water

Calculation of Thickness of Lens

Ratio used to estimate the thickness of the basal freshwater lens.

Basal ground water, a term that originated in Hawaii and is commonly used in island hydrology, refers to freshwater bodies floating on, and in hydrodynamic equilibrium with, saltwater. Because of the shape of the basal ground-water body, it is commonly referred to as the freshwater lens. The base of the freshwater lens in basal-water reservoirs is calculated by the Ghyben-Herzberg relation:

$$h = \frac{t}{g - l},$$

where:

h = base of freshwater below mean sea level, in feet;
t = height of freshwater level above mean sea level, in feet;
g = specific gravity of seawater, = 1.025; and
l = specific gravity of freshwater, = 1.000.

Thus, the base of the freshwater lens will be 40 ft below sea level for every foot the freshwater level is above sea level.

Within the rift zones of Kilauea, substantial variations in permeability exist and, because of geothermal heating, the density contrast between freshwater and seawater also will vary. Thus, predictions of lens thickness made using the Ghyben-Herzberg relation will be unreliable.

Figure 4.2-1 shows areas underlain by basal ground water in the study area.

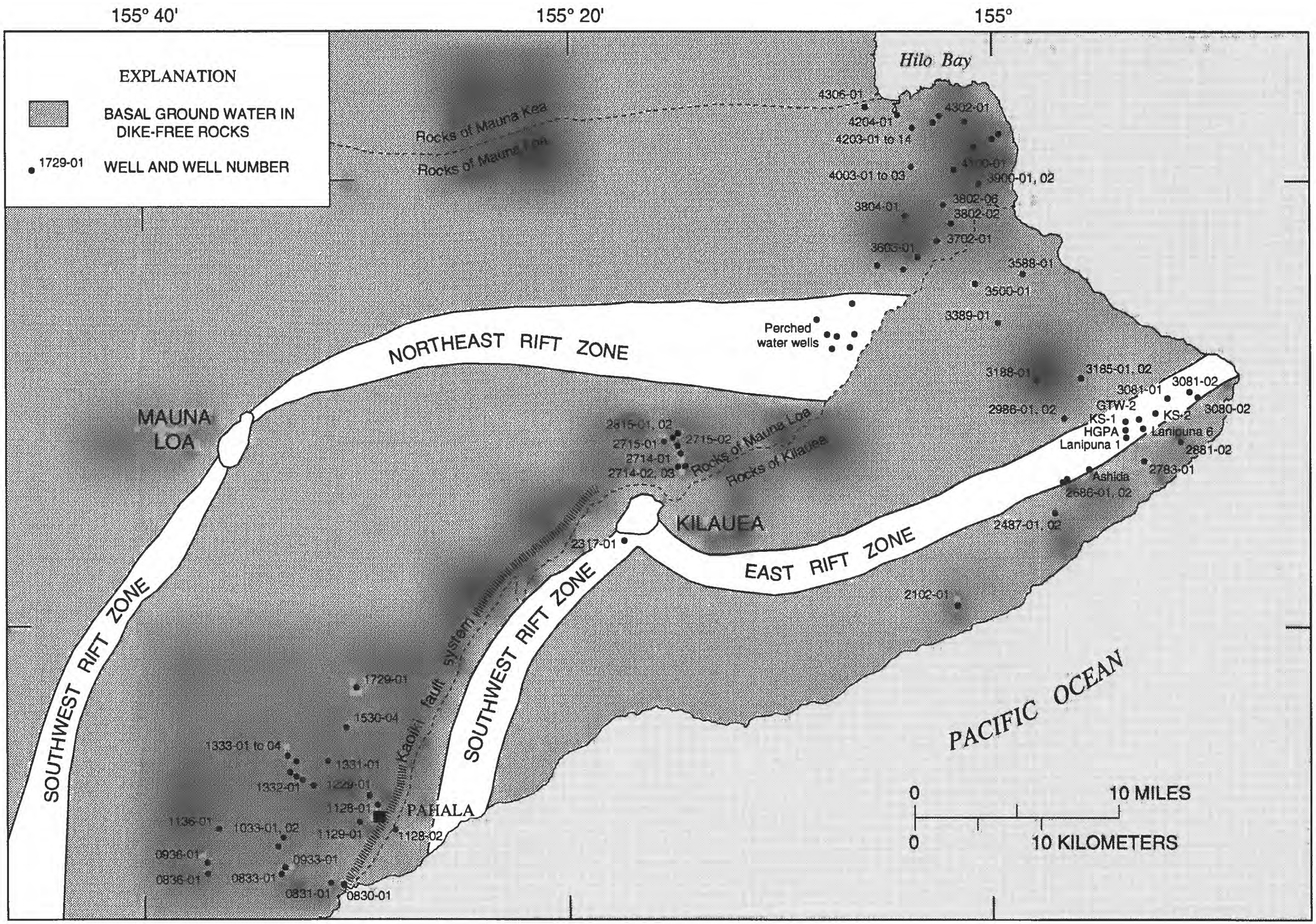


Figure 4.2-1. Basal ground water and well locations.

4.0 GROUND WATER

4.2 Occurrence

4.2.2 Dike-Impounded Ground Water

Dikes Impound Ground Water by Impeding Movement Toward Discharge Points

The height, depth, and movement of stored water depend on the orientation and number of dikes and on the contrast in the permeability between the dikes and the intruded rocks.

Dikes, primarily those vertical and parallel to the rift zone, can impound ground water because they generally are less permeable than the rocks they intrude. Dikes impound or divert ground water by either preventing or slowing movement toward discharge points. The height, depth, and movement of the stored water depend on the orientation and number of dikes and on the contrast in permeability between the dikes and the intruded rocks. At great depths, the water-storage capacity of the rocks and their ability to transmit water are reduced significantly by the reduction in void space and by an increase in the number of dikes. Because little is known about the movement of dike-impounded water at great depths, the thicknesses of these ground-water bodies at high altitudes were estimated to be from the top of the water level to sea level only .

