HUALALAI VOLCANO: A PRELIMINARY SUMMARY OF GEOLOGIC, PETROLOGIC, AND GEOPHYSICAL DATA

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ABSTRACT

Hualalai Volcano is the third youngest on the Island of Hawaii. Three rift zones striking northwest, north, and south-southeast have been the loci of all late Pleistocene and Holocene eruptions. Recent detailed and reconnaissance geologic mapping and ^{14}C age determinations indicate that about 95 percent of Hualalai's surface is Holocene, about 55 percent is less than 3,000 years old, and 25 percent is less than 1,000 years old.

Tholeiitic basalt does not occur on the subaerial surface of Hualalai, but has been encountered in a few drillholes and has been dredged from the submarine portion of the northwest rift zone. We infer that Hualalai, like other Hawaiian volcanoes, is dominantly tholeiitic lava and has a thin cap of alkalic lava. The available tholeiitic basalt is mostly olivine-controlled lava that has as much as 30.8 percent MgO. Major-element, trace-element, and isotopic data indicate that Hualalai tholeiitic basalt is most similar to that of Mauna Loa but that their garnet-bearing mantle sources are different.

The subaerial alkalic lava is chiefly alkali olivine basalt with minor hawaiite and trachyte. The alkalic basalt contains varied amounts of olivine, clinopyroxene, and plagioclase phenocrysts and has as much as 16 percent MgO (ankaramite); much is differentiated beyond olivine control. Xenoliths of mafic and ultramafic rocks are common in many alkalic vent deposits and flows. The alkalic basalt of Hualalai can be produced by 5–10 percent partial melting of a source enriched in the light rare-earth elements.

Trachyte occurs in one large cone and its associated flow, as xenoliths in several basaltic vents, and in one drillhole. Gravity and aeromagnetic data support the interpretation that these rocks, the most silicic lava on the Island of Hawaii, were erupted in significant amounts during the late Pleistocene and subsequently have been thinly mantled by alkalic basalt lava flows.

Seismic studies indicate that seismicity within Hualalai is low, and there is no evidence of current magmatic movement such as occurs on Kilauea and Mauna Loa. An intrusion probably occurred in 1929, when earthquakes shook the region for more than a month. Resistivity and electrical self-potential surveys indicate that residual heat from magmatic intrusions may lie at shallow levels. We believe that Hualalai may well erupt again within the next few decades and that precursory seismic activity may be short.

INTRODUCTION

LOCATION AND GEOLOGIC SETTING

Hualalai Volcano occupies the western part of the Island of Hawaii (fig. 20.1) and makes up about half of the area commonly referred to as the Kona district. Hualalai rises to a height of 2,523 m (8,271 ft) above sea level, covers an area of about 850 km^2 (about 325 mi^2), and has a subaerial volume of about 600 km^3 (about 144 mi^3). Alkalic lava on its southern, eastern, and northeastern flanks is interbedded with tholeiitic Mauna Loa lava.

Hualalai has three rift zones that strike northwest, north, and south-southeast from a point about 5 km east of its summit. The subaerial part of the prominent northwest rift zone, 2–4 km wide (fig. 20.2), is 24 km long to the ocean; bathymetry suggests that it may continue another 70 km offshore. The ill-defined north rift zone (fig. 20.3), about 10 km long and 5 km wide, contains less than 5 percent of the vents and has been inactive during the last 2,000 years. The south-southeast-trending rift zone (fig 20.4), 3–5 km wide, is about 13 km long and, like the others, is marked by prominent cinder and spatter cones.

This progress report summarizes recent work by the U.S. Geological Survey on Hualalai, including geologic mapping, ^{14}C age determinations, petrographic studies, major-element chemical analyses, trace-element analyses, and geophysical studies.

PREVIOUS WORK

Stearns and Macdonald (1946) mapped Hualalai in reconnaissance fashion, and named all of the alkalic rocks the Hualalai Volcanic Series, which included the Waawaa Volcanics (trachyte cone and flow) at its base. These units are currently called the Hualalai Volcanics and Waawaa Trachyte Member. Macdonald (1968) noted that most of the surface vents and flows are alkali olivine basalt. Richter and Murata (1961) and Jackson and others (1981) studied xenoliths in a lava flow erupted in 1800.

Clague and others (1980) discussed the petrology of 19 prehistoric and historical alkali basalt flows of Hualalai. Clague

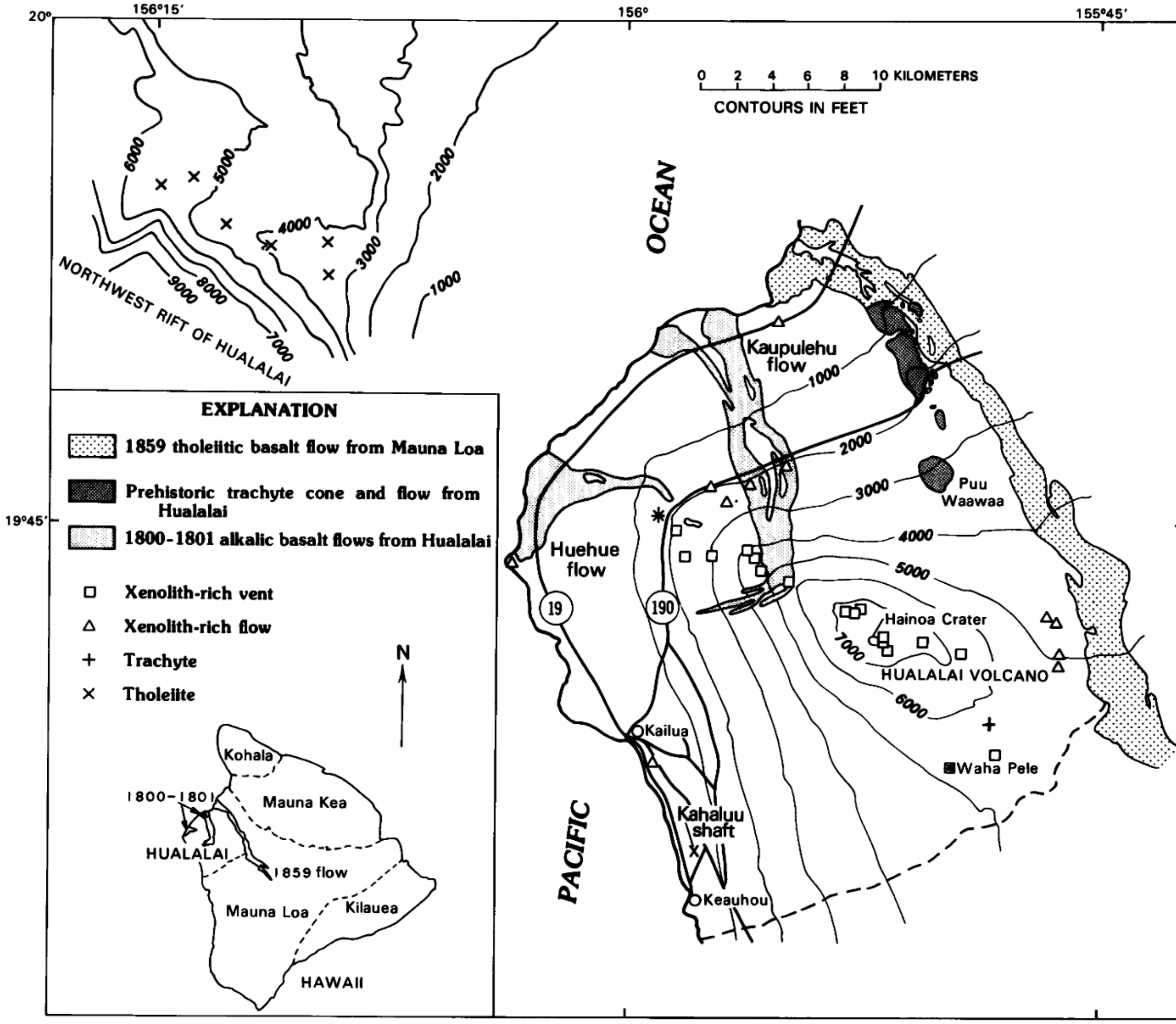

FIGURE 20.1.—Hualalai Volcano, including part of submarine northwest rift zone. Inset shows location of Hualalai on Island of Hawaii. Samples dredged from northwest rift are all tholeiitic basalt and picritic tholeiitic basalt. Symbol at Waha Pele indicates picritic tholeiitic basalt and trachyte blocks in maar deposit and xenoliths in flow from same vent. Other location with both trachyte and tholeiitic basalt, 1 km southwest of 1801 vent, is water well that encountered trachyte overlying tholeiitic basalt, both beneath more than 300 m (1,000 ft) of alkalic basalt flows. Third tholeiitic basalt location is from Kahaluu water shaft, where tholeiitic basalt occurs as shallow as 75 m (229 ft) below surface. Bathymetry from Campbell and Erlandson (1979). Dashed line marks approximate southern edge of Hualalai.

