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Geology and petrology of Mahukona Volcano, Hawaii

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Abstract. The submarine Mahukona Volcano, west of the island of Hawaii, is located on the Loa loci line between Kahoolawe and Hualalai Volcanoes. The west rift zone ridge of the volcano extends across a drowned coral reef at about −1150 m and a major slope break at about −1340 m, both of which represent former shorelines. The summit of the volcano apparently reached to about 250 m above sea level (now at −1100 m depth) and was surmounted by a roughly circular caldera. A second rift zone probably extended toward the east or southeast, but is completely covered by younger lavas from the adjacent subaerial volcanoes. Samples were recovered from nine dredges and four submersible dives. Using subsidence rates and the compositions of flows which drape the dated shoreline terraces, we infer that the voluminous phase of tholeiitic shield growth ended about 470 ka, but tholeiitic eruptions continued until at least 435 ka. Basalt, transitional between tholeiitic and alkalic basalt, erupted at the end of tholeiitic volcanism, but no postshield-alkalic stage volcanism occurred. The summit of the volcano apparently subsided below sea level between 435 and 365 ka. The tholeiitic lavas recovered are compositionally diverse.

Introduction

Hawaiian volcanoes evolve through a sequence of eruptive stages that can generally be deciphered for the subaerial portions of the volcanoes by detailed mapping (Stearns 1946). This evolutionary sequence is now thought to include four main stages and begins with an early small-volume submarine alkalic-preshield (Loihi) stage, which is followed by a voluminous tholeiitic-shield stage, a small-volume alkalic postshield stage, and finally, following a period of volcanic quiescence, a very small-volume alkalic-rejuvenated stage (see summary in Clague and Dalrymple 1987). The tholeiitic-shield stage apparently includes a relatively small-volume phase during the submarine growth of the volcano (Moore et al. 1982), a voluminous phase during which the shoreline is continuously reworked by new lava flows (Moore and Campbell 1987; Moore 1987), and a waning stage of lower volume that postdates formation of a pronounced slope-break at the end of the voluminous phase (Moore and Clague 1987). The earliest part of the postshield stage may include abundant transitional and even some tholeiitic lavas (Frey et al. 1990).

In this paper we attempt to reconstruct the volcanic history of a submerged Hawaiian volcano named Mahukona. A series of drowned coral reefs (Moore and Campbell 1987) provide timelines that, coupled with the compositions of the lavas, constitute data similar to that obtained by mapping on land. The estimated ages and petrology are combined with information on eruption depth determined from the sulfur contents of the basalt glasses to reconstruct the geologic evolution of Mahukona Volcano.

Previous work

Mahukona Volcano is located between Hualalai and Kahoolawe volcanoes (Fig. 1). The region that includes Mahukona Volcano was named the Kohala Terrace by Campbell (1984) because it is an extensive shallow area offshore from Kohala Volcano. Moore and Campbell (1987) first identified the western part of the Kohala Terrace as a separate, previously unknown, Hawaiian volcano on the basis of the depth to the slope break, which is deeper than that of Kohala Volcano by several hundred meters. They proposed the name Mahukona Volcano after the nearest settlement on Kohala Volcano. Moore and Campbell (1987) inferred that the major break in slope corresponds to the position of the shoreline when the main tholeiitic shield stage, and its reworking of the shoreline by flowing lava, ceased.

Detailed bathymetry of the area (Campbell 1987) reveals a series of five terraces at average depths of −150 m, −430 m, −680 m, −950 m, and −1150 m and a slope break at about −1340 m on the Kohala

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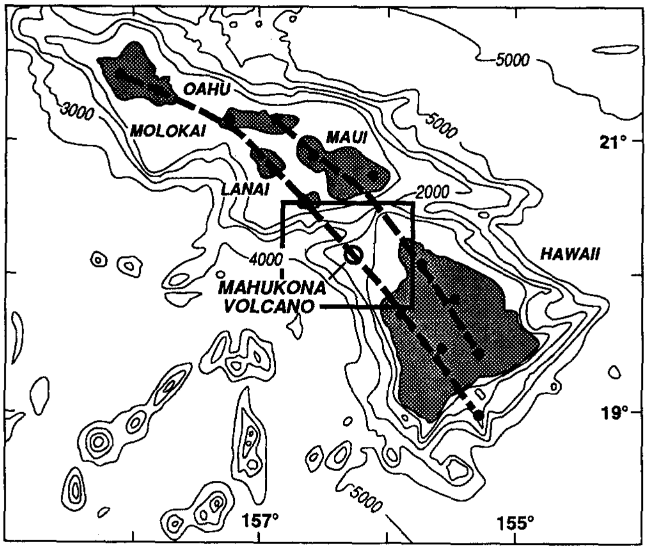

Fig. 1. Map showing the location of Mahukona Volcano in the Hawaiian Islands. The two *dashed lines* indicate the Loa (southern) and Kea (northern) loci lines (Dana 1849; Jackson et al. 1972). The box indicates the area shown in Fig. 2

Terrace (Fig. 2). Prior to the present study, the two shallowest of these terraces were sampled and shown to be drowned coral reefs (Moore and Fornari 1984; Moore and Clague 1987). These drowned coral reefs are paleoshorelines that serve as time horizons and aid in unraveling the volcanic history of the area (Moore and Clague 1987, 1988). They have all been dated by ^{14}C and U-series techniques (Moore et al. 1990; Ludwig et al. 1991); the ages support the following sequence of ages inferred by Moore and Campbell (1987) from youngest to oldest and shallowest to deepest: 14 ka, 130 ka, 280 ka, 365 ka, and 435 ka. Moore and Campbell (1987) inferred that the vigorous shield stage on Mahukona Volcano had ceased by 530 ka, the age they inferred for the roughly −1275 to −1400 m (average −1340 m) break in slope on the northwest and southeast sides of Mahukona Volcano.

The detailed bathymetry also defines a west-trending rift zone ridge and two large cones along this ridge. The westernmost of these cones rises at least 350 m above the rift zone whereas the eastern cone, located near the main slope break, is roughly 125 m high. These cones are surprisingly large; for comparison, two of the largest subaerial cones on Hawaii, the Puu Waawaa trachyte cone on Hualalai Volcano and Puu Makanaka on Mauna Kea Volcano, are each about 150 m high, and Puu Oo on Kilauea Volcano is about 130 m high. The bathymetry suggests that several smaller cones occur upslope from the eastern of the two large cones, between and slightly north of the two large cones, and west of the large western cone along the rift zone. East of the −1150 m reef on the broad nearly-flat terrace between the −1150 m and the −950 m reefs is a slight depression centered at roughly 20° 5′ N, 156° 10′ W. This depression, interpreted to be a filled caldera, is nearly encircled by the 1100 m isobath and is shown as a small shaded area in Fig. 2.

New work

In February 1988, samples were dredged from Mahukona Volcano using the *R/V Farnella*, a British vessel under lease to the U. S. Geological Survey. We focused

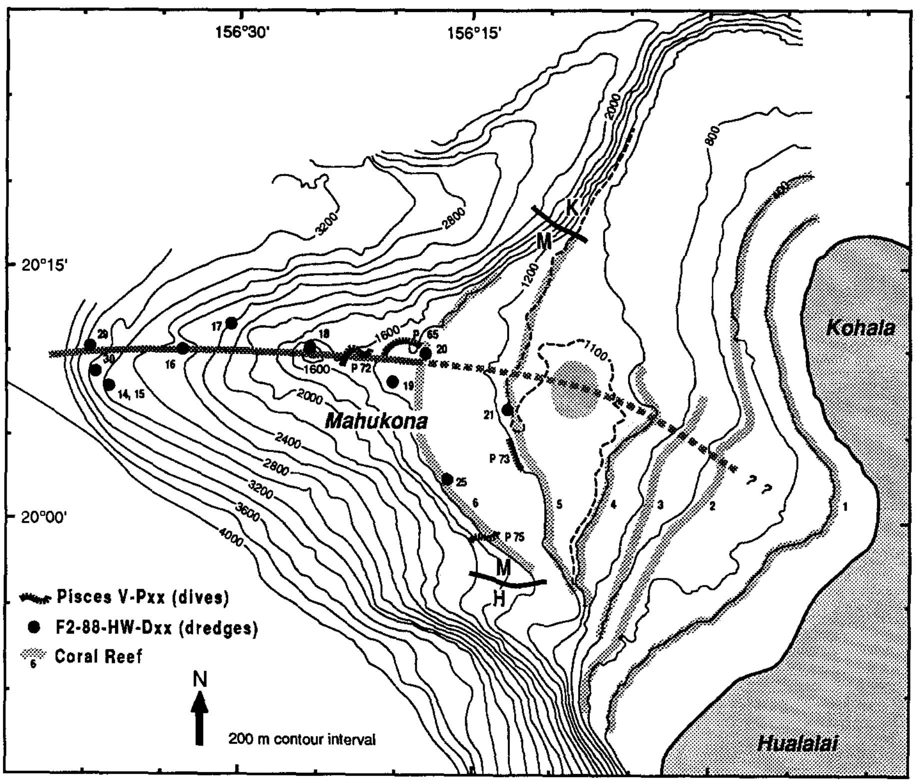

Fig. 2. Bathymetric map of Mahukona Volcano showing sample locations. Drowned coral reefs are numbered sequentially from youngest to oldest. The bathymetric map was constructed by combining the bathymetry of Campbell (1987) for the region east of 156° 30′ with bathymetry from Wilde et al. (1978), modified by addition of our new survey lines and geophysical lines collected during the GLORIA sidescan survey completed in 1986 and some additional bathymetry from Campbell (unpublished data), for the area west of 156° 30′. The shallowest five reefs were mapped by Moore and Campbell (1987). The northern end of reef 6 marks the contact between Mahukona and Kohala Volcano to the north whereas the southern end of reef 6 marks the contact between Mahukona and Hualalai Volcano to the south. The stippled oval encircled by the −1100 m contour is a depression that may mark the location of the summit caldera

on two targets, the western rift zone and the two deepest terraces which we inferred were constructed on Mahukona Volcano (Fig. 2). The detailed location data for the eleven dredges are given in Clague et al. (1988).