The number of dikes in a rift zone decreases toward the surface. Thus, in uneroded rift zones such as those of Kilauea, dikes are sparse at shallow depths. On the lower slopes, therefore, the presence of a sufficient number of dikes capable of impounding ground water at altitudes substantially above sea level is unlikely. Ground-water levels in the lower slopes of the east rift zone of Kilauea are only a few feet above sea level and are at about the same altitude as water levels in adjacent basal-water bodies outside the rift zone.

Areas underlain by dike-impounded ground water in the study area are shown in figure 4.2-2.

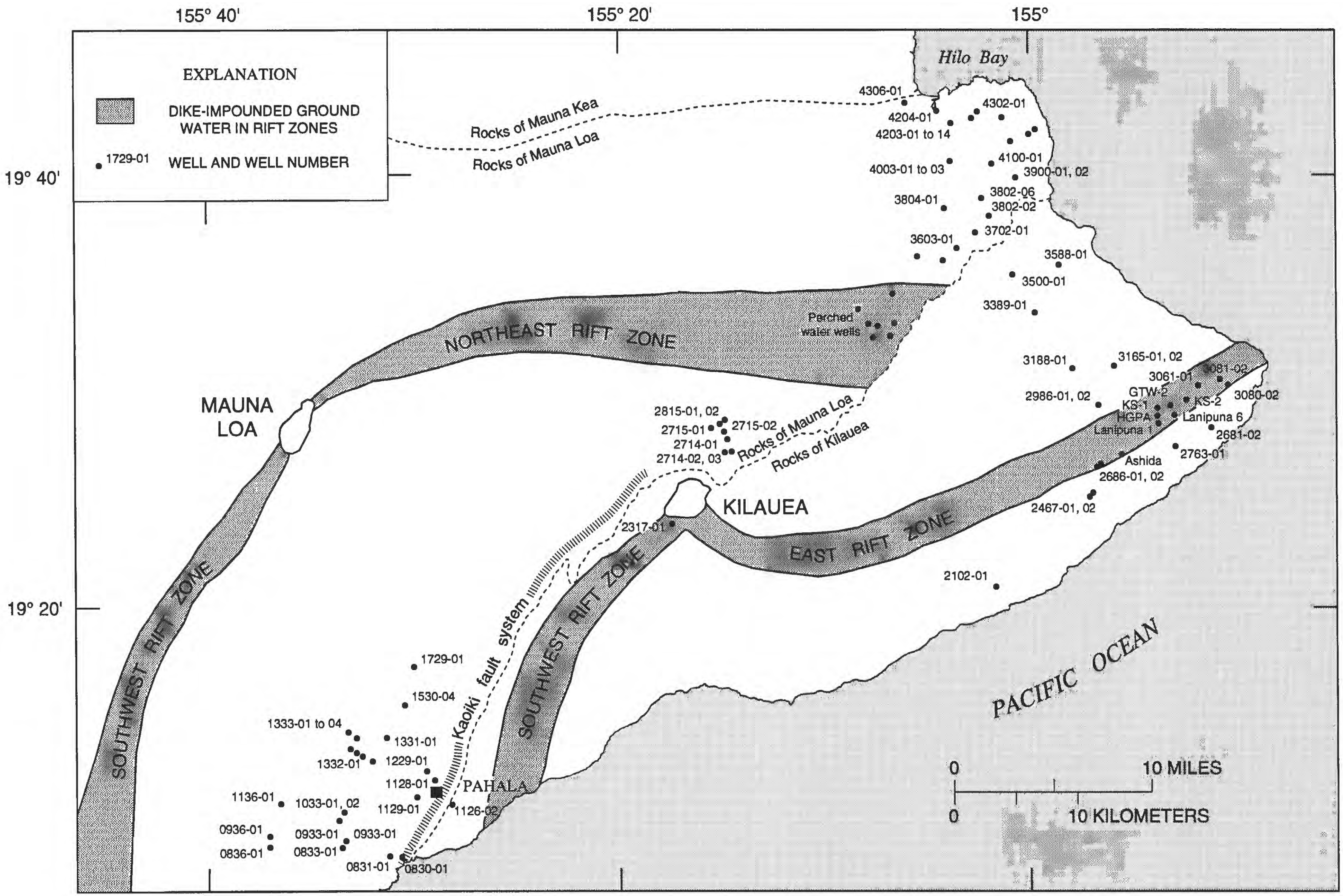


Figure 4.2-2. Dike-impounded ground water and well locations.

4.0 GROUND WATER

4.2 Occurrence

4.2.3 Perched Ground Water

Ground Water Perched on Ash and Low-Permeability Volcanic Materials

Numerous ground-water bodies are perched on ash and other volcanic material of low permeability in the lavas of Kilauea and Mauna Loa.

Numerous ground-water bodies are perched on ash and other volcanic material of low permeability in the lavas of Kilauea and Mauna Loa (fig. 4.2-3), but none are known to be large enough to have a major effect on the hydrology of Kilauea. Several drilled holes tapped perched ground water in the lavas of Mauna Loa, and in the area northeast of Kilauea's summit (fig. 4.2-3), but none of these wells yielded much water. West of Kilauea, many short tunnels tap perched ground water at altitudes above the town of Pahala and provide irrigation water for sugarcane. The most notable perching layer is the widespread Pahala Ash, which underlies the youngest lava sequence of Kilauea and Mauna Loa.