(1982) described tholeiitic basalt from the submarine northwest rift zone; much of our discussion of the tholeiitic shield lying hidden beneath the surficial alkali basalt flows is based on that study.

ACKNOWLEDGMENTS

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STRATIGRAPHY

We have mapped all of Hualalai Volcano in reconnaissance fashion and have completed detailed mapping of lava flows and vent deposits in most of the area, including five of the eight 7½-minute

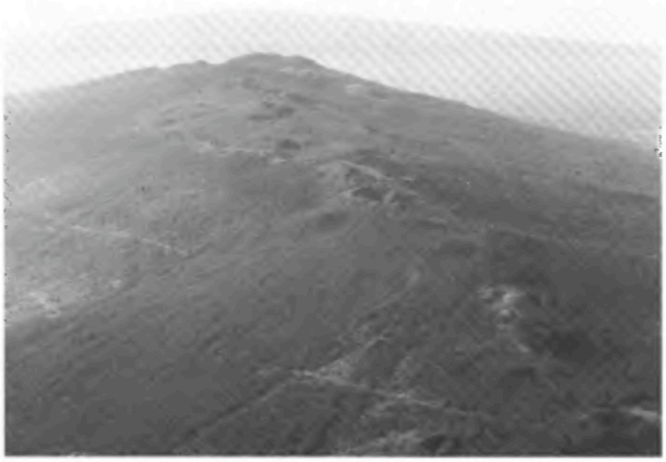

FIGURE 20.2.—Aerial view looking southeast over part of northwest rift zone of Hualalai Volcano. Mauna Loa is in background. Main 1800 vent is in center (no light-colored grass on flow), and another previously unmapped 1800 vent and flow are in lower right corner. Cone slightly to left of main 1800 vent and in front of it was nearly buried by 1800 flow.

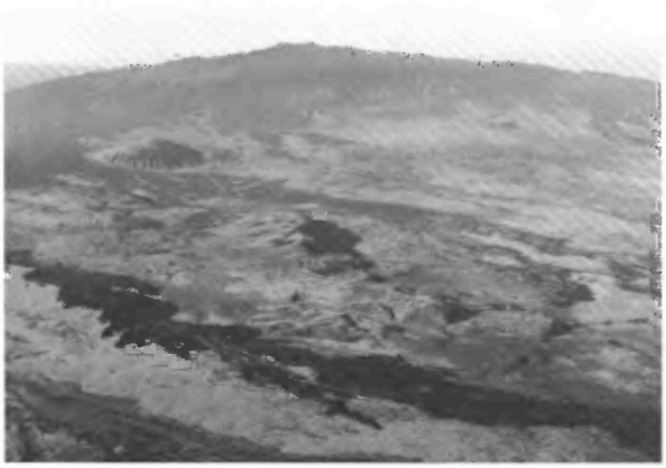

FIGURE 20.3.—Aerial view of Hualalai Volcano from north. Dark flow in foreground is 1859 Mauna Loa flow. Large cone with pronounced radial drainage is Puu Waawaa, consisting of trachyte. A trachyte flow from that cone forms steep hummocky topography, partly casting a shadow, in center of photograph. Dark flow in front of Puu Waawaa is dated at 2,030±80 yr B.P. A few small basaltic cones of the diffuse north rift zone are visible behind Puu Waawaa.

quadrangles that cover Hualalai. The mapping has been supplemented by ^{14}C ages presented in table 20.1. The generalized age-distribution map that summarizes this effort is shown in figure 20.5, and data on areas covered by lava of different age are given in table 20.2. Paleomagnetic studies (D.E. Champion, unpub. data, 1985) and future ^{14}C ages may modify these numbers slightly. The data in table 20.2 show that about 95 percent of Hualalai's surface is Holocene, as noted by Stearns and Macdonald (1946), and 25 percent is covered by lava that is <1,000 years old.

FIGURE 20.4.—Aerial view looking north-northwest across upper south-southeast rift zone of Hualalai Volcano. Most visible cones and flows are Holocene in age. Haleakala Volcano on Maui is in distance.

Hualalai has erupted about 0.2 km^3 of basalt per century during the last 3,000 years. This figure is an order of magnitude less than the 2.9 and 2.2 km^3 erupted per century by Mauna Loa and Kilauea, respectively, during historical (post-1820) time (Lockwood and Lipman, chapter 18; Macdonald, 1955).

PLEISTOCENE UNITS

Rocks of Pleistocene age that crop out on the subaerial surface of Hualalai include the Waawaa Trachyte Member (fig. 20.3), a few vent deposits and associated short flows of hawaiite, and a few alkalic basalt lava flows. Funkhouser and others (1968) reported a K-Ar age of 0.4±0.3 Ma for the Waawaa Trachyte Member; more recent K-Ar determinations suggest that the trachyte is about 105 ka (G.B. Dalrymple, written commun., 1985). The volume of the Waawaa cone and flow is about 5.5 km^3, the largest volume single eruption known on the island.

The oldest dated basaltic flows on Hualalai are three flows of age 12–13 ka; each overlies another basalt flow of limited areal extent. We consider it unlikely that any older large flows will be discovered.

A cluster of cones that are mostly Pleistocene in age occurs in the summit area of the volcano (fig. 20.6). Lava dated at 12,950±150 yr B.P. underlies the northeastern part of the village of Kailua and could have come only from the summit area. The summit crater (fig. 20.6) exposes dozens of flow units that suggest eruption on a satellitic shield, like Mauna Ulu on Kilauea Volcano. Near the end of the shield-building eruption, phreatic explosions ejected blocks of gabbro and diabase from a subsurface intrusion. Overlying the resulting tuff is a thin (≤1 m) lava flow of mixed hawaiite and alkali olivine basalt. A cone that overlies all of these deposits has been dated at 8,770±200 yr B.P.