Additional observations and sampling were conducted during a *Pisces V* dive program to explore the Kohala Terrace in June, 1988. Two dives explored the upper part of the rift zone and another two dives explored the deepest terrace and the slope break and sampled the reefs and lavas that drape them (Fig. 2).

Two dredges were empty (D14 and D15), and most others recovered only a few small lava chips. Most dredges along the western rift zone had essentially no pulls, but behaved as if the dredge was pulling through mud: a large block of mud was recovered in D29. The only large recoveries of volcanic rock came from D18 on the large volcanic cone on the west rift zone, and from D19, which attempted to sample the deepest reef at the main slope break at about −1340 m but instead recovered 100 kg of picrite pillow fragments. D25 successfully sampled the deepest coral reef along the main slope break, recovering about 10 kg of coquina. Most of the dredges were rigged with a small separate pipe dredge that was canvas lined to recover mud or sand; some of the measured glass compositions are for individual sand-sized glass fragments recovered in these pipe dredges.

The first *Pisces V* dive, Dive P65, traversed 4 km east from the base of the eastern cone on the west rift zone, across a low swale, and up to the main slope break at −1326 m. The dive ended near the site of D20. A north-trending ridge extending from the cone is underlain by a well-bedded sandy hyaloclastite up to 15 m thick (Fig. 3a) which is overlain by a chalky white calcarenite. These two lithologies indicate that the slope break occurs at a former shoreline and confirm that the coral reef sampled at D25 occurs on the northwest, as well as on the southwest, side of Mahukona Volcano. Several additional north-trending ridges on which lava is exposed (Fig. 3b), rather than hyaloclastite, were traversed as we moved east up a steep slope before eventually ending the dive on a carbonate sand plateau (Fig. 3c) with scattered pillows located above the main slope break. Just before ascending onto the carbonate platform, a second area with carcarenite was discovered at about the same depth as that capping the hyaloclastite (Fig. 3d).

The second dive on Mahukona Volcano, dive P72, traversed 3 km along the west rift zone between the two largest cones. There were some hints in the bathymetry that a poorly developed reef might occur at a depth of about −1550 m. No evidence for such a reef was found, but a sequence of pillow lava, pillow joint block talus, and pillow scree composed largely of chips of pillow crusts was sampled. In places, grey and white sand is ponded between pillows (Fig. 3e), but covers <10% of the area explored. These massive pillows are commonly ≥1 m in minimum dimension.

Dive P73 explored the west-facing slope of the −1150 m reef, which is located up to 10 km east of the main slope break of Mahukona Volcano. The submersible reached bottom at −1110 m, east of the west-facing reef escarpment on poorly cemented carbonate debris, mantled by a thin veneer of unconsolidated carbonate sediment. The submarine traversed west and down the reef face, which is a gentle slope with some steeper areas. Samples were collected from small coral outcrops 3-4 m across. The reef face was followed for about 4 km south. Scattered to concentrated trains of basalt rubble are common in chutes on the reef face.

Dive P75 traversed 3 km up the main slope break on the southwest flank of the volcano from about −1495 to −1295 m. Small outcrops of reef carbonate occur at −1495 m and −1405 m (Figs. 3f and 3g). Above these reef outcrops, the surface is covered by basalt rubble and outcrops of broken pillow basalt (Fig. 3h).

Slope break and drowned coral reefs on Mahukona Volcano

Moore and Campbell (1987) originally recognized that Mahukona was a volcano separate from Kohala because the slope break ringing the northwest, north, and northeast flanks of Kohala is about −1000 m deep, whereas to the southwest a slope break occurs at roughly −1275 m and deepens to about −1400 m just north of the submarine northwest rift zone of Hualalai Volcano. The contact between Mahukona Volcano and Kohala Volcano, marked by this depth change at the break in slope, occurs at about 20° 16.5′N Lat., 156° 09.3′W Long. (Fig. 2). However, since Kohala Volcano has grown on its east flank, Mahukona Volcano extends some distance east beneath Kohala. On the southwest side, the slope break that separates Mahukona Volcano from Hualalai Volcano to the south extends at least as far south as 19° 57′N Lat., 156° 57′W Long. (Fig. 2).

Two drowned reefs have been sampled and dated from Mahukona Volcano. The deeper reef (−1340 m) occurs near the main slope break (reef 6 on Fig. 2) and has been sampled near the west rift zone (Dive P65) and along the southwest flank (D25); this reef is dated by U-series at 463±8 ka (Ludwig et al. 1991). The next shallower and younger reef (and the deepest terrace identified by Moore and Campbell (1987), reef 5 on Fig. 2), at −1150 m, was dredged (D21) and also sampled during dive P73; three samples from this reef are dated by U-series at 406±12, 360±12, and 475±38 ka (Ludwig et al. 1991). This reef probably drowned during the rapid rise in sea level at about 435 ka (Moore and Campbell 1987). The shallower reef marks a shoreline of Mahukona Volcano because it is sub-parallel to the slope break of the volcano 25 km to the west. Moreover, the lavas that drape the reef are geochemically similar to those recovered in dredges that unambiguously are part of Mahukona and distinct from Mauna Kea and Hualalai lavas recovered further to the east draping younger reef terraces (Moore and Clague 1988) or lavas from Kohala Volcano (Feigenson et al. 1983; Lanphere and Frey 1987; Garcia et al. 1989). We