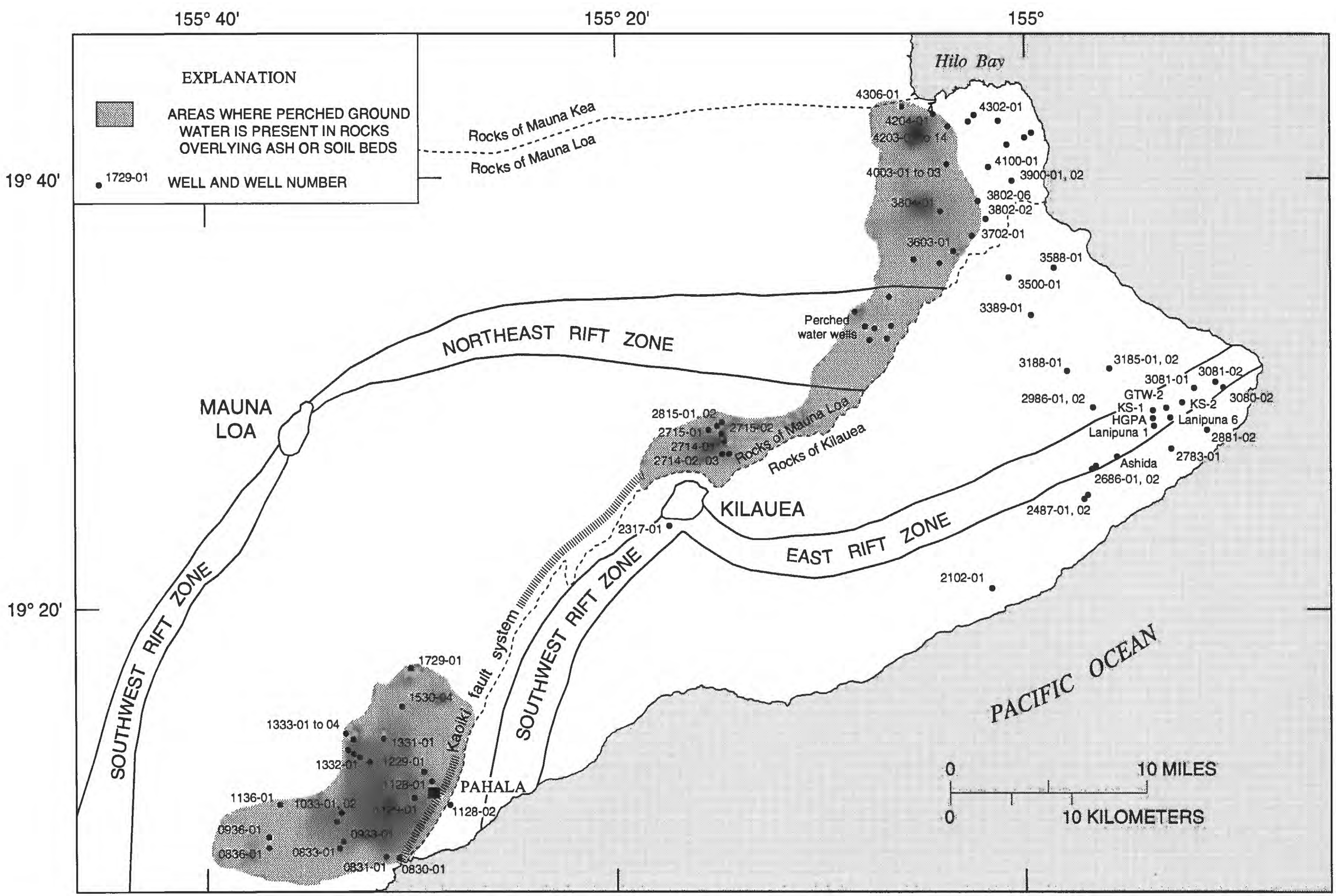


Figure 4.2-3. Perched ground water and well locations.

4.0 GROUND WATER

4.3 Quantity, Direction, and Gradient of Ground-Water Flow

About 1,000 Million Gallons of Water Per Day Moves in a Southeastward Direction From Mauna Loa Toward Kilauea

Kilauea receives about 1,250 Mgal/d of ground-water recharge from rainfall. An additional 1,000 Mgal/d moves southeastward from the volcanic rocks of Mauna Loa toward or into ground-water reservoirs in the volcanic rocks of Kilauea. A substantial part of this ground-water flow is diverted by the east and southwest rift zones of Kilauea Volcano; thus, much of the ground water from Mauna Loa is prevented from flowing into the south slopes of Kilauea. The ground-water gradient is gentle in dike-free aquifers and steep in dike-intruded aquifers.

The direction of ground-water flow generally is from the summit areas of the volcanoes to the sea, except locally where the flow is diverted by less permeable rocks such as dikes, fault debris, and sediments. The flow of ground water in the rift zones generally is along the strike of the dikes or along the long axis of the rift zones. The flow of perched water follows the surface of the perching unit, generally in the direction of the dip of the lava flow on which the perching unit was deposited.

The slope of the water table indicates the general direction of ground-water flow in an aquifer, and its gradient, or steepness, is an indication of either the rate of flow or the permeability of the aquifer. The water-table configuration is determined by contouring water levels measured in the area. A water-level contour map for the lower slopes of Kilauea and Mauna Loa is shown in figure 4.3. On the upper slopes of the rift zones, where only one water-level measurement was available, contours were estimated by Jackson and Kauahikaua (1987) on the basis of apparent water levels from measurements of electrical resistivity.