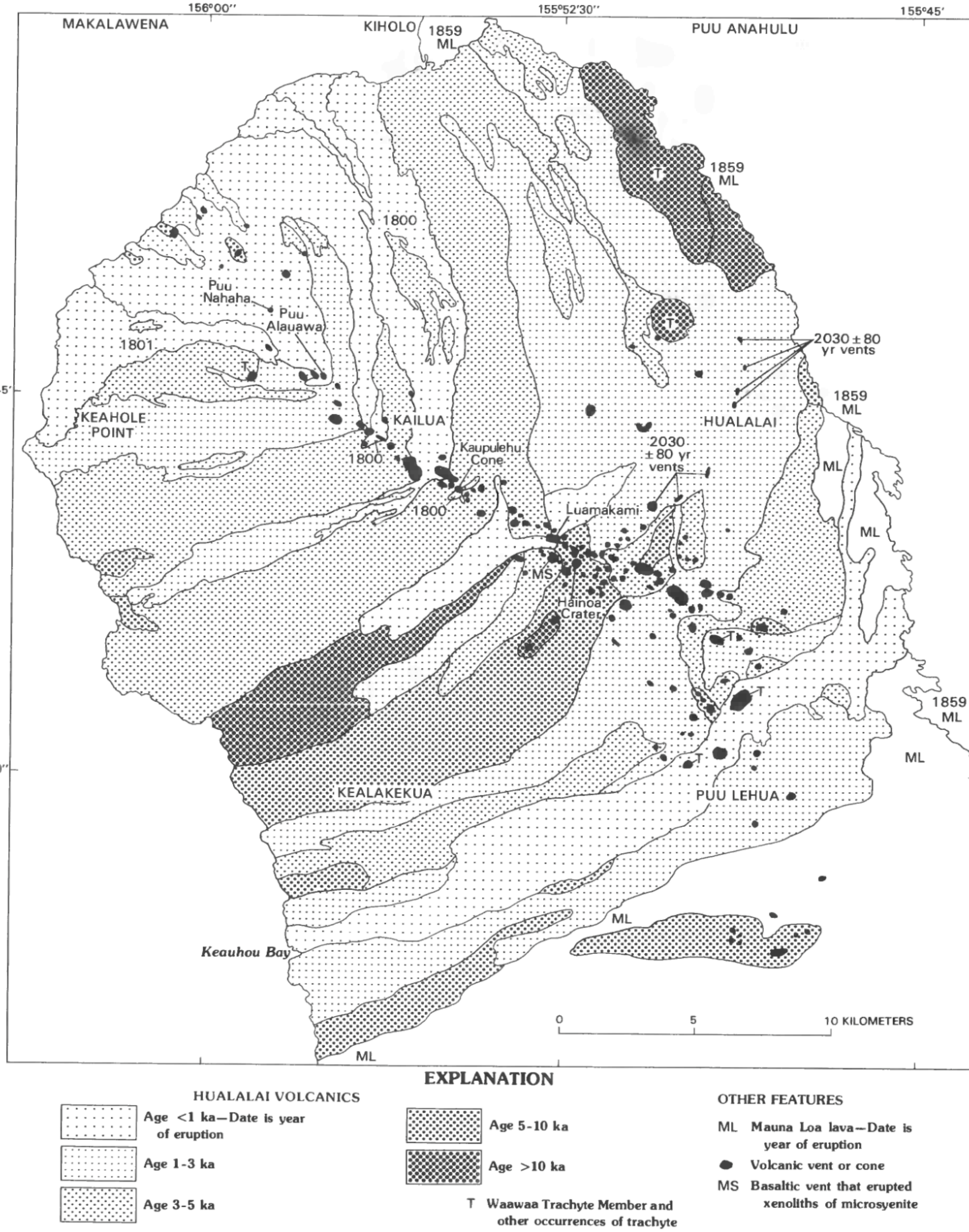

FIGURE 20.5.—Generalized geologic map of Hualalai Volcano showing age distribution of lava and locations of vents. Not all smaller vents are shown. Names of USGS 7½-minute topographic quadrangles used in mapping are shown in all capital letters.

TABLE 20.1.—*Carbon-14 ages of samples from Hualalai Volcano*

Sample	Laboratory Number	Age (yr B.P.)	Unit from which sample taken
79-15	W-4634	<200	An A.D. 1800 lava flow
82-75	W-5124	<200	An A.D. 1800 lava flow
79-8	W-4394	300±60	Young Luamakami flow
84-175	W-5531	710±150	Waha Pele flow
84-150	W-5491	900±110	Flow from large vent 3 km northeast of Waha Pele
82-129	W-5130	1030±60	Flow from cone 2 km northwest of Luamakami
84-170	W-5522	1180±200	Flow from vent 4.5 km north-northwest of Waha Pele
78-2	W-4171	2030±80	Flow from vent 3 km southeast of Puu Waawaa
79-3	W-4388	2290±70	Flow from vent 1 km west of Waha Pele
82-20	W-5068	2350±80	Old Luamakami flow
82-8	W-5073	2390±60	Cone 3 km northeast of Hainoa Crater
82-19	W-5076	2670±80	Cone 700 m east-northeast of Hainoa Crater
84-115	W-5559	3030±200	Flow 8 km northwest of Hainoa Crater
82-113	W-5127	3100±80	Cone 700 m northwest of Luamakami
78-12	W-4376	3600±70	Flow along Highway 190 4 km north-northwest of Kailua
84-119	W-5562	3610±200	Flow 900 m west of Puu Waawaa
82-131	W-5132	3990±70	Spatter 300 m northwest of Hainoa Crater
82-23	W-5070	4390±70	Flow from cone 1 km west of Hainoa Crater
79-10	W-4378	4720±80	Second highest flow in west Malekule pit crater
83-9	W-5297	6360±100	Flow from cone 1.6 km southeast of Hainoa Crater
83-14	W-5299	8770±200	Cone 60 m north of Hainoa Crater
78-5	W-4371	9490±100	Flow 10 km north-northwest of Puu Waawaa
78-11	W-4391	10,370±150	Flow 3 km north-northwest of Keauhou Bay
79-1	W-4365	12,230±150	Flow 4 km north of Puu Waawaa
82-1	W-5056	12,950±150	Flow 3 km east northeast of Kailua

TABLE 20.2.—*Areas of Hualalai Volcano's surface covered by lava of different ages*

[Quadrangle names refer to USGS 7½-minute topographic map sheets; percent figures give the percentage of the Hualalai part of each quadrangle covered by lava of that age group]

Quadrangle	Age group of lava: <1 ka (km^2)	(percent)	1-3 ka (km^2)	(percent)	3-5 ka (km^2)	(percent)	5-10 ka (km^2)	(percent)	>10 ka (km^2)	(percent)
Makalawena -----	22	68.3	5	15.5	5	15.5	0.2	0.6	0	0
Kiholo ---------	95	59.2	25	15.6	40	24.9	0.5	0.3	0	0
Puu Anahulu ----	0	0	48	57.5	8	9.6	0.5	0.6	27	32.3
Hualalai -------	29	18.1	72	45.0	42	26.3	17	10.6	0	0
Kailua ---------	16	8.8	27	14.8	78	42.9	44	24.2	17	9.3
Keahole Point --	2	3.6	16	28.6	36	64.3	2	3.6	0	0
Kealakekua -----	21	27.3	24	31.2	10	13.0	22	28.6	0	0
Puu Lehua ------	16	27.1	25	42.4	2	3.4	16	27.1	0	0
Total ----------	201	24.8	242	30.0	221	27.3	102.2	12.6	44	5.4
Cumulative Percent -------		24.8		54.8		82.1		94.7		100.1

HOLOCENE UNITS

We have divided the Holocene lava flows of Hualalai into four age groups, based on our detailed and reconnaissance mapping and on ^{14}C ages: 10–5 ka, 5–3 ka, 3–1 ka, and <1 ka. About 55 percent of the surface has an age of less than 3 ka and 25 percent less than 1 ka. In contrast, Holcomb (1981) determined that 90 percent of the surface of Kilauea Volcano is younger than 1 ka, and Lockwood and Lipman (chapter 18) found that 40 percent of Mauna Loa is younger than 1 ka.

Inspection of figure 20.5 suggests that locations of vents of different ages are generally random; however, two important aspects of the volcano's overall morphology require discussion. First, the coastal part of the volcano north of the town of Kailua (figs. 20.5, 20.7) is a lava delta that has been built mostly in the last 3,000 years. The northwest rift zone, marked by spatter cones and ramparts, forms the axis of this feature; lava has built the volcanic pile nearly equally on both sides of the rift zone.

Second, the coast south of Kailua is relatively straight (fig. 20.7), and lava deltas are fewer. Some of the oldest subaerial flows on the volcano occur in this area; marine erosion typically has straightened the shoreline, whereas farther north erosion has not overcome the constructional landforms.

Several vent deposits and associated flows of Holocene age merit individual description. The eruptions of 1800–01 occurred from five separate vent areas (fig. 20.5) and extruded more than

FIGURE 20.6.—Aerial view looking north over summit area of Hualalai Volcano. Actual summit at elevation 2,521 m (8,271 ft) is between two large craters in center of photograph. Small crater barely visible just beyond Hainoa Crater (largest crater) is dated at 8,770 ± 200 yr B.P.; cone in right middle distance is dated at 2,670 ± 80 yr B.P.

300×10^6 m^3 of alkali olivine basalt. The main 1800 flow swept more than 30 m up a cone 450 m north of the vent (fig. 20.2), carried hundreds of thousands of large mafic and ultramafic xenoliths (fig. 20.8) farther downslope, and destroyed fishing villages when it reached the sea (Brigham, 1909).

