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Mahukona: The missing Hawaiian volcano

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ABSTRACT

New bathymetric and geochemical data indicate that a seamount west of the island of Hawaii, Mahukona, is a Hawaiian shield volcano. Mahukona has weakly alkalic lavas that are geochemically distinct. They have high $^3He/^4He$ ratios (12–21 times atmosphere), and high H_2O and Cl contents, which are indicative of the early stage of development of Hawaiian volcanoes. The He and Sr isotopic values for Mahukona lavas are intermediate between those for lavas from Loihi and Mauna Loa volcanoes and may be indicative of a temporal evolution of Hawaiian magmas. Mahukona volcano became extinct at about 500 ka, perhaps before reaching sea level. It fills the previously assumed gap in the parallel chains of volcanoes forming the southern segment of the Hawaiian hotspot chain. The paired sequence of volcanoes was probably caused by the bifurcation of the Hawaiian mantle plume during its ascent, creating two primary areas of melting 30 to 40 km apart that have persisted for at least the past 4 m.y.

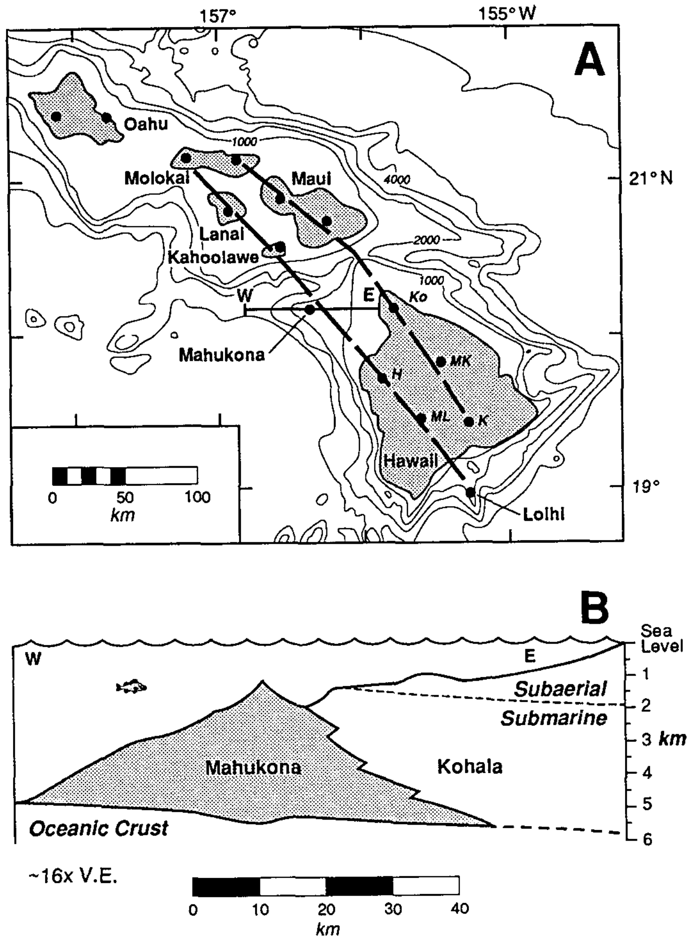

Figure 1. A: Map of southern Hawaiian Islands showing location of Mahukona volcano and paired sequence of volcanoes that forms islands (connected by dashed heavy lines). Black dots are individual volcano centers (after Moore et al., 1982); for island of Hawaii, they are: Ko—Kohala; H—Hualalai; MK—Mauna Kea; ML—Mauna Loa; K—Kilauea. E-W is location of profile of Mahukona (in B). B: Cross section of Mahukona volcano and western flank of Kohala volcano. Submarine-subaerial contact for Kohala is based on inferred location of lowest coral terrace, which has subsided more than 1 km since it was formed (Moore and Campbell, 1987).