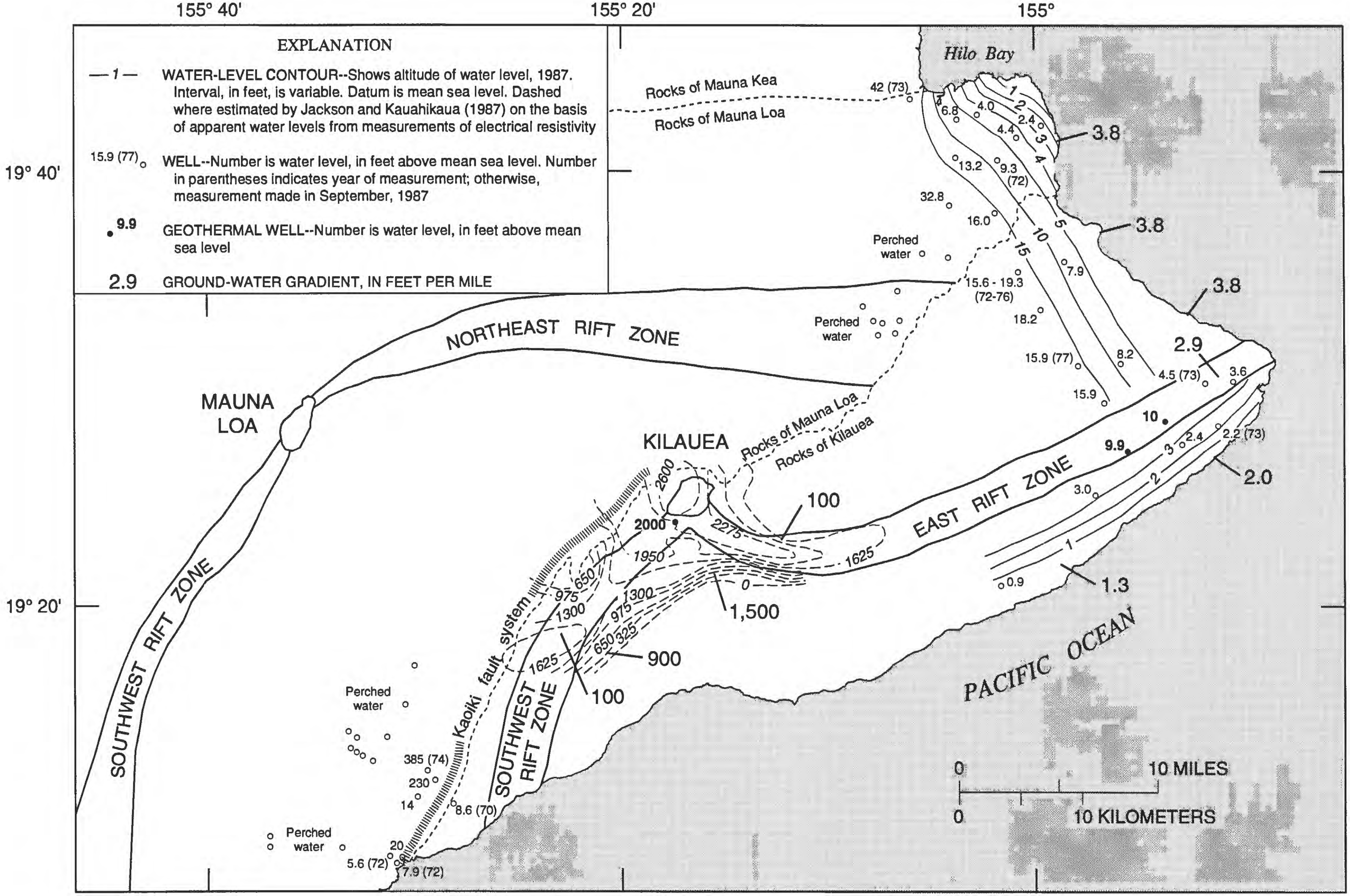


Figure 4.3. Water-level contours, water levels, geothermal water levels, and ground-water gradients.

4.0 GROUND WATER

4.4 Hydraulic Conductivity

Hydraulic Conductivity Ranges From Less Than 5 Feet Per Day to More Than 6,000 Feet Per Day

Hydraulic conductivity of the aquifers in the east rift zone of Kilauea is estimated to be less than 5 ft/d in the area underlying the upper slopes, where dike intrusions are abundant, and greater than 6,000 ft/d in the lower slopes, where dike intrusions are sparse or nonexistent. The hydraulic conductivity of aquifers outside the east rift zone generally exceeds 6,000 ft/d.

Hydraulic conductivity (K), the capacity of a unit thickness of an aquifer to transmit water, multiplied by the aquifer thickness (b) equals the transmissivity (T) of the aquifer, or $T = Kb$.

Because few aquifer tests have been done in the study area, the hydraulic conductivity of the aquifers was estimated by using Darcy's law in the form of $Q = TIL$,

where: Q = ground-water flow, in cubic feet per day;
T = transmissivity, in cubic feet per foot per day;
I = hydraulic gradient, in feet per mile; and
L = width of cross section of ground-water flow, in miles.

The following steps were used to solve for:

(1) T in the equation $Q = TIL$. Ground-water flow, Q, was made equal to ground-water recharge calculated for each aquifer.

(2) K in the relation $T = Kb$,
where: K = hydraulic conductivity, in feet per day; and
b = aquifer thickness, in feet.

For aquifers containing unheated basal water outside the rift zones, the thickness (b) was set equal to 40 times the water level above mean sea level; and for aquifers containing geothermally heated basal water, b was set equal to 70 times the water level above mean sea level on the basis of the assumption that the density contrast between saltwater and freshwater was decreased by heating. The aquifer thickness for ground water impounded by dikes to high altitudes in the upper slopes of the Kilauea rift zones was made equal to the height of the water level above sea level.

A map showing calculated hydraulic conductivities of selected subareas is shown in figure 4.4. The calculated hydraulic conductivities for the areas north and south of Kilauea's lower east rift zone differ by a factor of two. An assumption that about 25 percent of the ground-water flow in the lower east rift zone (57 Mgal/d) moves into aquifers south of the rift zone increases calculated conductivities south of the rift zone to 6,670 ft/d, approximately equivalent to values calculated for the area north of the rift zone (6,410 ft/d). This assumption reduces the calculated conductivity of the lower east rift zone to a comparable value, 7,100 ft/d.