The 1801 vents of the Huehue flow form a spatter rampart aligned down the slope of the volcano. This orientation caused the lava to flow longitudinally within the rampart. The flows are almost entirely tube-fed pahoehoe. A second vent slightly uphill and south of the main 1801 vents fed a small flow that overlies the main 1801 flows. This younger 1801 vent must have had extremely gentle eruptive activity because no rampart or cone was constructed along the eruptive fissure. A previously undiscovered 1800–01 vent at 1,296-m (4,250 ft) elevation on the northwest rift zone fed small aa flows down both the north and west flanks of the rift system. The fifth 1800–01 vent occurs within the much older Kaupulehu cone. The eruption veneered part of the cone and fed small flows in three directions. The eruptive sequence of the five vents is not known, but the main activity of the eruptive sequence appears generally to have migrated downslope.

The next youngest major eruption apparently occurred from Luamakami, 1 km northwest of the summit, at 300 ± 60 yr B.P., and produced flows that swept down both the north and southwest flanks of Hualalai. After extrusion of about 200×10^6 m^3 of alkali olivine basalt, collapse at one vent caused a minor phreatic explosion that deposited fragments of contact-metamorphosed basalts derived from the walls of the conduit (fig. 20.9).

FIGURE 20.7.—Aerial view looking north along western coast of Hualalai Volcano. Keauhou Bay is in foreground, dark flow from Waha Pele forming its north side. Town of Kailua is in middle distance. Lava flow of 1801 is large dark patch in distance.

The next youngest major eruption occurred at Waha Pele, on the south-southeast rift zone (figs. 20.10, 20.11), at 710 ± 150 yr B.P. As basaltic magma approached the surface, it apparently intersected a perched water table, resulting in massive phreatic explosions. Fragments of trachyte and basalt as large as 0.4 m in diameter were distributed over an area of at least 10 km^2. Later in the eruption, basaltic magma reached the surface, vigorous Strombolian activity built a wide low cone of spatter, and a large flow was extruded. This flow, which has a subaerial volume of at least 400×106 m^3, entered the sea, forming the north side of Keauhou Bay (fig. 20.7), and continued underwater for less than 1 km (J.G. Moore and D.A. Clague, unpublished data). Xenoliths of gabbro and dunite are locally common in the flow.

Another sequence of eruptions occurred on the northwest rift about 800 years ago. The vents formed then include Puu Nahaha, Puu Alauawa, and an unnamed vent about 200 m uprift from Puu Alauawa. Puu Nahaha is the oldest of these three vents and erupted mainly olivine-poor aa that flowed to the ocean on a broad front. Puu Alauawa is the next youngest and erupted plagioclase-rich pahoehoe that formed a large channel and tube system on the steep

FIGURE 20.8.—Xenoliths of 1800 Hualalai flow. Note that most of host basalt has drained away.

FIGURE 20.9.—East rim of Luamakami, Hualalai Volcano. Light-colored rocks, mainly on right, are thermally metamorphosed basalt ejected during phreatic explosion at end of eruption 300 ± 60 yr B.P.

slopes near the vent. Finally, the unnamed vent erupted and formed both pahoehoe and aa flows of olivine-rich lava. A perched lava pond formed above the eruptive fissure; no rampart or cone exists. These flows were dominantly constrained within the channel and tube system developed during the eruption of Puu Alauawa, and the result was a large flow that traveled about 10 km (northwestward) to the ocean, forming a lava delta about 3 km wide. Most of the short flows near the vent are dense aa flows, whereas the main flow is pahoehoe that partly transforms to a slabby aa near the ocean. These eruptive vents migrated uprift during the eruptive sequence. The ages of their flows are constrained by identical and unique paleomagnetic orientations for the earliest and latest flows (D.E. Champion, written commun., 1985).

FIGURE 20.10.—Waha Pele area of Hualalai Volcano from the east. Waha Pele, dated at 710 ± 150 yr B.P., is in center of photograph (arrow); dark flow from it extends to left out of photograph. Cone and flow just beyond it is dated at 2,290 ± 70 yr B.P. Light-colored areas in foreground and middle distance are underlain by trachytic debris ejected during phreatic first phase of Waha Pele eruption. Cone in right foreground consists of ankaramite with abundant mafic and ultramafic xenoliths. Part of Kailua is visible in distance.

FIGURE 20.11.—Aerial view north across part of the south-southeast rift zone of Hualalai Volcano. Waha Pele and its flow are in foreground; grassy light-colored areas just beyond Waha Pele are underlain by explosively ejected trachyte debris. Flow in right middle distance is dated at 900 ± 110 yr B.P. Large lava channel below horizon in center is part of extensive flow dated at 1,180 ± 200 yr B.P. Sharp cone on left horizon probably is about 3,000 years old; note prominent pahoehoe channel issuing from it. Part of Kohala Volcano is in distance.

An unnamed vent 3 km northeast of Waha Pele (fig. 20.12) erupted about 900 ± 110 years ago. Initial high fountaining distributed basaltic cinders and small xenoliths of trachyte over a wide area and built a large low spatter cone about 1 km in diameter and 40–60 m high. Continued voluminous production of lava constructed a satellitic shield within the older cone, and floods of lava

FIGURE 20.12.—Unnamed vent 3 km northeast of Waha Pele. This vent, dated at 900±110 yr B.P., is source of flow on right side of figure 20.10. Note partly collapsed satellitic shield in lower left corner; shield fills crater of older spatter cone that formed during early stages of eruption.

rafted away parts of the cone. The flow, which has an estimated volume of 800×10^6 m^3 (one of the largest in Hawaii), moved 4 km south and 12 km north-northeast of the vent. The final events in the eruptive history of this remarkable vent were collapse of the summit of the shield to form small nested pit craters and a small eruption of alkali olivine basalt, richer in olivine and plagioclase phenocrysts than the previously erupted material, that built a small cone and flow within one of the pit craters.

Underlying part of the previously described flow are the products of another large eruption that occurred at 1,180±200 yr B.P. The vent for this eruption, again unnamed, is 4.5 km north-northeast of Waha Pele. High fountaining distributed basaltic cinders and xenoliths of trachyte over a wide area. Voluminous pahoehoe flows spread northeast and southeast. These flows, which we have not yet finished mapping, are thinner than those of the 900-year-old eruption but still have a volume in excess of 400×10^6 m^3.

The youngest eruption on the diffuse north-trending rift zone occurred at about 2,030±80 yr B.P. This eruption was unusual in that left-stepping echelon eruptive vents, which occur over a distance of 8 km, cut obliquely across the general strike of the rift zone, changing orientation from N. 10° W. at the northern end to N. 50° E. at the southwestern end (fig. 20.5). Similar changes in vent alignment occur over shorter distances on the northeast rift zone of Mauna Loa. It appears that the eruptive dike was fed from a reservoir beneath Hualalai's summit and followed a radial fracture extending northeastward. When it reached the northeast flank of Hualalai, a stress field probably induced by Mauna Kea caused a change in strike of the eruptive vents until they were parallel to the edge of the Mauna Kea edifice. Lava erupted at the lower elevation (1,130 m; about 3,700 ft) first and gradually broke out higher on the volcano's flank to the south and southwest as the eruption progressed, reaching elevations around 1,830 m (about 6,000 ft). We estimate the volume of this eruption to be at least 400×10^6 m^3.

PETROLOGY

THOLEIITIC SHIELD STAGE

Flows of tholeiitic basalt and picritic tholeiitic basalt of the shield stage are not exposed on the subaerial surface of Hualalai. However, the presence of a tholeiitic shield beneath the subaerial alkalic flows is confirmed by the recovery of tholeiitic basalt by dredging on the submarine northwest rift zone (Clague, 1982). In addition, tholeiitic basalt has been recovered in several water wells, and picritic tholeiitic basalt occurs as xenoliths at Waha Pele; these rocks probably are from subsurface parts of Hualalai.

The locations where tholeiitic lava has been found are shown in figure 20.1, and chemical analyses of several samples are presented in table 20.3. The discovery of tholeiitic basalt from Hualalai indicates, as with other Hawaiian volcanoes, that the vast bulk of the volcano is made of tholeiitic lava and that alkalic lava occurs in relatively small volume in the late stages of volcano growth (Clague, 1982).