INTRODUCTION

Although Hawaii is one of the best-studied hotspot chains in the ocean basins, many aspects of its submarine features are poorly known. New bathymetric maps produced by computer contouring digital bathymetric data for parts of the southeastern Hawaiian Ridge (Campbell, 1987) led to the recognition of a distinct seamount about 50 km west of Kohala volcano on the north end of the island of Hawaii (Fig. 1). Moore and Campbell (1987) suggested that this feature might be a small Hawaiian shield volcano and named it "Mahukona," the name of the closest settlement to the volcano on the island of Hawaii. The recognition of this volcano is especially important because it fills a gap in the paired sequence of volcanoes that forms the Hawaiian Islands (Fig. 1). Jackson et al. (1972) drew attention to the paired sequence of volcanoes in the Hawaiian-Emperor chain, although they credited Dana (1849) for first recognizing the two lines of volcanoes that form the Hawaiian Islands. Jackson et al. (1972) noted that the shield volcanoes in the two lines are fairly evenly spaced, except for a large gap in the western chain between Kahoolawe and Hualalai volcanoes. They suggested that a small bathymetric high near the middle of the gap might mark the position of a submarine shield. Herein we present new bathymetric data and geochemical analyses of lava dredged from the summit of Mahukona volcano that confirm that it is an independent Hawaiian volcano.

BATHYMETRY AND AGE

Previous maps of Mahukona placed its summit at ~1450 m (Wilde et al., 1980), ~1250 m (Campbell, 1987), and <1225 m (Clague and Moore, 1988) below sea level. Our multibeam bathymetric survey of Mahukona, made during dredging, shows that it is only 1080 m below sea level. The differences in elevation from these three surveys are probably not due to recent volcanism, because all of the lavas recovered are from the summit of the volcano and have well-developed palagonite rims on the glassy rinds of the pillow lavas. Previous surveys used single-beam methods and therefore probably missed the summit of the volcano. Our study utilized the Seabeam system on the R/V *ATLANTIS II*, and we were able to survey a swath across the volcano. Because of time limitations, we were only able to survey the summit area of the volcano. Figure 2 is a compilation of our Seabeam survey and previous single-beam data.

We have estimated the size of Mahukona using the data presented in Figure 2 and assuming that the buried east side of the volcano has a slope similar to the west side and the lavas are interfingered with those from Kohala volcano. Thus, Mahukona volcano is about 70 km long, 33 km wide, and reaches a maximum height of just over 4 km above the abyssal sea floor (Figs. 1B and 2). This is somewhat larger than Loihi (35 km long, 25 km wide, and between 2 and 3 km maximum height), but much smaller than most Hawaiian volcanoes (e.g., Kohala, a medium-sized Ha-

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waiian volcano, is ~100 km × 40 to 50 km × 6 to 8 km). Several prominent ridges radiate outward from a central high on Mahukona (Fig. 2). Three ridges extend westward, and two or three less-prominent ridges extend eastward. If these ridges are rift zones, which seems likely, they point to the center of Mahukona volcano. This center is a topographic high that rises about 470 km above our inferred contact with Kohala volcano, which continued to erupt and covered the eastern flank of Mahukona after it became extinct (Fig. 1B). Clague and Moore (1988) have proposed that the summit of Mahukona is to the east of the summit high, but this seems inconsistent with the orientation of the possible rift zones.

There is no summit platform on Mahukona, which indicates that the volcano probably didn't reach, or grew above, sea level. Otherwise, wave erosion and/or coral growth would have created a flat summit platform. However, if the summit of Mahukona is 25 km to the east of the topographic high that we consider to be the summit of the volcano, then a summit platform was formed and the volcano was once subaerial (Clague and Moore, 1988).