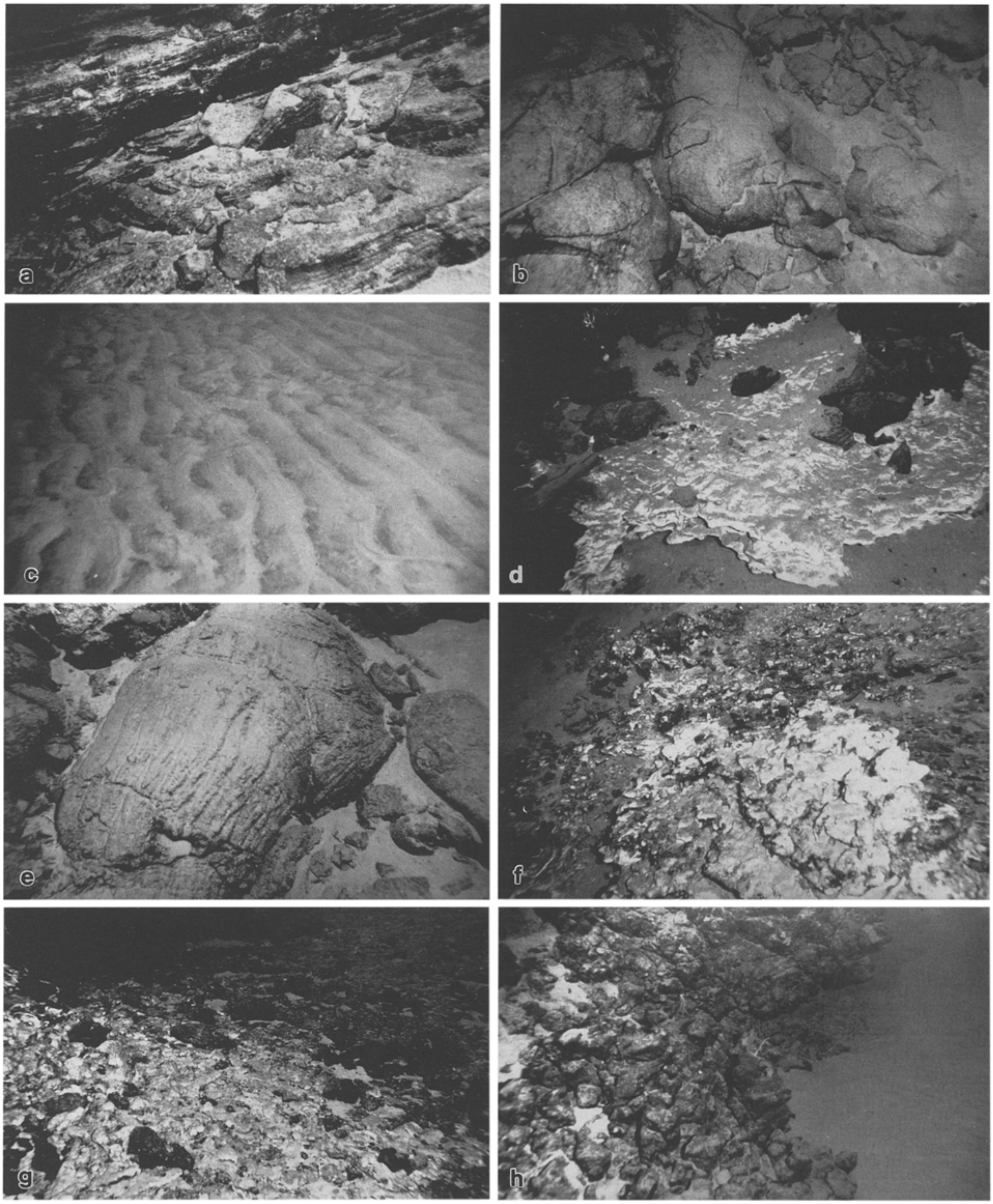

Fig. 3a–h. Bottom photographs taken from the *Pisces V* submersible. Field of view varies but is about 2–3 m across. **a** Bedded hyaloclastite dusted with pelagic sediment at −1330 m during dive P65. The hyaloclastite overlies pillow basalt and underlies reef carbonate deposits. **b** Elongate pillow lavas exposed on steep slope during dive P65. The pillows are deeply fractured and heavily dusted with pelagic sediment. **c** Carbonate sand plateau above the break in slope on dive P65. The sand has large-scale ripples formed by strong bottom currents. **d** Fragmented pillow lavas surrounded by coralline algae and coquina deposits on dive P65. This carbonate deposit is at about the same depth as the hyaloclastite shown in **a**. **e** Below the slope break, only pillow lava with heavy sediment cover occurs on dive P72. **f** Carbonate beachrock of high-Mg calcite coralline algae and dark aragonite coral fragments on dive P75. **g** Numerous rounded basalt cobbles are set in the carbonate beachrock on dive P75. **h** Above the reef outcrops along the slope break, a flow of subaerially erupted (low-S content) tholeiitic basalt drapes the reef at the slope break on dive P75. Similar lava flows are exposed above the slope break

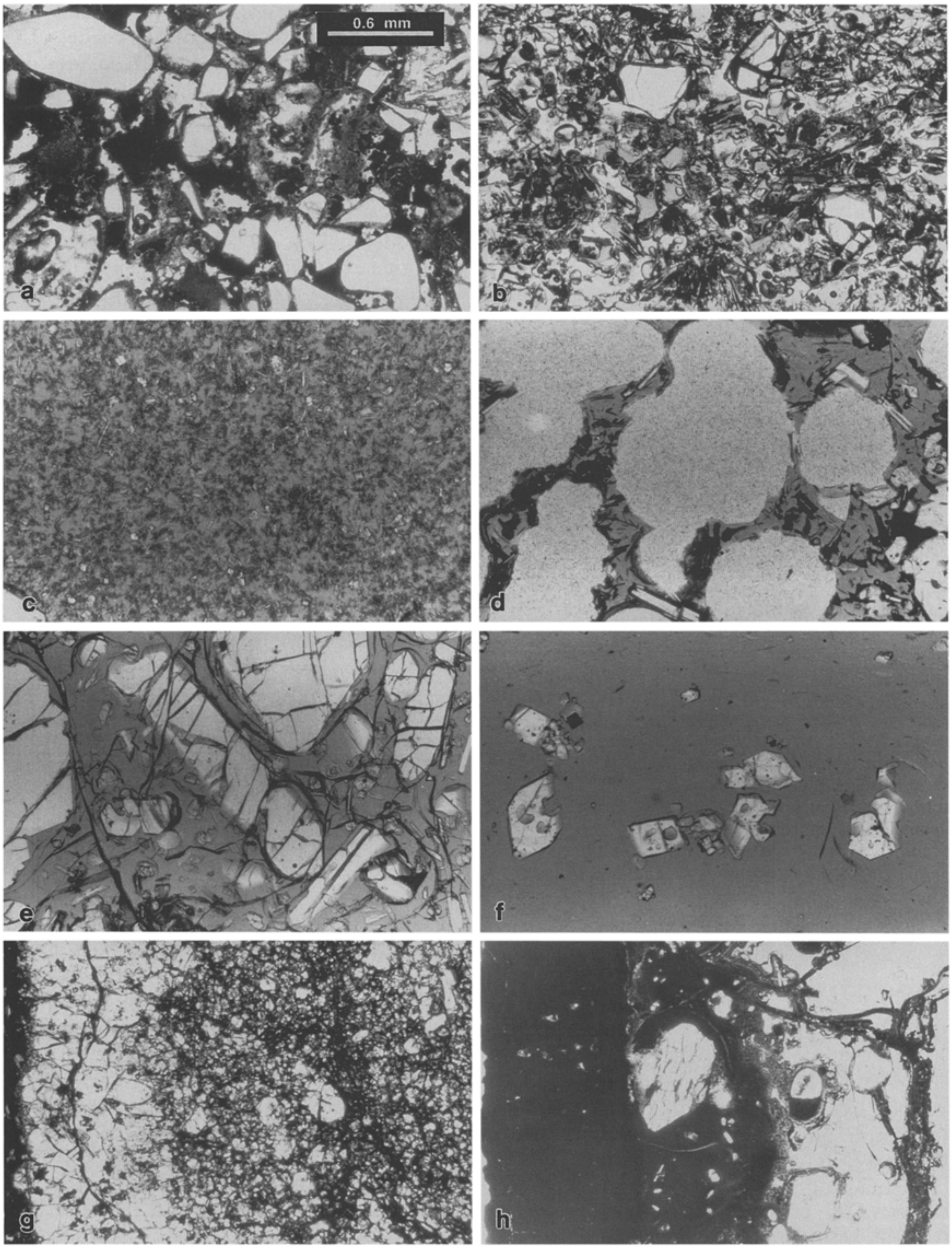

Fig. 4a–h. Photomicrographs of samples from Mahukona Volcano. Scale bar in **a** applies to all photomicrographs. **a** Volcanic sandstone from D21 is olivine sand with rare biogenic carbonate detritus and rock fragments. This volcanic sandstone is a reworked beach sand similar to that on modern green sand (olivine) beaches. **b** Hyaloclastite sample P65-2 collected from the outcrop shown in Fig. 3a showing abundant fresh glass and broken olivine crystals. The hyaloclastite contains glass of a single composition and no lithic fragments or carbonate detritus. This hyaloclastite probably formed in a manner analogous to formation of littoral cones. **c** Dive sample P75-7 showing abundant microlites in tholeiitic basalt flow draping the slope break. The microlites form during subaerial flow, prior to quenching as the flow enters the sea. **d** Sample D19-1 contains up to 50% vesicles. **e** Sample D30-1 is a tholeiitic picrite from about 3010 m depth on the west rift zone. The sample also contains minor amounts of clinopyroxene and plagioclase. **f** Sample D17-6 showing euhedral olivine microphenocrysts set in unaltered dense glass. Note the abundant Cr-spinel and fluid and glass inclusions within the olivine crystals. **g** Recrystallized dunite xenolith in sample P73-4. Coarser-grained rim consists of orthopyroxene. **h** Sample D29-1 showing 1 mm of botryoidal Mn-oxides surrounding about 1 mm of glass replaced by palagonite

conclude that the −1150 m reef is on the west flank of Mahukona Volcano and that the summit of Mahukona Volcano is located east of D21.

Descriptions of volcanic samples

Recovered volcanic rocks include pillow fragments, volcanic breccia, hyaloclastite, and volcanic sandstone. Volcanic sandstone, hyaloclastite, and breccia were recovered in dredges D20, D21, and D25, and hyaloclastite was recovered by the *Pisces V* submersible as samples 2 and 3 from dive P65. Volcanic sandstone recovered in D21 is an olivine sand with rare volcanic lithic fragments and biogenic carbonate detritus (Fig. 4a). It resembles the beach sands presently forming near South Point where olivine is concentrated from littoral cone deposits by the winnowing action of wind and surf. Hyaloclastite was recovered on dive P65 as samples 2 and 3 (Fig. 3a). This hyaloclastite is composed entirely of homogeneous glass fragments and broken olivine crystals (Fig. 4b) and apparently formed near a littoral cone or an eruptive vent in shallow water. Samples from D20 and D25 and samples P65-8B, P73-3, and P75-7 contain abundant microlites in the quenched glass (Fig. 4c). Moore and Clague (1987) interpreted similar textures observed in samples collected offshore Hualalai and Mauna Loa Volcanoes to indicate subaerial eruption and subsequent flow of lava into the sea where it quenched. Lavas that contain >5% vesicles occur in D18, D19, and D21, and as samples P65-2 and 3, P72-8, P73-3, and P75-1. Many of these lavas are highly vesicular, commonly containing up to about 50% vesicles (Fig. 4d). The volcanic breccia, hyaloclastite, and sandstone, and microlite-rich glassy and highly vesicular (except D18 and P72-8) samples were recovered either from the slope break or from deposits draping the −1150 m reef, in accord with subaerial eruption and submarine quenching or with eruption in shallow water.

Picrite basalt containing greater than 15% modal olivine was recovered in D16, D19, D21, D29, D30 (Fig. 4e), and as sample 4 from *Pisces V* dive P73, and samples 5 and 8 from dive P72. Lavas that contain plagioclase and augite, in addition to olivine, were recovered in D16, D18, D19, D29, and D30 and as *Pisces V* samples P65-2, 3, and 5, P72-1, 2, and 3, and P75-1. Some samples, such as those from D17, contain euhedral microphenocrysts of olivine in fresh dense glass (Fig. 4f). Rare samples in D19 and D20 and samples P75-4 and 7 contain small gabbro xenoliths up to 1 cm across that consist of intergrown plagioclase and augite, with minor olivine and interstitial glass. Sample P73-4 contains an irregularly shaped, recrystallized dunite xenolith that is nearly surrounded by an orthopyroxene reaction rim (Fig. 4g).