The submarine tholeiitic basalt samples contain only olivine and spinel phenocrysts with the exception of two samples that also contain plagioclase and clinopyroxene. The picritic tholeiitic basalt samples contain euhedral olivine phenocrysts, subhedral to anhedral kink-banded olivine xenocrysts, extremely rare orthopyroxene

TABLE 20.3.—*Compositions of tholeiitic basalt samples from Hualalai Volcano*

[Major elements analyzed by X-ray fluorescence by J.S. Wahlberg, J. Taggart, and J. Baker; partial chemistry by B. Lai, H. Neiman, and E. Engleman, trace elements by X-ray fluorescence by H.J. Rose, J. Lindsay, B. McCall, G. Sellers, and R. Johnson; all of the USGS. KK7812–11 and KK9–2 are submarine samples from the northwest rift zone; K–11 and K–13 are from the Kahaluu water shaft (fig. 20.1)]

Sample	KK7812-11	K-13	K-11	KK9-2
	Major elements (weight percent)			
SiO_2	46.8	51.1	51.4	50.8
Al_2O_3	8.48	13.0	13.8	13.3
Fe_2O_3	1.29	3.03	5.67	2.33
FeO	10.4	8.16	5.79	8.43
MgO	23.0	9.79	7.86	7.57
CaO	6.49	10.3	10.6	10.6
Na_2O	1.36	2.01	2.05	2.15
K_2O	.20	.25	.22	.33
H_2O^+	.20	.04	.17	.36
H_2O^-	.08	.07	.27	.05
TiO_2	1.33	1.95	1.97	2.14
P_2O_5	.14	.18	.16	.24
MnO	.12	.17	.17	.16
CO_2	.04	.03	.28	<.01
Total	100.0	100.1	100.4	98.4
	Trace elements (ppm)			
Rb	4	3	<2	8
Sr	168	244	244	296
Y	14	22	25	24
Zr	77	100	97	131
Nb	<5	<5	7	12

xenocrysts, and rare small gabbroic xenoliths. The olivine-porphyritic and picritic samples plot on olivine-control lines and can be related by fractionation and accumulation of olivine of variable forsterite content. Hualalai tholeiitic basalt has trace-element and isotopic ratios distinct from Mauna Loa, Kilauea, and Loihi tholeiitic basalt and is also isotopically distinct from the overlying alkalic basalt (Clague, 1982). These differences are illustrated in table 20.4, which shows that Hualalai tholeiitic basalt is most similar to that of Mauna Loa, but that the trace-element and isotopic differences between tholeiitic basalt from the different volcanoes require that the source regions be different compositionally. The large variations in La/Yb and La/Y ratios indicate a major role for garnet in the generation of Hawaiian tholeiitic basalt. Further modeling of the major-element, trace-element, and isotopic data is in progress and will be presented elsewhere.

TABLE 20.4.—*Elemental and isotopic ratios in tholeiitic lava from Hualalai and other Hawaiian volcanoes*

[Helium data from Kurz and others (1983); other data from Clague (1982)]

	Hualalai	Mauna Loa	Kilauea	Loihi
La/Sm	2.2	1.8–2.0	2.2–2.8	2.4
La/Yb	3.6	4–5	6–8	6.0
La/Y	.36	.4	.5– .7	.55
K_2O/P_2O_5	1.7	1.8	2.0	1.5
$^{87}Sr/^{86}Sr$	.70373	.70374–.70386	.70348–.70379	.70347–.70357
$(^3He/^4He)_{Atm}$	14.4–17.6	8.0–8.6	13.4–14.7	24.4–31.9

ALKALIC STAGE

The surficial flows of Hualalai Volcano are alkali olivine basalt or basalt transitional to hawaiite, with the exception of the Waawaa Trachyte Member cone and its flow. Trachyte also occurs as blocks in the maar deposit at Waha Pele, as a subsurface flow (drilled near the 1801 vents, figs. 20.1, 20.5), and as small chips in the cinder deposits of two other vents. These occurrences suggest that trachyte is relatively widespread on Hualalai, but that most exposures have been buried beneath subsequent alkalic basalt flows. Chemical analyses of trachyte from three of these locations are presented in table 20.5, and the locations are shown in figure 20.1. Some of the trachyte samples contain rare (<2 percent) modal nepheline.

Clague and others (1980) presented geochemical data for 17 samples of prehistoric alkali basalt flows and 15 samples from the 01 eruptions. They reached the following conclusions: (1) The historical flows are nearly homogeneous, although several samples reflect accumulation and resorption of olivine, plagioclase, and clinopyroxene xenocrysts. (2) The prehistoric flows are chemically similar to the historical flows, although they include lava that underwent fractionation leading to hawaiite. (3) The alkalic basalt magma can be derived by 5–10 percent partial melting of a garnet-bearing source that is enriched in the light rare-earth elements. (4) The source region for alkalic basalt beneath Hualalai is particularly rich in K_2O compared to that beneath other Hawaiian volcanoes.

TABLE 20.5.—*Compositions of trachyte samples from Hualalai Volcano*

[Data for HAW-15 from Basaltic Volcanism Study Project (1981). Samples 67–101A and 67–104 are accidental blocks collected by T. Wright. Analyses are classical wet chemistry by G. Riddle of the USGS; --, not determined]

Vent	Pau Waawaa	Waha Pele	Unnamed vent 3 km northeast of Waha Pele
Sample	HAW-15	67-101A	67-104
	Major elements (weight percent)		
SiO_2	62.99	63.10	62.84
Al_2O_3	18.04	17.79	17.86
Fe_2O_3	4.42	2.24	2.67
FeO	0	1.35	.90
MnO	.32	.52	.49
CaO	.71	0.79	.66
Na_2O	7.19	7.63	7.18
K_2O	4.87	4.97	4.90
H_2O^+	1.31	.26	.67
H_2O^-	1.31	.04	.16
TiO_2	.45	.50	.48
P_2O_5	.13	.12	.13
MnO	.29	.30	.27
CO_2	.11	.00	.00
Cl	--	.06	.01
F	--	.09	.08
Total	100.8	99.71	99.27
	Trace elements (ppm)		
Rb	108	--	--
Sr	48	--	--
Y	23	--	--
Zr	905	--	--
Nb	127	--	--

Some of the alkali basalt vent deposits are aphyric, whereas others contain phenocrysts of olivine, olivine and plagioclase, or olivine, clinopyroxene, and plagioclase (table 20.6). The most abundant lava type is olivine-porphyritic basalt. There is no clear correlation of phenocryst mineralogy with either age or location of the vents on the volcano; however, as noted earlier, clusters of vents with similar mineralogy occur locally.

TABLE 20.6.—*Comparative abundance of phenocryst assemblages in samples of alkali basalt from Hualalai Volcano*

[Based on study of 256 samples of vent deposits, bombs, and cognate blocks]

Phenocryst assemblage	Percent of samples
Olivine	37
Olivine + plagioclase	24
Olivine + pyroxene	8
Olivine + plagioclase + pyroxene	24
Plagioclase	2
Aphyric	5

We now have analyses of about 300 samples of alkalic lava representing all the vents and many flows on the modern surface. Chemical analyses of 21 dated flows are presented in table 20.7. The analyses of alkalic basalt, trachyte, and tholeiitic basalt from tables 20.3, 20.5, and 20.6 and other unpublished analyses are plotted on the Macdonald-Katsura alkali-silica diagram in figure 20.13. We have also plotted magnesium-variation diagrams (fig. 20.14) using all available analyses of Hualalai lava. In addition, Peterson and Moore (chapter 7) compare Hualalai analyses with those from other Hawaiian volcanoes. Most of the plots display wide scatter that partly reflects varied phenocryst populations. The plot of Al_2O_3 against MgO has the tightest cluster of data and best shows the importance of olivine control; some scatter occurs at the low-magnesia end, as differentiation has proceeded beyond olivine control. Alkalic lava is olivine-controlled only at relatively high MgO contents.