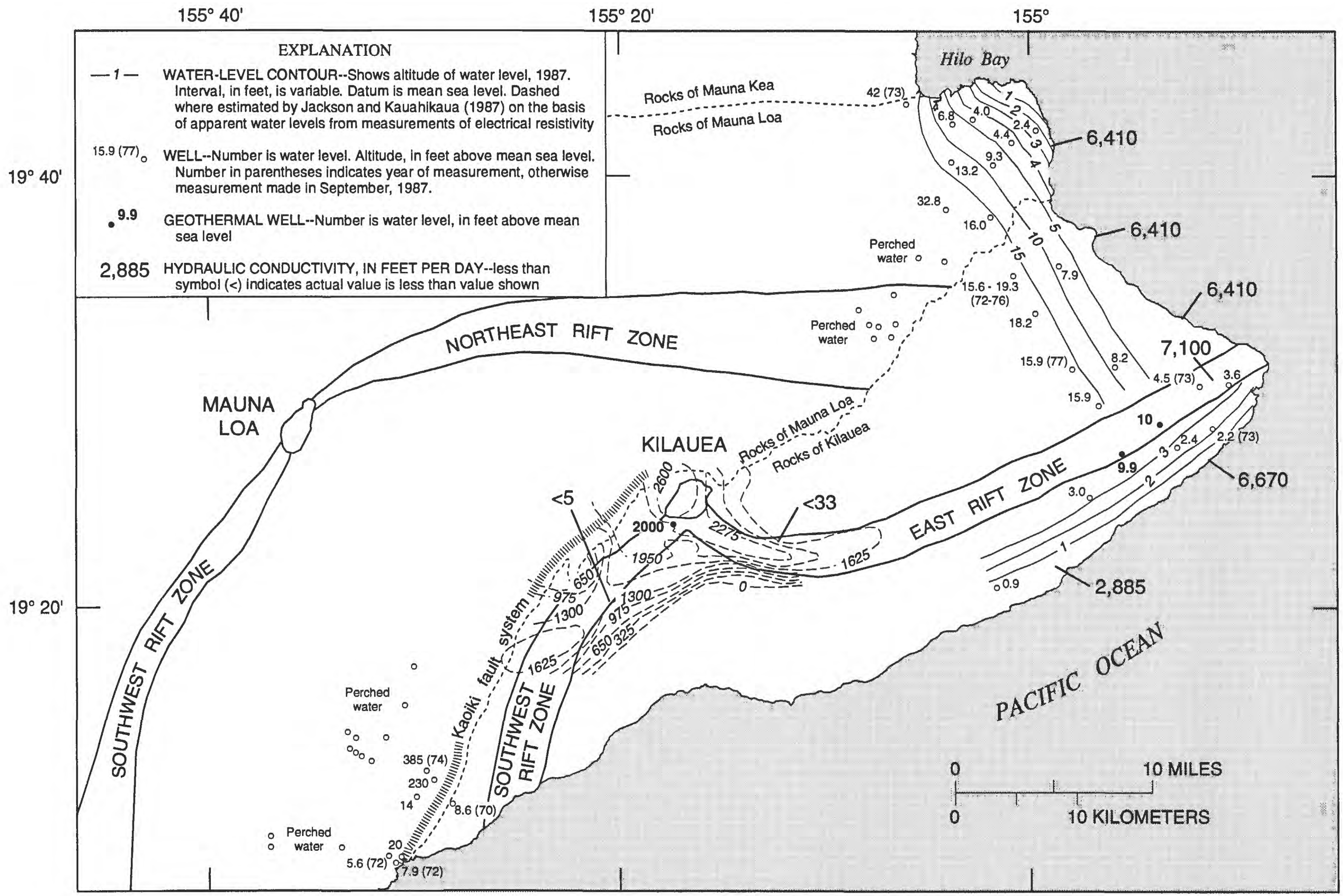


Figure 4.4. Water-level contours, water levels, geothermal water levels, and hydraulic conductivity.

5.0 ROCK TYPES AND GEOLOGIC STRUCTURES AFFECT GROUND-WATER FLOW

High Contrast in Permeability Between Lava Flows and Dikes, and Between Lava Flows and Weathered Ash Largely Determines the Occurrence and Movement of Ground Water

Rock types and geologic structures, consisting mostly of combinations of lava flows, dikes, and weathered ash deposits, largely determine the occurrence and movement of ground water in Kilauea and adjacent areas.

The rocks and geologic structures that determine ground-water occurrence and movement in the areas of Mauna Loa and Kilauea Volcanoes are shown in figure 5.0 and are briefly described as follows:

Mauna Loa Volcano

On the northeast flank of Mauna Loa, permeable, dike-free lavas transmit large quantities of ground water to the east and under the lower east slopes of Kilauea, recharging dike-free lava flows on the east flank of Kilauea.

In the northeast rift zone of Mauna Loa, dike-intruded lavas at depth presumably underlie and traverse the lower east flank and lower east rift of Kilauea, diverting ground water impounded by dikes in the rift zone into Kilauea lava. No wells have been drilled deep enough to tap ground water impounded by dikes in the lavas of Mauna Loa.

On the east flank of Mauna Loa, permeable, dike-free lavas transmit ground water toward and into downgradient water-bodies on the east flank of Kilauea.

On the south flank of Mauna Loa, dike-free lavas transmit large quantities of ground water to the southeast toward the southwest rift of Kilauea. The Kaoiki fault system parallels the southwest rift zone of Kilauea and diverts ground water on the south flank of Mauna Loa to the southwest. This diversion is indicated by large spring discharges at the shore end of the fault near Ninole.

The southwest rift zone of Mauna Loa has little effect on the hydrology of Kilauea because of its distance from Kilauea.

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On the east flank of Kilauea, north of the east rift zone, permeable, dike-free Kilauea lavas are underlain by lavas of Mauna Loa and the dike-intruded northeast rift zone of Mauna Loa. A large volume of ground-water recharge to the east flank of Kilauea comes from underflow from Mauna Loa.

In the upper slopes of the east rift zone of Kilauea, dikes impound ground water to high altitudes. The dikes on the lower slopes do not impound ground water to high altitudes. The flow of geothermally heated ground water from the lower slopes to the south is significant on the basis of geochemical data discussed in the next section, but movement to the north is not obvious.