The glassy rims on samples from Mahukona are commonly altered to palagonite as thick as 1 mm. In addition, most samples are coated by deposits of Mn-oxides that also reach thicknesses of about 1 mm (Fig. 4h). The vesicular pillow fragments generally have thinner glassy rims than the denser pillow fragments and also tend to have thinner deposits of Mn-oxides. The outer layer of palagonitized glass and Mn-oxides apparently has spalled off these vesicular lavas.

Compositions of basalt glasses

Eighty-three glasses were analyzed at the U. S. Geological Survey in Menlo Park on a 9-spectrometer ARL-SEMQ electron microprobe using natural and synthetic standards. The analytical precision and accuracy can be assessed from the analyses of Smithsonian Institution glass standards A-99 and VG-2 (Table 1) which were run interspersed throughout the microprobe run.

The glasses analyzed (Tables 2–6) are from: (1) lava fragments recovered by dredge or submersible; and (2) sand-sized glass fragments recovered in the pipe dredge dragged behind the chain-bag dredge (denoted in Table 2 by a "g" in the sample number). We anticipated that the glass recovered in the pipe dredge would be from the same flows sampled by the chain-bag dredge, but this did not turn out to be the case for several dredges.

Three glass compositions determined on sand grains from the pipe dredges are not plotted on the figures because they are compositionally distinct from all other glasses from Mahukona Volcano (Table 6). We suspect that these are airfall from younger eruptions of Mauna Kea (D18g3) and Hualalai Volcanoes (D18g2 and D29g3); these glass grains are the only grains analyzed from the pipe dredges recovered along the west rift zone that are subaerially degassed (≤0.02 wt.% S). The glass inferred to be from Mauna Kea is compositionally similar to the high Fe-Ti basalts of the Hamakua Volcanics (Frey et al. 1990). One additional glass composition (D29g2 in Table 2) is also distinct from the rest of the analyzed Mahukona samples, but it occurs as 3 of 9 analyzed grains and contains 0.062 wt.% S. The location of D29 on the distal end of the west rift zone makes it unlikely that a submarine-erupted glass could be trans-

Table 1. Comparison between wet chemical and microprobe analyses of glass standards

	VG-2[1]	VG-2[2] $n=19$	A-99[1]	A-99[2] $n=15$
SiO_2	50.81	50.56 ±0.30	50.94	51.00 ±0.43
Al_2O_3	14.06	14.13 ±0.29	12.49	12.71 ±0.35
FeO*	11.84	11.69 ±0.10	13.30	13.28 ±0.12
MnO	0.20	0.21 ±0.01	0.15	0.20 ±0.01
MgO	6.71	6.99 ±0.05	5.08	5.11 ±0.05
CaO	11.12	11.07 ±0.21	9.30	9.26 ±0.18
Na_2O	2.62	2.78 ±0.06	2.66	2.80 ±0.05
K_2O	0.19	0.19 ±0.01	0.82	0.82 ±0.03
P_2O_5	n.a.	0.22 ±0.02	n.a.	0.45 ±0.04
TiO_2	1.85	1.82 ±0.03	4.06	3.99 ±0.06
S	n.a.	0.134±0.008	n.a.	0.017±0.003

[1] wet chemical analysis
[2] mean microprobe analysis and 1-sigma standard deviation
n.a. = not analyzed, * all Fe as FeO

Table 2. Average glass compositions of samples dredged deeper than slope break at −1340 m

Sample	D16	D17	D17g	D18	D18g1	D29	D29g1	D29g2	D30	D30g
n	6	8	3	6	1	4	1	3	1	3
Type	T	T	T	Tr	T	T	T	T	T	Tr
SiO_2	51.9	52.4	52.6	47.5	50.8	51.4	51.8	49.6	51.3	47.3
Al_2O_3	14.1	13.8	13.7	14.8	14.3	14.1	13.5	13.6	13.8	14.7
FeO*	10.2	10.2	10.3	11.8	11.2	10.3	10.6	11.1	10.4	11.8
MnO	0.16	0.16	0.15	0.18	0.17	0.16	0.18	0.17	0.15	0.17
MgO	6.43	6.78	6.77	6.25	6.97	6.80	6.64	7.66	6.61	6.31
CaO	10.7	9.76	9.71	11.7	12.0	11.2	10.8	11.6	10.6	12.0
Na_2O	2.63	2.81	2.72	2.90	2.35	2.50	2.41	2.56	2.56	2.82
K_2O	0.39	0.51	0.52	0.47	0.45	0.32	0.42	0.40	0.38	0.46
P_2O_5	0.29	0.36	0.29	0.28	0.18	0.24	0.27	0.30	0.28	0.26
TiO_2	2.57	2.65	2.57	2.80	1.79	2.28	2.38	2.59	2.67	2.74
S	0.096	0.051	0.051	0.066	0.048	0.101	0.116	0.062	0.083	0.053
Total	99.5	99.5	99.4	98.7	100.2	99.4	99.0	99.6	98.8	98.6

g in sample number indicates glass sand recovered in pipe dredge
T is tholeiitic basalt and Tr is transitional basalt

Table 3. Average glass compositions for *Pisces V* samples from deeper than slope break at −1340 m

Sample	P72-2,3,4	P72-5,6	P72-7	P72-8
n	3	2	3	2
Type	T	T	T	T
SiO_2	50.5	51.9	52.7	52.4
Al_2O_3	14.0	14.2	14.1	13.7
FeO*	11.0	10.2	10.2	10.2
MnO	0.16	0.15	0.15	0.15
MgO	7.08	6.77	5.97	6.14
CaO	11.9	10.3	9.83	9.99
Na_2O	2.37	2.72	2.76	2.89
K_2O	0.44	0.43	0.52	0.50
P_2O_5	0.22	0.30	0.35	0.34
TiO_2	1.78	2.50	2.70	2.69
S	0.045	0.057	0.047	0.046
Total	99.5	99.5	99.3	99.0

Table 5. Average glass compositions of lavas draping the −1150 m terrace

Sample	D21-10,18	D21-3,4	D21-6	P73-3	P73-4	P73-5
n	2	3	1	1	1	1
Type	T	T	T	T	T	T
SiO_2	52.1	51.8	48.6	52.0	52.9	52.6
Al_2O_3	13.6	14.2	14.4	13.3	13.9	13.5
FeO*	11.2	10.0	11.0	11.8	11.0	10.8
MnO	0.17	0.17	—	0.17	0.17	0.17
MgO	6.17	6.82	7.27	6.04	5.80	6.35
CaO	10.2	11.3	11.5	10.2	10.0	10.5
Na_2O	2.54	2.60	2.78	2.62	2.50	2.49
K_2O	0.48	0.37	0.43	0.48	0.44	0.39
P_2O_5	0.33	0.26	0.26	0.34	0.28	0.23
TiO_2	2.98	2.33	2.76	2.84	2.67	2.55
S	0.036	0.047	0.031	0.010	0.057	0.043
Total	99.8	99.9	99.0	99.8	99.7	99.6

Table 4. Average glass compositions for samples from the slope break at about −1340 m

Sample	D19	D20	D25-4	D25-7	P65-1	P65-2,3	P65-5	P65-7,8B	P75-4	P75-5,6,7
n	7	1	1	2	1	3	2	2	1	3
Type	T	T	T	T	T	T	T	T	T	T
SiO_2	51.8	51.6	52.4	50.9	53.0	51.1	53.1	51.9	52.0	52.2
Al_2O_3	14.3	13.6	13.0	13.5	13.3	14.3	14.0	13.4	13.7	13.3
FeO*	9.69	11.8	12.6	11.8	10.1	10.5	10.2	11.7	11.7	11.7
MnO	0.16	0.17	0.19	0.18	0.14	0.16	0.15	0.18	0.17	0.17
MgO	6.96	6.15	5.73	6.05	6.26	6.51	5.46	6.09	6.17	6.16
CaO	11.2	10.1	10.2	10.6	9.65	10.6	9.56	10.4	10.4	10.0
Na_2O	2.47	2.52	2.62	2.54	2.83	2.57	2.79	2.57	2.50	2.55
K_2O	0.37	0.46	0.44	0.39	0.54	0.41	0.60	0.44	0.44	0.47
P_2O_5	0.25	0.33	0.33	0.28	0.30	0.35	0.39	0.30	0.33	0.33
TiO_2	2.34	2.94	3.06	2.76	2.68	2.65	2.91	2.91	2.65	2.76
S	0.033	0.020	0.011	0.014	0.028	0.033	0.029	0.015	0.012	0.017
Total	99.6	99.7	100.6	99.0	98.8	99.1	99.2	99.9	100.1	99.7

Table 6. Average glass compositions of airfall glass from Hualalai and Mauna Kea Volcanoes

Sample	D18g2	D18g3	D29g3
n	3	1	1
Type †	H	MK	H
SiO_2	53.0	49.7	53.8
Al_2O_3	13.9	13.1	13.3
FeO*	10.4	15.4	10.3
MnO	0.17	0.16	0.18
MgO	6.69	4.72	6.59
CaO	10.60	7.39	11.08
Na_2O	2.33	2.78	2.33
K_2O	0.40	0.71	0.32
P_2O_5	0.19	0.57	0.20
TiO_2	2.21	4.77	2.28
S	0.008	0.009	0.010
Total	99.9	99.3	100.4

†H is Hualalai tholeiite, MK is Mauna Kea high Fe-Ti basalt

ported from any volcano other than East Maui, and the composition of this glass does not resemble those of lavas dredged from the Haleakala Ridge (Moore et al. 1990). We conclude that this glass, though compositionally distinct from others from Mahukona Volcano, is probably from Mahukona.