Part of this study was designed to evaluate changes in lava chemistry through time. Because we have not yet completed mapping all of the volcano, we cannot at this time construct a detailed stratigraphic history of the surface flows. However, we have analyses of 18 alkalic basalt flows dated by ^{14}C that range in age from 12,950 yr B.P. to the historical 1800–01 flows. These samples can be used to evaluate time-dependent compositional changes. The major- and trace-element data from these samples are given in table 20.6, arranged from oldest to youngest. We have examined K_2O/P_2O_5, Zr/Nb, Zr/Y, Rb/Sr, and K/Rb ratios as a function of time and find no correlations that indicate systematic chemical changes through the last 13,000 years of volcanic history. In addition, we have analyzed samples from the 1800 flow, the 1801 flow, and one prehistoric vent deposit for $^{87}Sr/^{86}Sr$ ratio, and all are within analytical precision at 0.70362 ± 0.00001.

The data for the younger alkalic lava, combined with that for the much older tholeiitic lava recovered from the submarine northwest rift zone, display the same inverse correlation between $^{87}Sr/^{87}Sr$ and Rb/Sr (or La/Sm) ratios seen at other Hawaiian volcanoes (Chen and Frey, 1983; Clague and others, 1983; Feigenson, 1984; Roden and others, 1984). More detailed analysis of the alkalic basalt erupted during the last 13,000 yr may show subtle time-dependent chemical variations. However, at the present time we can only compare the groups of tholeiitic and alkalic lava flows to evaluate chemical changes over long time periods. As at Haleakala, East Molokai, Kauai, and Oahu, the samples with the most enriched trace-element ratios and the least radiogenic isotopic ratios are of younger alkalic basalt. These data can be explained by mixing of melts derived from several sources (see Chen and Frey, 1983), but they imply a complex petrogenesis of the lava.

XENOLITHS

The A.D. 1800 Kaupulehu flow on Hualalai Volcano is well known for its abundant coarse-grained xenoliths (Richter and Murata, 1961; Jackson, 1968; Jackson and others, 1981), and many prehistoric vent deposits and flows also contain abundant

TABLE 20.7—*Composition of alkali basalt samples from historical and prehistoric dated flows of Hualalai Volcano*

[All ages given in years B.P. and derived from ^{14}C determinations, except for historical 1800–01 flows. Major element data from rapid wet-chemical analyses by D. Kobilis, except those for sample 67–101, average 1800, 1801 toe, and vent, which are classical wet chemical analyses from Clague and others (1980). Trace elements analyzed by energy-dispersive X-ray flourescence by W. Bohrson; except those from the historical 1800– flows, which are from Clague and others (1980). --, not determined]

Sample --	82-1A	79-1	78-11	78-5	79-10	82-23	82-131	78-12	81-22	82-7	81-92	81-47	81-86	82-129	81-152	81-153	67-101	81-91	Avg 1800	Toe 1801	Vent 1801
Age -----	12,950	12,230	10,370	9,490	4,720	4,390	3,990	3,600	2,670	2,390	2,350	2,290	1,180	1,030	900	900	710	300	150	149	149
Major elements (weight percent)																					
SiO_2 ---	45.6	46.2	47.0	46.0	46.5	46.1	46.3	47.7	46.9	47.9	46.7	47.5	45.9	47.1	46.6	47.3	46.74	47.3	46.55	46.10	46.48
Al_2O_3 --	13.7	11.8	10.9	12.8	13.2	12.9	13.9	15.2	14.8	15.4	14.1	13.8	13.9	14.4	14.9	13.9	14.60	16.2	14.64	13.18	14.67
Fe_2O_3 --	3.8	1.5	1.8	2.9	3.2	2.6	5.7	2.6	7.9	2.8	2.5	5.5	4.6	2.1	3.0	3.4	2.12	1.8	2.97	3.30	2.36
FeO ----	8.4	10.4	10.4	9.1	9.1	9.6	6.8	10.1	5.2	10.3	9.5	7.0	8.1	10.7	9.6	9.7	10.35	10.3	9.80	8.86	10.24
MgO ----	10.8	13.5	14.7	10.5	10.7	11.2	11.3	5.4	6.7	6.0	9.6	10.0	9.7	9.7	8.7	10.3	9.20	6.1	9.04	11.86	9.17
CaO ----	10.4	10.1	9.3	11.5	10.2	10.1	10.0	10.1	10.3	8.7	10.3	10.4	9.8	10.4	10.2	8.0	10.67	8.3	10.15	11.41	10.35
Na_2O ---	2.2	2.2	2.1	2.3	2.5	2.3	2.4	3.2	3.3	3.6	2.5	2.5	2.4	2.6	2.8	3.0	2.71	3.6	2.90	2.26	2.77
K_2O ----	.65	.65	.56	.78	.83	.76	.69	1.27	1.17	1.2	.69	1.03	1.21	.9	.85	1.15	.811	1.37	.91	.66	.87
H_2O^+ ---	.99	.21	.21	.25	.13	.67	.83	.22	.46	.57	.20	.22	.19	.65	.38	.48	.10	.16	.07	.02	.09
H_2O^- ---	--	.05	.03	.11	.05	--	--	.12	.10	--	.07	.19	.22	--	.09	--	.06	.19	.05	.02	.05
TiO_2 ---	2.1	1.9	1.9	2.0	2.0	1.9	2.0	2.9	2.5	2.7	1.9	2.2	2.3	2.3	2.2	2.2	2.06	2.6	2.40	1.82	2.27
P_2O_5 ---	.24	.22	.20	.27	.28	.25	.27	.38	.37	.43	.27	.32	.33	.31	.31	.36	.25	.47	.28	.22	.28
MnO ----	.19	.20	.18	.21	.21	.14	.16	.20	.18	.17	.17	.19	.18	.18	.23	.21	.18	.19	.19	.18	.19
CO_2 ----	.01	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.04	.02	.02	.01	.02	.01	.02	.01
Cl -----	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	.02	--	.03	.03	.03
F ------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	.06	--	.05	.04	.06
Total	99.1	99.0	99.3	98.7	98.9	98.5	100.4	99.4	99.9	99.8	98.5	100.9	98.9	101.4	99.9	100.0	99.94	98.6	100.04	99.98	99.89
Trace elements (ppm)																					
Rb -----	15	11	14	--	16	30	28	28	32	37	19	25	32	35	24	21	18	40	34	31	34
Sr -----	380	340	267	--	411	408	412	510	487	599	347	425	468	430	441	438	424	582	456	360	417
Y ------	19	21	14	--	21	21	22	29	28	25	21	20	22	22	21	19	23	31	21	17	18
Zr -----	114	113	87	--	123	119	122	181	177	202	121	138	144	151	134	134	137	215	147	115	143
Nb -----	15	18	13	--	22	19	20	35	31	32	16	18	24	22	18	18	22	38	--	--	--
Ni -----	252	420	533	--	312	331	330	58	101	71	229	210	233	206	166	134	187	76	152	520	290