On the upper slopes of the southwest rift zone of Kilauea, ground-water levels are at high altitudes. Ground-water levels on the lower slopes is unknown. On the south flank of Kilauea, permeable lavas contain few dikes, but because of the limited recharge, ground-water flow in them is relatively slow except in the eastern part, which receives large quantities of heated water from the lower east rift zone of Kilauea.

The subsurface Pahala Ash beds are widespread but discontinuous; they underlie the youngest lava sequence of Mauna Loa and Kilauea and act as perching units for numerous ground-water bodies. The effect of discharge from perched-water bodies on the hydrology of Kilauea is probably insignificant, because the only known large perched-water bodies are located some distance away from Kilauea in the lavas of Mauna Loa.

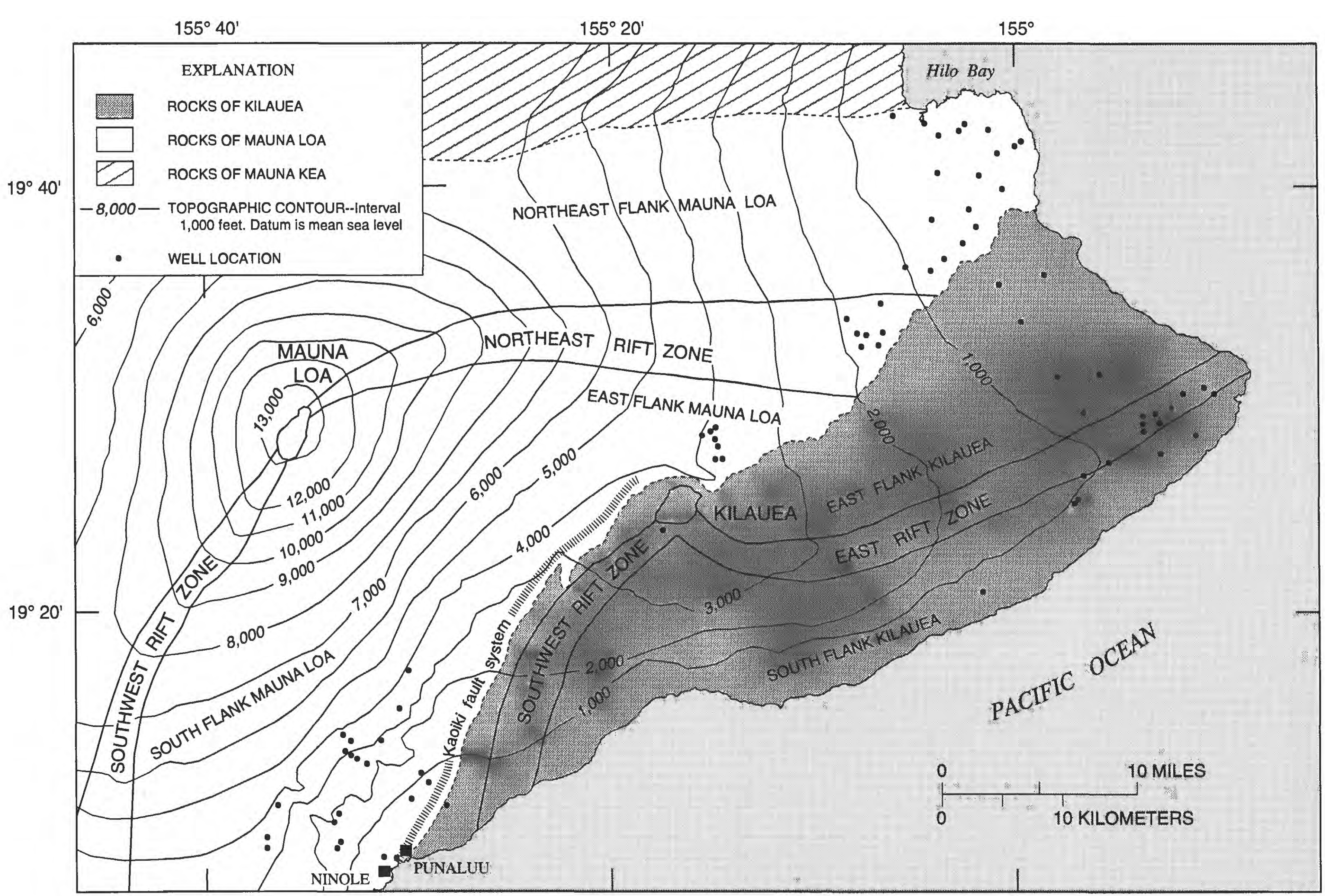

Figure 5.0. Locations of rocks and geologic structures that determine ground-water occurrence and movement.

6.0 GROUND-WATER TEMPERATURE

Water Geothermally Heated: Mixing of Rainwater With Geothermally Heated Vapor and Water Determines Temperature of Ground Water

The temperature of ground water in the east rift zone of Kilauea Volcano is the result of cold ground water mixing with geothermally heated water.

The temperature of shallow ground water in the east rift zone of Kilauea is strongly affected by geothermal heating. The mixture of cold ground water with geothermally heated water determines the temperature of the ground water. At depths of 7,000 ft below mean sea level, water temperature in wells generally exceeds 300°C (Thomas, 1987). Temperature of the ground water measured after drilling in the east rift zone of Kilauea is shown in figure 6.0 in conjunction with other ground-water temperatures and air-temperature contours.