The glass analyses from Mahukona Volcano are subdivided into those dredged from the west rift zone deeper than the main slope break (Table 2), those recovered by the *Pisces V* submersible during dive P72 from below the main slope break (Table 3), samples from along the main slope break (Table 4), and samples that drape the −1150 m reef (Table 5).

The glasses are tholeiitic basalt of variable composition except for two analyses transitional between tholeiitic and alkalic basalt (Fig. 5). The transitional basalt includes all the pillow fragments recovered in D18 from a roughly 350 m high cone at about 1600 m depth on the west rift zone, and all the analyzed glass sand grains from D30 located at about 2700 m depth on the west rift zone. The tholeiitic glass compositions vary from

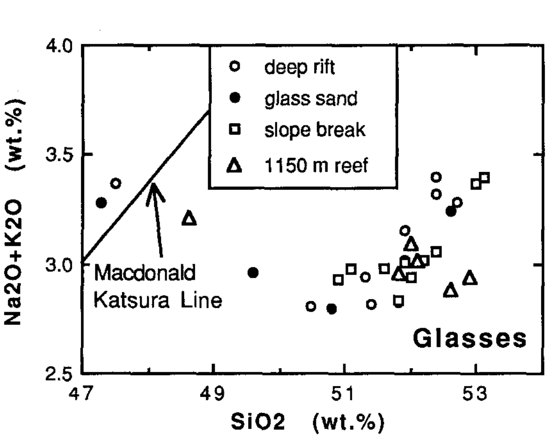

Fig. 5. Alkali-silica diagram for glasses from Mahukona Volcano. Two glass compositions plot just within the alkalic basalt field, but are termed transitional basalt in the text. The one point at about 49% SiO_2 is an analyzed sand grain from a minidredge: it is compositionally distinct from the remaining Mahukona samples

48.6 to 53.0 wt.% SiO_2, and 5.5 to 7.7 wt.% MgO. The glass compositions are plotted on MgO-variation diagrams in Fig. 6 with fields enclosing submarine glass compositions from Kilauea (26 flow units from Dixon et al. in press), and Mauna Loa (17 flow units from D. A. Clague, unpublished data), and two glass compositions from Koolau Volcano on Oahu (Clague and Hazlett 1989; D. A. Clague, unpublished data). The tholeiitic glasses from Mahukona are remarkable in that they include some low TiO_2 compositions unlike other Hawaiian tholeiities, and compositions that span the range of major-element chemistry observed for Kilauea and Mauna Loa. Six of the Mahukona glasses have higher K_2O than Kilauea glasses with similar MgO content, and three Mahukona glasses have lower K_2O than Mauna Loa glasses with similar MgO contents. Similarly, a few of the Mahukona glasses have higher CaO than observed for any Kilauea or Mauna Loa glass. The two glass compositions with $TiO_2 < 2$ wt.% have even lower TiO_2 than the few analyzed low-TiO_2 glasses from Koolau Volcano on Oahu, but they are also somewhat lower in MgO. These low-TiO_2 glass compositions are highly unusual and are also characterized by lower SiO_2 and P_2O_5 and higher CaO. Thus, although these glasses resemble Koolau glasses in their low TiO_2 contents, they are not similarly high in SiO_2 and low in CaO. None of the well-studied Hawaiian volcanoes include tholeiitic lavas with a range of compositions as broad as that observed from Mahukona Volcano at a given MgO content.

Despite the range in compositions represented, the dominant trends are roughly parallel to those for glasses from Kilauea and Mauna Loa. The trend of decreasing Al_2O_3 and CaO as MgO decreases below about 7 wt.% is consistent with the onset of plagioclase and augite crystallization, as experimentally determined (Helz and Thornber 1988), and empirically observed for Kilauea and Mauna Loa lavas (Wright and Fiske 1971).

The two transitional basalt samples have lower SiO_2, and higher Al_2O_3 and CaO, and slightly higher FeO* than tholeiitic glasses with the same MgO content, but have similar K_2O, P_2O_5, and TiO_2; Na_2O in the transitional glasses is comparable to that in the high-Na_2O tholeiites that are most like Koolau compositions. Two tholeiitic samples (D29g2 in Table 2 and D21-6 in Table 5) have compositions between the transitional lavas and the main group of tholeiitic lavas (Fig. 5).

S content of glasses

The low sulfur contents of many of the glasses (<0.02 wt.%, Fig. 7a) demonstrate that these lavas erupted above sea level (Moore and Clague 1987). Many of the samples from the deep parts of the rift contain moderate S contents (0.05–0.12 wt.% S) similar to those in glasses from the Puna Ridge of Kilauea Volcano. Dixon et al. (in press) interpreted such intermediate S contents as resulting from mixing of primitive undegassed magma and magma degassed at the top of the

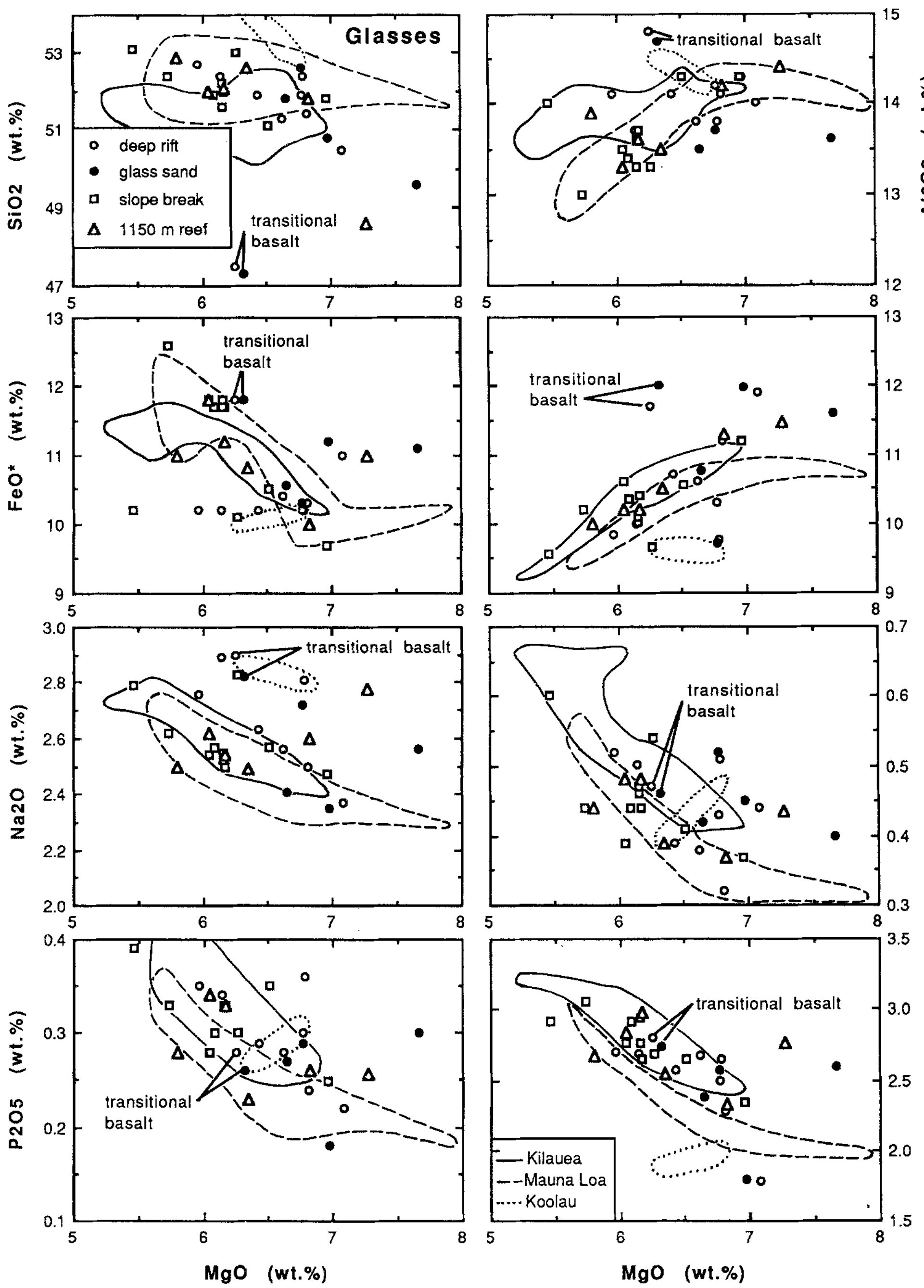

Fig. 6. MgO-variation diagrams for the Mahukona glass compositions in Tables 2-5. Fields for tholeiitic glasses from Koolau, Kilauea, and Mauna Loa Volcanoes, all analyzed using the same microprobe set-up and standardization, are shown for comparison. See text for data sources. The two transitional compositions are identified

magma reservoir or erupted and recycled back into the magma chamber. The abundance of intermediate-S glasses on Mahukona Volcano suggests that the summit of the volcano was subaerial so that these reservoir magmas could degas.