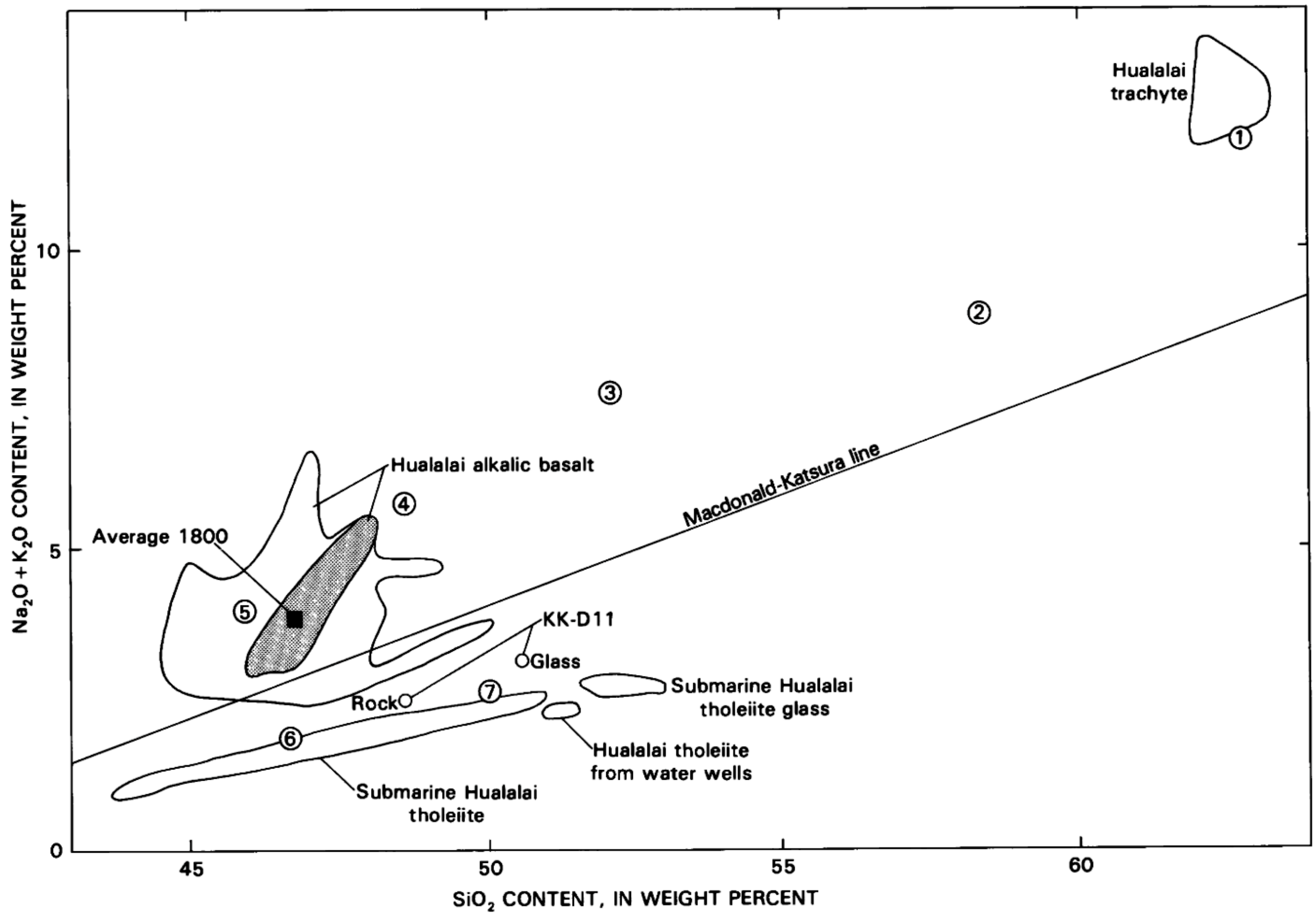

FIGURE 20.13.—Alkali-silica diagram showing the fields for Hualalai lava groups. Shaded Hualalai alkalic basalt field is from Clague and others (1980) and large unshaded field is based on about 300 new analyses. Sample KK–D11, dredged from northwest rift zone, is chemically distinct from other dredged or drilled tholeiitic samples in that it has higher alkali contents and has trace-element signature intermediate between tholeiitic basalt and alkalic basalt. Circled numbers are average Hawaiian compositions from Macdonald (1968): 1, trachyte; 2, benmoreite; 3, mugearite; 4, hawaiite; 5, alkalic basalt; 6, picritic tholeiitic basalt; 7, tholeiitic basalt.

xenoliths. Richter and Murata (1961) briefly described the remarkable occurrence of xenoliths in discrete cobble beds at about 950 m elevation in the Kaupulehu flow. More recently, Jackson and Clague (1982) presented a detailed plane-table map of this site, and Jackson and others (1981) presented data on the lithology, size, shape, density, mineralogy, and chemistry of xenoliths from the site. During our detailed mapping of Hualalai Volcano we have discovered numerous additional vents and flows and several pyroclastic deposits that contain xenoliths, commonly in great numbers. These sites are shown on figure 20.1. With a few exceptions, these new sites, like those described previously, contain dunite and gabbro xenoliths; no lherzolite or garnet-bearing xenoliths have been found. A few vents and flows have either nearly all dunite or nearly all gabbro.

Three sites are distinctive in that the coarse-grained xenoliths occur in pyroclastic deposits; these include the gabbro and diabase xenoliths in a tuff at Hainoa Crater (fig. 20.1), angular blocks of gabbro and syenite as loose blocks on the surface in the vicinity of Malekule (fig. 20.5), and a lag deposit of mainly dunite with less common wehrlite and gabbro from just east of Hainoa Crater. The lag deposit apparently formed as a wind-winnowed cinder deposit, but the other two deposits resulted from phreatic eruptions. The xenoliths in the tuff surrounding Hainoa Crater are mostly diabase with accumulated olivine and clinopyroxene; they probably formed as cumulates in a lava lake within the crater. The xenoliths in the area of Malekule include gabbro and varieties of syenite bearing biotite, apatite, or zircon. These samples apparently represent the cumulates formed in a shallow magma reservoir associated with trachyte erupted early in the alkalic stage at Puu Waawaa and other locations.

Xenoliths in the 1800 Kaupulehu flow are dominantly dunite and wehrlite with metamorphic textures (Kirby and Green, 1980). Only five percent of the xenoliths are dikes, sills, and veins, whereas about one-third are cumulates ranging from dunite, wehrlite, troctolite, clinopyroxene gabbro, and olivine-clinopyroxene gabbro to anorthosite. Orthopyroxene-bearing xenoliths are rare but include

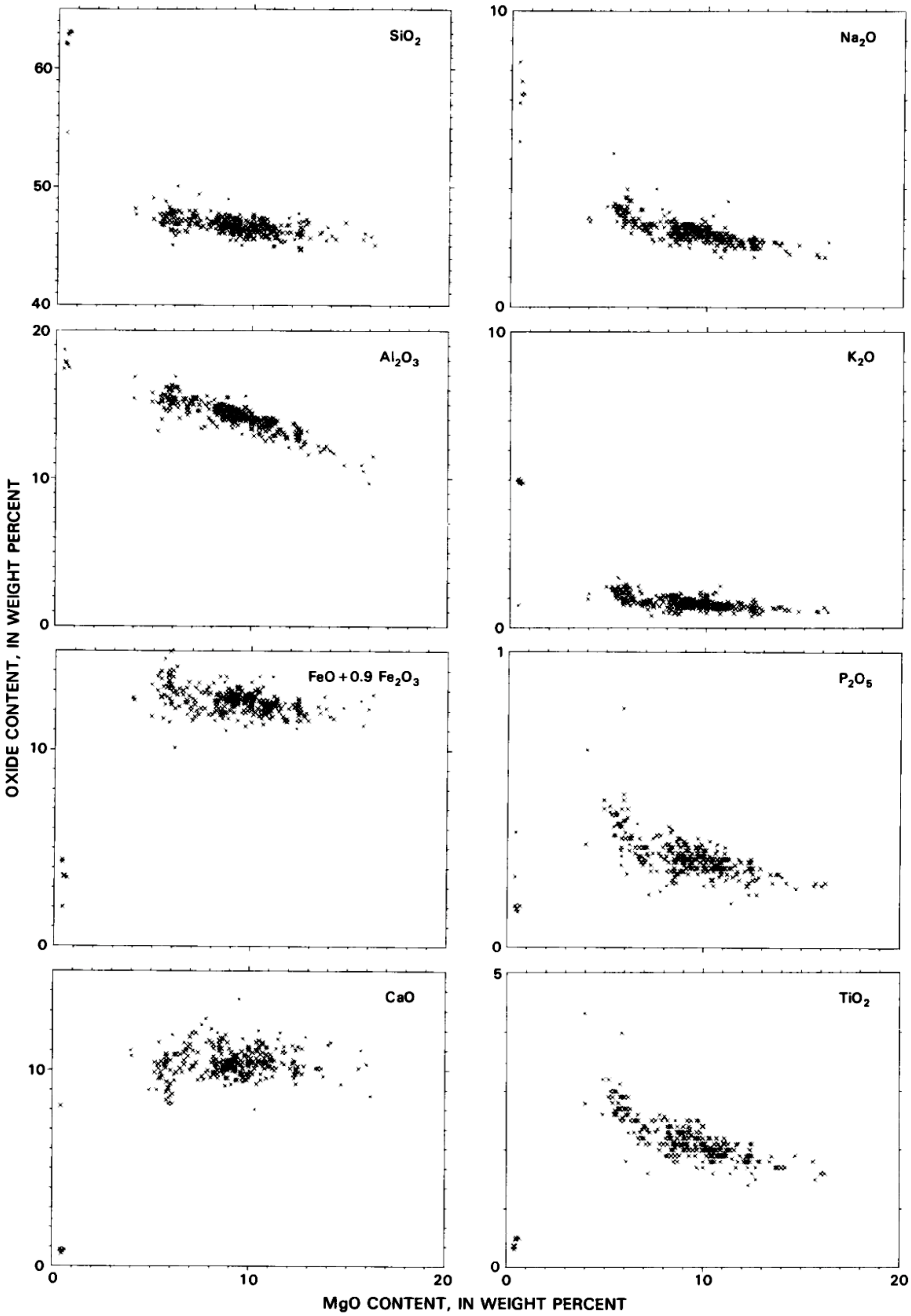

FIGURE 20.14.—Magnesia-variation diagrams for alkalic lava samples from Hualalai Volcano.

websterite and norite. Preliminary analysis of these samples indicates that some are probably cumulates related to the alkalic and tholeiitic lava of Hualalai Volcano, whereas others are related to tholeiitic basalt of the underlying oceanic crust (D.A. Clague, unpub. data, 1985).