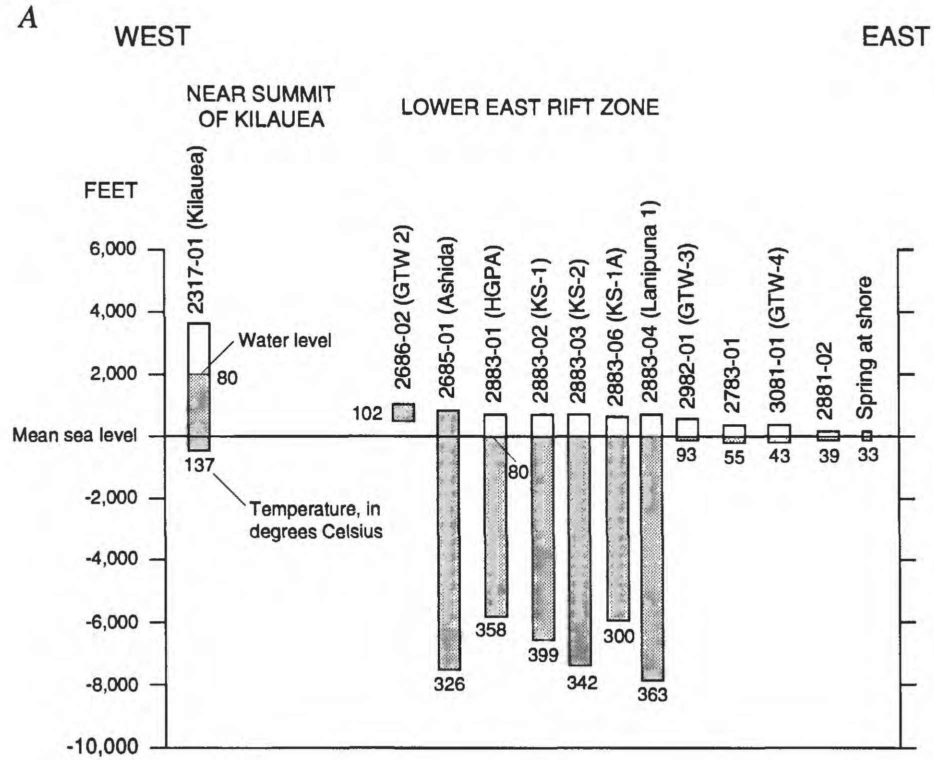

Figure 6.0. *A*, Temperature of geothermally heated ground water in the east rift zone of Kilauea Volcano.

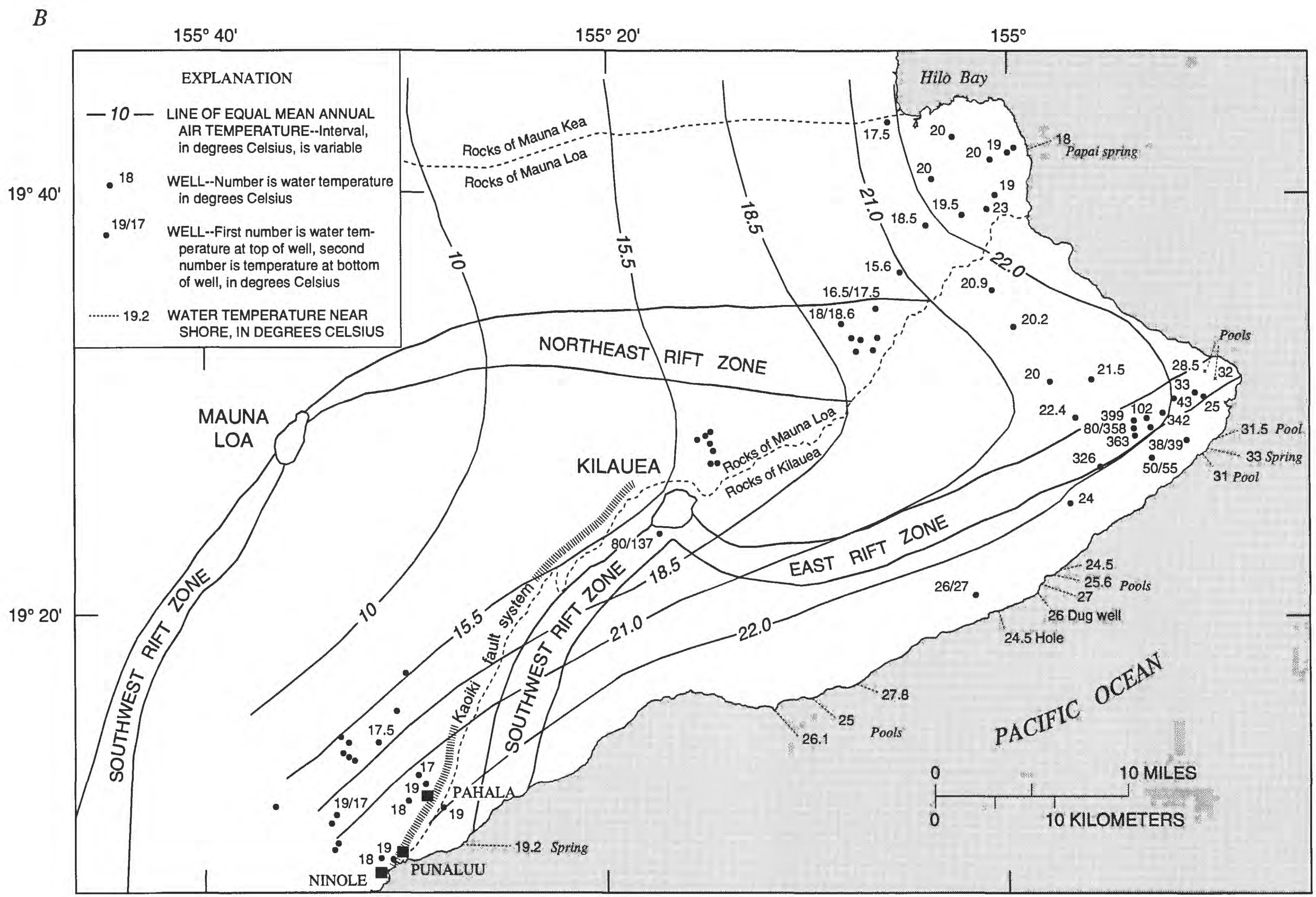

Figure 6.0. *B*, Lines of equal mean annual air temperature and water temperatures.