The S content varies weakly as a function of depth (Fig. 7b) such that all the lavas recovered deeper than 1600-1700 m contain >0.05 wt.% S and all those recovered shallower than 1600-1700 m contain <0.07 wt.% S. All the glasses with <0.02 wt.% S were recovered either at the slope break or draping the −1150 m reef. However, not all the lavas recovered above the slope break contain <0.02 wt.% S. Some of these may have erupted after the slope break or reef subsided below sea level so they erupted in shallow water. Moore and Calk (in press) showed that glasses quenched during shallow water eruption in Iceland contain 0.04-0.07 wt.% S, values comparable to those in many of the Mahukona glasses, especially the glass sands (Fig. 7).

Whole-rock chemistry

Nineteen samples were analyzed for major element chemistry by X-ray fluorescence spectrometry (Table 7). The olivine-rich character of the samples is evident from the high MgO contents, which range from 8.55 to 24.3 wt.%. All but four of the samples have >10 wt.% MgO, and five samples have >15 wt.% MgO. The whole-rock analyses show the variable compositions at

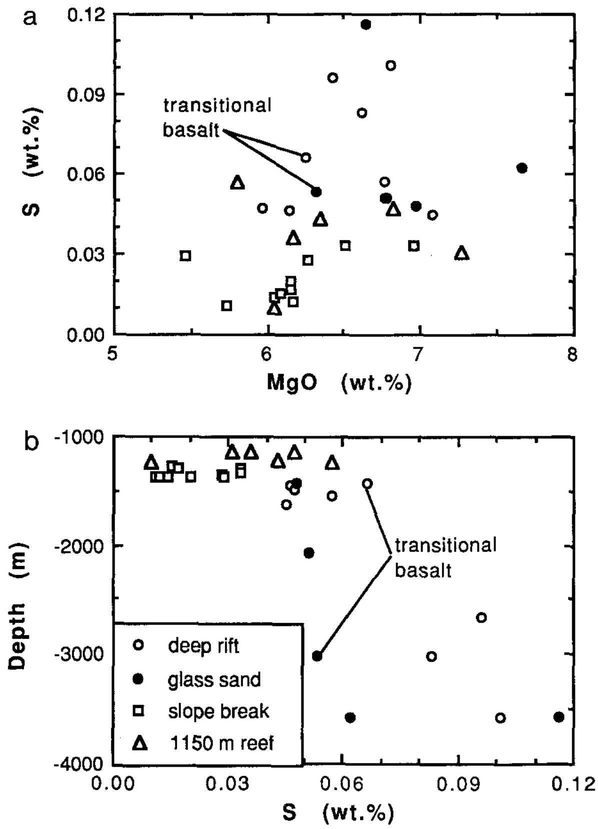

Fig. 7. a Plot of S vs MgO showing the range of S contents and that S content is not related to composition. **b** Plot of depth vs S content showing that lavas recovered shallower than about 1600 m contain <0.07 wt.% S whereas those recovered deeper than 1600 m contain >0.05 wt.% S. See text for discussion

similar MgO contents and the dominant olivine control of the high-MgO samples (Fig. 8). The trends that dominate the glass compositions are caused by crystallization of olivine, augite, and plagioclase. The trends dominating the whole-rock data are caused mainly by fractionation and accumulation of olivine. The lack of apparent plagioclase and augite control of the whole-rock compositions indicates that although plagioclase and augite have crystallized in many of the glasses, these crystals were not removed from the magma to any appreciable degree.

The transitional basalt plots slightly within the tholeiitic field, rather than within the alkalic field as is the case for the glass compositions (Fig. 9a). The whole-rock data has lower Na_2O contents compared to the microprobe data on the glasses. The uncertainty in Na_2O content and the position of these two samples close to the Macdonald-Katsura line led us to refer to these compositions as transitional.

A plot of Al_2O_3/CaO ratio vs MgO (Fig. 9b) shows that the tholeiitic compositions fall into three groups: one with Al_2O_3/CaO of about 1.35, a second with Al_2O_3/CaO of about 1.25 (which includes the transitional basalt), and a solitary sample (P72-3) with Al_2O_3/CaO of about 1.1. This latter sample also contains anomalously low SiO_2, FeO*, TiO_2, P_2O_5, and Na_2O, and high CaO and Al_2O_3. This sample is the same as one of two distinctive glass compositions already discussed.

Nearly all the lavas, including the transitional basalt, have constant K_2O/P_2O_5 of about 1.5 (Fig. 9c). The one sample with high K_2O/P_2O_5 is P72-3, the unusual sample discussed above. One picrite sample (D19-9) has low K_2O/P_2O_5 (0.5) which may be caused by an analytically imprecise K_2O analysis at such a low concentration. The glass analysis of this sample has K_2O/P_2O_5 of 1.48. The transitional and all the tholeiitic lavas, except P72-3, apparently are generated by variable degrees of partial melting from sources having the same K_2O/P_2O_5 ratio. The diversity of tholeiitic basalt compositions evident from the whole-rock and glass compositional data may be characteristic of the waning phase of tholeiitic volcanism on Hawaiian volcanoes. During the more vigorous part of the shield stage, diverse magma batches introduced from the mantle are probably homogenized with other magma batches residing in a subcaldera magma reservoir. However, the decreased magma supply rate at the end of the tholeiitic shield stage may be insufficient to maintain a large well-mixed subcaldera magma reservoir.

Summit caldera of Mahukona Volcano

The summit of Mahukona is located east of the −1150 m reef. A likely location of the summit is the 6.5–8 km diameter depression encircled by the −1100 m contour (Fig. 2). This depression occurs on the broadest terrace and the reefs located east and west of this depression have different orientations (Fig. 2). We have diagramatically shown the depression as a nearly filled summit caldera with a rift zone extending to the west and another rift zone inferred to extend towards the southeast. At least two rift zones must extend away from any summit caldera in order to accommodate the extension that occurs across the rift as dikes are emplaced. Using this location of the summit, the summit would have subsided below sea level shortly after the −1150 m reef drowned at 435 ka.

The −950 and −690 m reefs built on the slope to the southeast of the depression are apparently constructed on the flank of Mauna Kea Volcano, whose lavas drape these reefs (Moore and Clague 1988). However, the voluminous shield stage on Mauna Kea did not end until about 250 ka (Frey et al. 1990), and those voluminous lavas should have prevented the formation of the −950 m (365 ka) and −690 m reefs (280 ka). Only the −430 m (130 ka) reef occurs on the northeast flank of Mauna Kea, as predicted by the inferred age of the end of voluminous shield building. It is unclear why these voluminous flows from Mauna Kea did not prevent the development of reefs from 365 to 250 ka. Possibly a south-trending shoulder of Kohala Volcano not entirely covered by Mauna Kea allowed only a small amount of Mauna Kea lava to enter the reef area. Such lava was voluminous enough to build up the slope but small enough to permit reef growth and preservation.

Table 7. Whole-rock chemical analyses

Sample	D16-1	D17-9	D18-5	D18-6	D19-9	P65-1	P65-5	P65-6	P65-7	P65-8B
Type	T	T	Tr	Tr	T	T	T	T	T	T
SiO_2	46.4	50.5	46.2	47.1	44.0	50.8	50.9	50.3	49.8	49.6
Al_2O_3	7.76	11.7	12.8	13.7	8.46	12.5	12.4	12.7	11.9	12.0
Fe_2O_3	—	1.41	—	2.54	1.97	2.32	1.49	1.84	1.84	1.78
FeO	11.6[a]	9.80	12.4[a]	9.86	10.2	9.07	9.64	9.59	9.86	9.93
MnO	0.17	0.16	0.19	0.18	0.17	0.21	0.18	0.17	0.17	0.17
MgO	24.4	12.2	12.3	10.2	24.3	9.44	10.5	10.1	12.2	12.1
CaO	6.26	8.47	10.4	10.7	6.87	9.18	9.16	10.2	9.60	9.69
Na_2O	1.43	2.29	2.21	2.37	1.30	2.43	2.35	2.12	2.01	1.96
K_2O	0.20	0.43	0.39	0.43	0.09	0.50	0.45	0.35	0.33	0.32
TiO_2	1.39	2.29	2.26	2.41	1.41	2.58	2.40	2.32	2.24	2.19
P_2O_5	0.15	0.29	0.26	0.25	0.18	0.33	0.31	0.25	0.24	0.22
H_2O^+	—	0.27	—	0.41	0.53	0.64	0.43	0.37	0.36	0.37
H_2O^-	—	0.02	—	0.17	0.16	0.02	0.08	0.07	0.05	0.07
CO_2	—	<0.01	—	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total	99.8	99.8	99.4	100.3	99.6	100.0	100.3	100.4	100.6	100.3
Sample	P72-3	P72-5	P72-7	P72-8	P73-3	P73-4	P73-5	P75-1	P75-4	
Type	T	T	T	T	T	T	T	T	T	
SiO_2	49.5	49.0	50.3	50.3	50.1	46.6	47.2	50.7	49.9	
Al_2O_3	14.0	10.9	11.9	12.3	13.2	8.20	9.54	13.0	12.4	
Fe_2O_3	1.91	1.68	2.11	2.14	2.54	1.99	1.42	1.52	2.27	
FeO	8.27	10.01	9.80	9.50	8.87	9.64	9.88	10.15	9.12	
MnO	0.16	0.17	0.17	0.17	0.16	0.16	0.16	0.17	0.17	
MgO	9.89	15.1	11.6	10.6	8.99	23.3	19.2	8.55	10.9	
CaO	12.7	8.37	8.83	8.97	10.4	6.68	7.66	9.68	10.1	
Na_2O	1.93	2.07	2.31	2.31	2.22	1.42	1.58	2.45	2.09	
K_2O	0.34	0.33	0.44	0.45	0.38	0.18	0.22	0.46	0.33	
TiO_2	1.42	2.02	2.39	2.42	2.34	1.31	1.52	2.75	2.19	
P_2O_5	0.16	0.24	0.30	0.31	0.25	0.14	0.16	0.33	0.25	
H_2O^+	0.30	0.34	0.38	0.44	0.43	0.38	0.30	0.43	0.46	
H_2O^-	0.10	0.01	0.05	0.03	0.13	0.42	0.46	0.05	0.08	
CO_2	0.03	<0.01	0.02	0.02	0.03	0.08	0.06	<0.01	<0.01	
Total	100.7	100.2	100.6	100.0	100.0	100.5	99.4	100.2	100.3	