The presence of rocks from the oceanic crust, and the pressure inferred from CO_2 inclusions in olivine (Roedder, 1965) in the dunite xenoliths, indicate that the host lava rose rapidly from a depth of about 15–20 km. Clague and others (1980) infer from the lava compositions that some fractionation occurred prior to incorporation of the xenoliths and suggest that the magma fractionated at depth. We propose that this fractionation occurred near the base of the oceanic crust at a depth of about 20 km.

The few rare xenoliths found in the tholeiitic lava dredged from the northwest rift zone are shallow level cumulates similar to those that occur in tholeiitic lava from other Hawaiian volcanoes (Jackson, 1968).

GEOPHYSICAL STUDIES AND GEOTHERMAL POTENTIAL

SEISMICITY

The Hawaiian Volcano Observatory (HVO) has maintained a seismic station 3 km east of Hualalai's summit since 1971. During the last 16 years, no swarms of microearthquakes nor any harmonic tremor from a source beneath Hualalai were recorded. Each year, however, several magnitude-4 earthquakes occur on Hualalai, most commonly from a fairly deep source just off the coast near the northwest rift zone (HVO, unpub. data). This seismicity apparently is not related to magmatic movement within the volcano.

In 1929, an intense swarm of earthquakes, lasting over a month, occurred beneath Hualalai (Macdonald and others, 1983). It seems likely that magma was intruded close to the surface at that time.

GRAVITY

Hualalai is unique among the five volcanoes on the Island of Hawaii in having a gravity high of rather low amplitude that is offset from its summit and rift zones (Kinoshita and others, 1963). The amplitude of this anomaly is 50–60 mGal less than the anomalies over the other four volcanoes. The closed high is nearly 20 km south of Hualalai's summit and appears to be more related to the Kealakekua fault system on the west flank of Mauna Loa than to Hualalai. We suggest that the relatively low gravity (250 mGal) over Hualalai's summit and rift zones reflects the presence of relatively low density trachyte that is thinly mantled with mafic lava.

AEROMAGNETICS

The aeromagnetic data for Hualalai (Godson and others, 1981) are even more striking than the gravity data. Hualalai is the only one of Hawaii's five volcanoes with a pronounced aeromagnetic low over its rift zones and summit area. We interpret these results in the same manner as the gravity data: Hualalai's rift zones and summit are underlain by relatively nonmagnetic material, that is, trachyte. The alternative view, that there is abundant magma above the Curie temperature at shallow levels, seems less likely, given the relative lack of seismicity or significant ground deformation.

ELECTRICAL GEOPHYSICAL STUDIES

Jackson and Sako (1982) have run numerous electrical self-potential traverses across the rift zones and summit area of Hualalai. They report that Hualalai has anomalies similar to those over known heat sources on Kilauea Volcano. They estimate that the depths to the tops of the sources of anomalies near the 1800 vents and near the summit are 200 m and 500 m, respectively. We suggest that the heat probably is residual and associated with a cooling magma body emplaced in 1800.

Kauahikaua and Mattice (1981) carried out resistivity surveys on Hualalai; they found low-resistivity layers beneath the summit and near the 1801 vents and suggested that they might be targets for future geothermal exploration. We suggest that further exploration of the entire northwest rift zone for potential geothermal resources is warranted. The infrequency of eruptions combined with the significant self-potential and resistivity anomalies make Hualalai an attractive target.

VOLCANIC HAZARDS

The stratigraphic and geochronologic data that we have obtained permit a preliminary assessment of the hazards that future eruptions of Hualalai pose to the burgeoning population in the Kona district. These hazards are of two general types, caused by pyroclastic materials and by lava flows.

Pyroclastic deposits on Hualalai generally are of two types: the dominant type is cinders and spatter associated with cone or rampart building at vents; less abundant is debris resulting from explosive phreatic eruptions. The latter are quite rare, although two of the last three major eruptions (those of Luamakami about 300 years ago and Waha Pele about 700 yr ago) included explosive events. At Luamakami (fig. 20.8), phreatic explosions near the end of the eruption ejected blocks of thermally metamorphosed basalt as much as 1 m in diameter at least 100 m from the vent. The affected area was quite small, however; probably less than 0.5 km^2 was devastated.

Explosive phreatic eruptions that preceded basaltic effusion at Waha Pele were more significant. As mentioned earlier, ascending basaltic magma caused violent steam eruptions that ejected blocks of trachyte, picritic tholeiite, and alkali basalt as large as 0.4 m in diameter; fine ash covered an area of at least 10 km^2. This eruption likely would have destroyed anything living nearby, but its effects did not extend to the coast 16 km away, where both ancient and modern people as well as commerce have been concentrated.

Eruptions near sea level on the lower northwest rift zone, by analogy with the 1960 eruption of Kilauea (Richter and others, 1970), could result in local phreatic explosions during dominant Strombolian and effusive activity. Most vent deposits on Hualalai have formed typical cinder-and-spatter cones and spatter ramparts. Although the wide dispersal of cinders from some vents indicates that the eruptions may have been sub-Plinian, it seems unlikely that such eruptions would threaten populated areas.

Lava flows pose by far the greater danger. Hualalai's summit is only 15 km from Kailua; the average topographic gradient across the distance is 168 m/km, corresponding to a 9.5° slope. A flow as voluminous and fluid as that of 1800 could cover that distance in a few hours. Recent (younger than 3,000 yr B.P.) flows have originated at vents that are fairly evenly spaced along the northwest and south-southeast rift zones (fig. 20.5). Thus we cannot predict on that basis where the next activity will occur. On the other hand, the youthfulness of the terrain north of Kailua and the presence of the large self-potential anomaly near the 1800 vents imply that the next eruption may occur on the northwest rift zone. The location of the vent relative to the topographic axis of the rift is critical; a few tens or hundreds of meters to the north or south may determine whether the flows go north over relatively unpopulated ranchland or southwest into populated, industrialized areas. A flow from the southeast rift zone, if it gets within one or two kilometers of the sea, could also be devastating; total property values on the 700-year-old Waha Pele flow are approaching $1 billion. It seems unlikely that mitigating measures, such as diversion barriers, would be effective—the Waha Pele flow locally is more than 15 m thick and is 1.3 km wide at the ocean. Depending on the speed and size of any future flow, evacuation may be the only feasible measure.

The eruptive recurrence interval of Hualalai for all of Holocene time is on the order of 50 years (about 200 eruptions in 10,000 yr), though much longer for any specific point on it. However, our mapping and ^{14}C dating indicate that eruptions have occurred in clusters (groups of several eruptions over a few hundred years, separated by several centuries of inactivity). The current lack of magma-related seismicity and deformation provides no information about when the next eruption might occur. In 1800 the magma ascended quite rapidly from a depth of 15–20 km (Clague and others, 1980), judging from the size and abundance of the mafic and ultramafic xenoliths that it carried up from that depth. This rapid ascent implies that seismic detection of shallow, magmatic movement may precede actual eruptive activity by only a short time. The intervals between the latest Holocene eruptions, including the 186 years since the last one, lead us to suggest that a Hualalai eruption is highly probable within the next 200 years and could well occur during the next few decades.

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