The age of Mahukona volcano is unknown but we can estimate its minimum age. The age of a coral reef on the west flank of Kohala volcano has been inferred to be about 500 ka on the basis of a correlation with oxygen isotope stage 14 (Moore and Campbell, 1987). The reef is built on Kohala lavas that probably postdate volcanism of Mahukona volcano. Palagonite and Mn oxide crusts on Mahukona lavas can also be used to infer the relative age of the volcano. The crusts are patchy but somewhat thicker than on submarine lavas from nearby Hualalai volcano and are comparable to those on Kohala lavas. They are also much thinner than those on pillow lavas from Haleakala volcano (on the island of Maui), which formed about 1.0–1.5 Ma (Moore and Campbell, 1987). Thus, Mahukona is probably similar in age to its neighbor, Kohala volcano. No submarine lava from Kohala has been dated, but the oldest subaerial basalt with a reliable K-Ar age is 450 ka (McDougall and Swanson, 1972). Given that the volcanoes in the western chain tend to have formed shortly before volcanoes in the eastern chain (Clague and Dalrymple, 1987), Mahukona's minimum age is about 500 ka. Moore and Clague (1988) placed the end of Mahukona volcanism at between 350 and 440 ka. They believed tholeiitic lavas to the east of the summit high, in the area we have interpreted as Kohala volcano, to be from Mahukona. These lavas drape a coral reef dated as 440 ka.

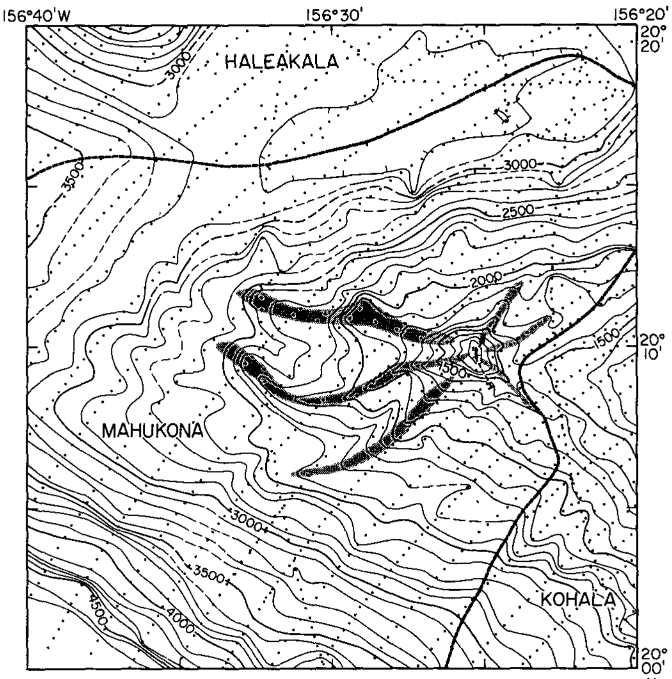

Figure 2. Bathymetric map of Mahukona based on Seabeam data for summit area and single-beam data from National Ocean Service Hydrographic Data Base elsewhere. Dots: Single-beam data locations. Heavy dashed lines separate Mahukona from Haleakala to north and Kohala to east. Prominent ridges, which are probably rift zones, are shaded along their crests. They radiate outward from summit high. Contour interval is 100 m. Summit of Mahukona is about 1080 m below sea level. Dredge haul was made at summit of Mahukona at 156°25.3′W, 20°9.8′N between 1080 and 1640 m below sea level (dashed line with arrow shows location and direction of dredge haul).

PETROLOGY AND GEOCHEMISTRY

One dredge haul was made around the summit of Mahukona; it recovered ~125 kg of volcanic rock. Most of the rocks are pillow-lava fragments with glassy rinds and radial structure. They have a thin palagonite rim on the glass and, locally, a Mn coating. Along the radial fractures a thin coating of iron oxide is present, but otherwise, the samples are unaltered. All of the lavas are moderately to strongly vesicular, even in the glassy rinds (~10–60 vol%). Such high vesicularity in Hawaiian pillow lavas is indicative of eruption in shallow to moderate water depths (100–1200 m) and is also characteristic of alkalic lavas from Loihi Seamount (up to 50 vol% vesicles; Moore et al., 1982), which rises to approximately 960 m below sea level and is the youngest Hawaiian shield volcano (Fornari et al., 1988). The absence of coralline material and the presence of pillow lavas on the shallowest part of the volcano also indicate that Mahukona probably never reached sea level.