X-ray fluorescence major element analyses by J. Taggart, A. Bartel, and D. Siems; classical determinations of FeO, H_2O^+, H_2O^-, and CO_2 by S. Pribble. Analyzed samples are pillow fragments consisting of the glass rind and crystalline interior except samples D16-1 and D17-9 which are of glassy rinds only. [a] indicates all Fe as FeO

The distribution of reefs shallower than the depression suggest that the summit may be located even farther to the east than we show in Fig. 2. The slope to the east of the depression could be an even shallower part of Mahukona Volcano which had the two reefs constructed on it. This interpretation places the summit of Mahukona to the east of the -690 m reef. Neither gravity nor magnetics data confirm such an easterly location of the summit, and such an easterly location would place the summit of Mahukona Volcano far to the east of the Loa loci line and within about 20 km of the summit of Kohala Volcano. Elsewhere in the islands the summits of adjacent volcanoes are spaced a minimum of 30–35 km apart. In this model, the summit of Mahukona Volcano would not have subsided below sea level until some unconstrained time after 365 ka.

Based on these arguments, we suggest that the summit of Mahukona is probably located at the depression between the -950 m and the -1150 m reefs, and that this depression may approximate the size of the summit caldera. The summit of Mahukona probably subsided below sea level shortly after 435 ka.

Geologic history of Mahukona Volcano

Mahukona Volcano was a large edifice before either Kohala or Hualalai Volcanoes, each of which lap onto lavas of Mahukona. The 463 ± 8 ka age of the reef at the slope break is also the approximate age of the end of voluminous tholeiitic eruptions of the main shield stage (Moore and Campbell 1987). Mahukona Volcano subsided at least 200 m during the waning stages of tholeiitic volcanism because the -1150 m reef is draped by tholeiitic basalt flows from Mahukona Volcano. This waning period of tholeiitic eruptions lasted at least from 463 ± 8 to 435 ka and was characterized by eruption of tholeiitic basalt of variable composition. Sea level was marked by the location of the -1150 m reef at 435 ka. This reef died when sea level rose relative to the subsiding volcano at rates in excess of 10 mm/year and the coral reef drowned (Moore and Campbell 1987).

Dredge 18D recovered lavas from 1500–1345 m depth on the large cone on the west rift. This cone must have formed when the shoreline was shallower than

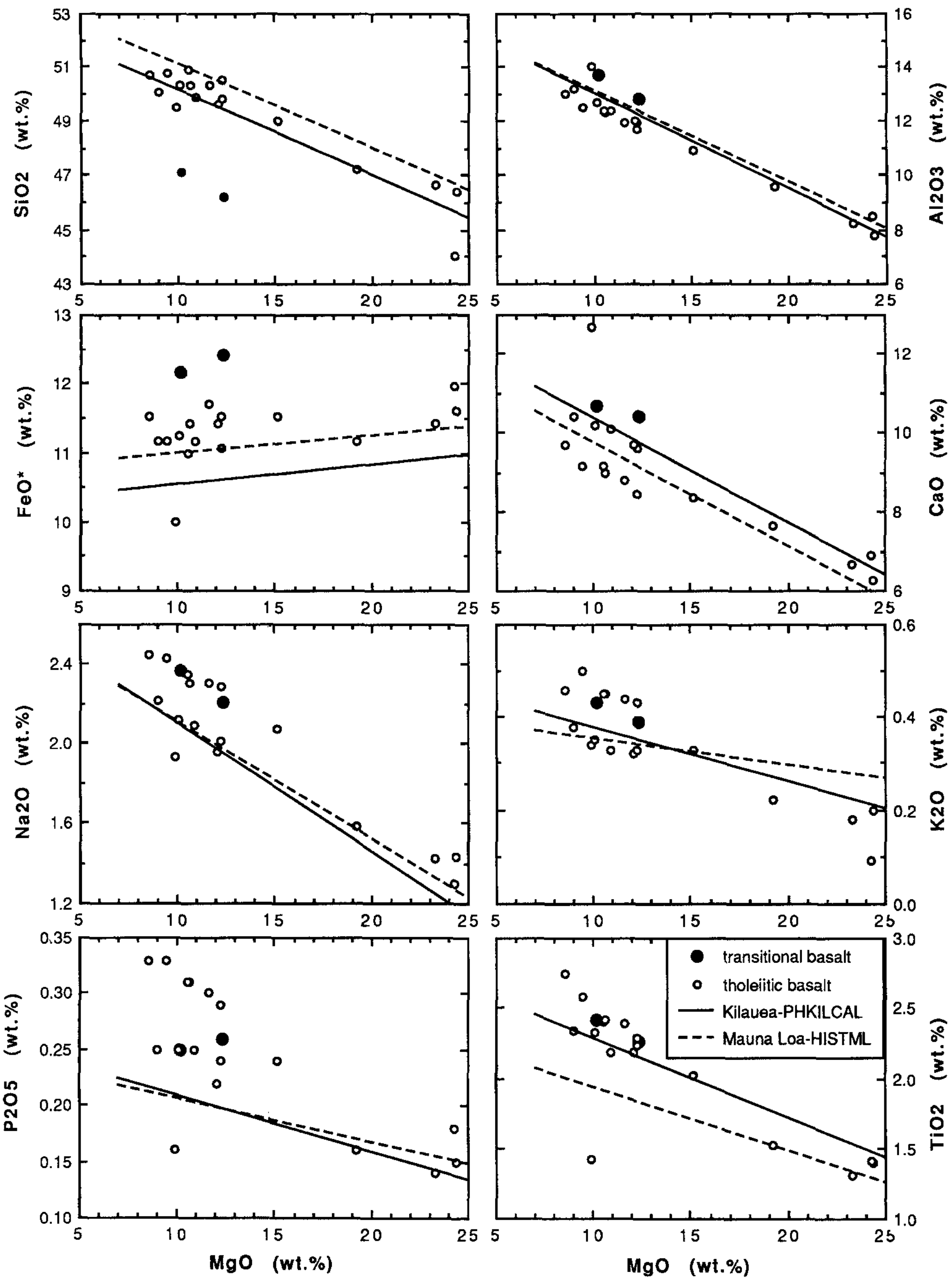

Fig. 8. MgO-variation diagrams for whole-rock analyses from Table 7. The dominant control among the tholeiitic lavas is variable olivine content. However, other smaller-scale variations indicate compositional variations that cannot be attributed to fractionation of the phenocryst assemblage present. The transitional basalt has higher FeO*, CaO, and Al_2O_3, and lower SiO_2 than tholeiitic basalt containing comparable MgO. However, Na_2O, K_2O, TiO_2, and P_2O_5 are comparable in the two lava types. Olivine control lines for prehistoric Kilauea (PHKILCAL) and historic Mauna Loa (HISTML) lavas from Wright (1971) are shown for comparison

– 1345 m because the lavas recovered did not erupt under subaerial conditions, as shown by the elevated S contents of the glasses, but also did not erupt in deep water as shown by the vesicular character of this transitional basalt. These constraints suggest that the large cone formed near the end of the tholeiitic shield stage or the beginning of the alkalic postshield stage. Other Hawaiian volcanoes commonly erupt lavas of transitional composition during the early part of the alkalic postshield stage (e.g. the basaltic postshield substage of Mauna Kea Volcano, Frey et al. 1990). We interpret the transitional lava from Mahukona to have erupted at the end of the tholeiitic shield stage or at the beginning of the alkalic postshield stage, which suggests a maximum age for the transitional basalt of 435 ka.