7.0 IDENTIFICATION OF GEOTHERMALLY MODIFIED GROUND WATER

Chloride-to-Magnesium Ratio Indicates Whether Ground Water Has Been Geothermally Modified

The ratio of chloride ion to magnesium ion provides an indication of the degree of hydrothermal modification of ground water. This ratio is a good tracer because it is independent of measured ground-water temperature and thus can be used to identify heated ground water that subsequently has cooled conductively.

Thomas (1987) suggests that ground water with a broad range in temperature and chemical composition, such as the geothermally modified ground water in the east rift zone of Kilauea, comes from several different sources. Thomas lists four possible sources for geothermally modified ground water in the east rift zone of Kilauea:

1. Cold meteoric water.
2. Cold seawater.
3. Hydrothermal fluids of meteoric origin.
4. Hydrothermally modified seawater.

Thomas (1987) considers the following factors to be convenient tracers for identifying some of the sources of recharge in the east rift zone of Kilauea:

1. Temperature identifies a hydrothermally modified source.
2. Chloride-ion concentration identifies seawater as a source.
3. The ratio of chloride ion to magnesium ion identifies a geothermally modified ground-water source of either fresh or saline origin. A ratio greater than 15 to 1 generally denotes geothermally modified ground water because magnesium is depleted by geothermal processes.

The chloride-ion to magnesium-ion ratio provides an indication of the degree of modification to ground water by hydrothermal processes. This ratio provides the best tracer because it is independent of measured ground-water temperature and thus can be used to identify ground water that has cooled conductively or moved away from hydrothermally active areas in the rift zone. The chloride-ion to magnesium-ion ratios of ground water in areas within and outside the east rift zone of Kilauea are shown in figure 7.0. The chloride-ion concentration and the dissolved-solids concentration of the water from selected wells are also shown.

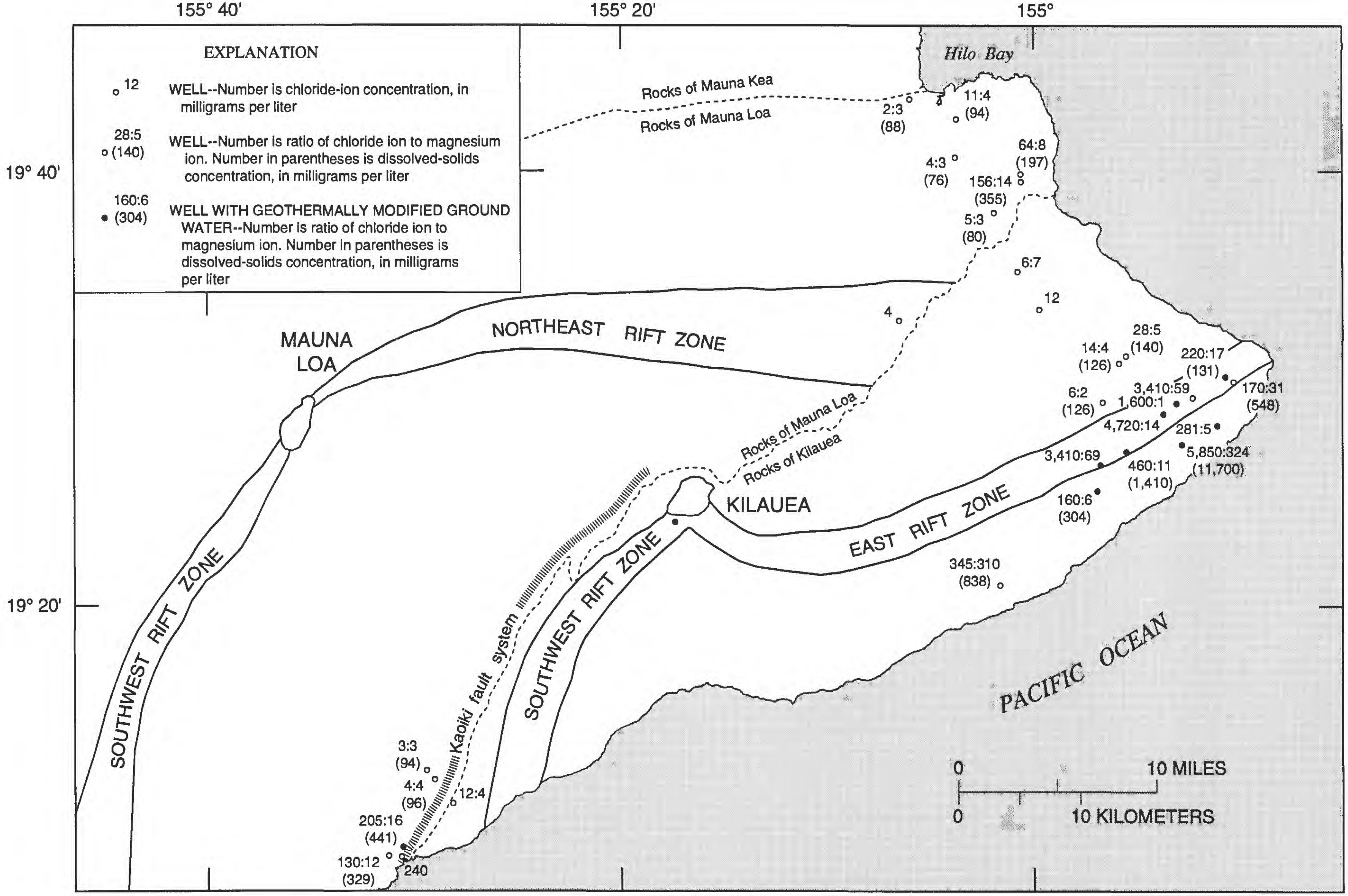

Figure 7.0. Wells with geothermally modified ground water, chloride concentrations, ratios of chloride ion to magnesium ion, and the dissolved-solids concentration of ground water.

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