No alkalic lavas were recovered from Mahukona which suggests that Mahukona Volcano may have stopped erupting at the transition from shield to alkalic postshield stages. Some other volcanoes in the Hawaiian Islands either lack an alkalic postshield stage (Koolau and Lanai) or have an alkalic postshield stage characterized by so few flows (Kauai, Niihau, West Molokai) that a sampling program such as that done on Mahukona might not recover any alkalic samples. The alkalic postshield stage lavas also tend to erupt near the summit because the distal parts of the rift zones become inactive as the rate of lava production declines during the waning eruptive stages (Clague 1987; Moore et al. 1990). Thus, any alkalic lavas that might have erupted on Mahukona would likely be located near the

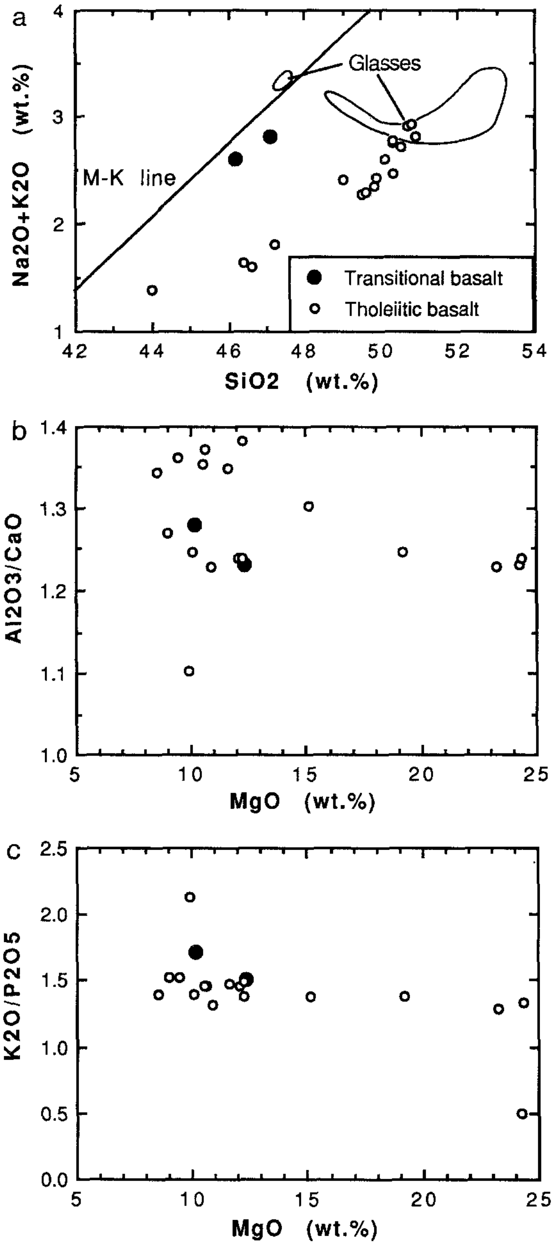

Fig. 9. **a** Alkali-silica diagram for the whole-rock data from Table 7. The fields for the glass data from Fig. 5 are shown for comparison. **b** Al_2O_3/CaO ratio vs MgO for the whole-rock compositions. Glass data not shown because large analytical uncertainty for Al_2O_3 introduces apparent scatter. **c** K_2O/P_2O_5 vs MgO for the whole-rock compositions. Glass data not shown because large analytical uncertainty for P_2O_5 data introduces apparent scatter

summit, which is now covered with carbonate deposits and onlapped by younger lavas from Mauna Kea Volcano.

Conclusions

1. Mahukona Volcano is a separate Hawaiian volcano, located between Kahoolawe and Hualalai on the Loa loci line, that once stood several hundred meters above sea level. The voluminous phase of the tholeiitic shield stage ended 463 ± 8 ka.
2. Tholeiitic lavas drape the -1150 m reef, demonstrating that waning tholeiitic eruptions continued until at least 435 ka. They were followed by a shallow subaqueous eruption of rare transitional basalt that formed an enormous cone on the west rift zone.
3. At the end of the voluminous shield stage, a small reef was constructed at the slope break at 463 ka and a second larger reef formed a terrace at -1150 m at 435 ka. The inferred summit of the volcano subsided below sea level between 435 ka and 365 ka.
4. Tholeiitic lavas recovered from Mahukona Volcano include diverse compositions including samples similar to those from Kilauea and Mauna Loa Volcanoes, and an unusual composition with low SiO_2, FeO*, Na_2O, TiO_2, P_2O_5, and Al_2O_3/CaO and high Al_2O_3, CaO, and K_2O/P_2O_5. Such diverse tholeiitic compositions have not been reported from individual volcanoes in Hawaii before; the diversity may be characteristic of the waning stage of tholeiitic volcanism.
5. The moderate S contents (0.03 wt.% $<$ S $<$ 0.07 wt.%) of some of the glasses suggest eruption in shallow water or extensive mixing of degassed and undegassed magmas in the sub-caldera reservoir, whereas the low S contents ($<$ 0.02 wt.%) of lavas draping the slope break and the -1150 m reef are consistent with subaerial eruption.

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References

Campbell JF (1984) Rapid subsidence of Kohala volcano and its effect on coral reef growth. Geo-Marine Lett 4:31–36

Campbell JF (1987) Bathymetric Atlas of the Southeast Hawaiian Islands. Hawaii Institute of Geophysics Technical Report 87-1:21 p

Clague DA (1987) Hawaiian xenolith populations, magma supply rates, and development of magma chambers. Bull Volcanol 49:577–587

Clague DA, Dalrymple GB (1987) The Hawaiian-Emperor volcanic chain. Part I. Geologic Evolution. U S Geol Surv Prof Paper 1350:5–54

Clague DA, Hazlett RW (1989) Geologic field guide to the Hawaiian Islands. International Geologic Congress field guide, 33 p

Clague DA, Moore JG, Torresan M, Holcomb RT, Lipman PW (1988) Shipboard report for the Hawaii GLORIA ground-truth cruise F2-HW-88, 25 Feb.–9 March, 1988. U S Geol Surv Open-File Report 88-292:54 p

Dana JD (1849) United States Exploring Expedition During the Years 1838, 1839, 1840, 1841, and 1842. New York, George C. Putnam, 756 p

Dixon JE, Clague DA, Stolper EM (1991) Degassing history of water, sulfur, and carbon in submarine lavas from Kilauea Volcano, Hawaii. J Geol, in press

Feigenson MD, Hofmann AW, Spera FJ (1983) Case studies on the origin of basalt II. The transition from tholeiitic to alkalic volcanism on Kohala Volcano, Hawaii. Contrib Mineral Petrol 84:390–405

Frey FA, Wise WS, Garcia MO, West H, Kwon S-T, Kennedy A (1990) Evolution of Mauna Kea Volcano, Hawaii: Petrologic and geochemical constraints on postshield volcanism. J Geophys Res 95:1271–1300

Garcia MO, Muenow DW, Aggrey KE, O'Neil JR (1989) Major element, volatile, and stable isotope geochemistry of Hawaiian submarine tholeiitic glasses. J Geophys Res 94:10525–10538

Helz RT, Thornber CR (1988) Geothermometry of Kilauea Iki lava lake, Hawaii. Bull Volcanol 49:651–668

Jackson ED, Silver EA, Dalrymple GB (1972) Hawaiian-Emperor Chain and its relation to Cenozoic circumpacific tectonics. Geol Soc Am Bull 83:601–618

Lanphere MA, Frey FA (1987) Geochemical evolution of Kohala Volcano, Hawaii. Contrib Mineral Petrol 95:100–113

Ludwig KR, Szabo BJ, Moore JG, Simmons KR (1991) Crustal subsidence-rate off Hawaii determined from $^{234}U/^{238}U$ ages of coral reefs. Geology 19:171–174

Moore JG (1987) Subsidence of the Hawaiian Ridge. U S Geol Surv Prof Paper 1350:85–100

Moore JG, Calk L (1991) Degassing and differentiation in subglacial volcanoes, Iceland. J Volcanol Geotherm Res 45:in press

Moore JG, Campbell JF (1987) Age of tilted reefs, Hawaii. J Geophys Res 92:2641–2646

Moore JG, Clague DA (1987) Coastal lava flows from Mauna Loa and Hualalai volcanoes, Kona, Hawai. Bull Volcanol 49:752–764

Moore JG, Clague DA (1988) Offshore geology of Mahuteona, Kohala, Mauna Kea, Mualalai, and Mauna Loa volcanoes to the northwest of Hawaii. EOS, Trans Am Geophys Union 69:1443

Moore JG, Clague DA, Ludwig KR, Mark RK (1990) Subsidence and volcanism of the Haleakala Ridge, Hawaii. J Volcanol Geotherm Res 42:273–284

Moore JG, Clague DA, Normark WR (1982) Diverse basalt types from Loihi Seamount, Hawai. Geol 10:88–92

Moore JG, Fornari DJ (1984) Drowned reefs as indicators of the rate of subsidence of the Island of Hawaii. J Geol 92:752–759

Moore JG, Normark WR, Szabo BJ (1990) Reef growth and volcanism on the submarine southwest rift zone of Mauna Loa, Hawaii. Bull Volcanol 52:375–380

Stearns HT (1946) Geology of the Hawaiian Islands. Hawaii Division of Hydrography Bull 8, 106 p

Szabo BJ, Moore JG (1986) Age of the −360 m reef terrace, Hawaii, and the rate of late Pleistocene subsidence of the island. Geol 14:967–968

Wilde P, Chase TE, Normark WR, Thomas JA, Young JD (1980) Oceanographic data off the southern Hawaiian Islands. Lawrence Berkeley Laboratory Publication 359, Lawrence Berkeley Laboratory, University of California, Berkeley

Wright TL (1971) Chemistry of Kilauea and Mauna Loa lava in space and time. U S Geol Surv Prof Pap 735:1–40

Wright TL, Fiske RS (1971) Origin of the differentiated and hybrid lavas of Kilauea Volcano, Hawaii. J Petrol 12:1–65