Lavas from seven petrographically and geochemically distinct rock groups were recovered from Mahukona. The pillow-rim glasses from these lavas range in MgO content from 5.7 to 6.8 wt% (Table 1). Whole-rock analyses for two samples without glass have MgO contents of 8.4 to 10.1

TABLE 1. ANALYSES OF LAVA FROM MAHUKONA VOLCANO

	MA-32	MA-1	MA-21	MA-12*	MA-3*
Major elements and volatiles (wt%)					
SiO_2	47.12	47.30	47.72	47.84	47.64
TiO_2	2.76	2.80	2.83	2.56	2.41
Al_2O_3	15.25	15.04	15.30	14.70	14.10
FeO	11.87	11.97	11.86	10.26	12.12
MnO	0.19	0.18	0.19	0.16	0.19
MgO	6.71	6.50	6.25	10.06	8.40
CaO	11.60	11.50	11.59	10.79	10.87
Na_2O	2.78	2.65	2.81	2.52	2.45
K_2O	0.48	0.44	0.48	0.45	0.65
P_2O_5	0.34	0.34	0.34	0.33	0.34
H_2O	0.547	0.607	0.692	--	--
CO_2	<0.005	<0.005	<0.005	--	--
CO	0.042	0.017	0.008	--	--
Cl	0.105	0.070	0.068	--	--
S	0.051	0.064	0.038	--	--
F	0.007	0.004	0.004	--	--
Total	99.85	99.12	100.07	99.67	99.17
Isotopes					
^4He (cm^3/g STP)	$>5.16x10^{-7}$	$1.08x10^{-8}$	$7.56x10^{-9}$	$1.79x10^{-8}$	$4.25x10^{-8}$
$^3He/^4He$ (material)	20.2±.1 (glass)	12.8±.2 (glass)	11.6±.2 (glass)	20.8±.9 (ol)	21.0±.1 (ol)
$^{87}Sr/^{86}Sr$	0.703678 ±0.000010	--	--	0.703732 ±0.000008	0.703676 ±0.000008
Modes (vol%)					
Olivine	0.1	0.1	0.1	0.7	1.1
CPX	0.0	0.0	0.0	0.1	0.1
Plag	0.0	0.3	0.0	0.2	0.3

Note: Microprobe analyses of major elements from pillow-rim and fused whole-rock glasses; high-temperature, mass spectrometric analyses of volatiles from pillow-rim glass; mass spectrometric analyses of Sr from glass and whole rock; He from glass and olivine (ol) (He by vacuo crushing). Modes (500 points/sample) are phenocrysts (grains >0.5 mm) in lavas.
*Fused whole-rock glass.

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wt% and are weakly olivine phyric (~1 vol%) with lesser amounts of clinopyroxene and plagioclase phenocrysts (Table 1). The glassy samples are weakly phyric with rare (0.1 vol%) olivine and plagioclase phenocrysts (Table 1).

The Mahukona lavas we recovered are weakly alkalic (i.e., they plot just above the Macdonald and Katsura line on an alkalies vs. SiO_2 diagram). Compared to alkalic lavas from the neighboring shield volcanoes, Kohala and Hualalai, Mahukona lavas are similar to those of Kohala (except for CaO), but are distinct from Hualalai lavas in most major elements (Fig. 3). Mahukona lavas are similar in composition to alkalic lavas from Loihi. Clague and Moore (1988) have reported collecting tholeiites from the lower flanks (>2400 m) of Mahukona.

Volatile abundances were measured for three samples using dynamic high-temperature mass spectrometry (Liu and Muenow, 1978). Volatiles were only released at temperatures above 700 °C, indicating that the glasses are fresh. S and C contents of the Mahukona glasses are low relative to other Hawaiian submarine glasses (e.g., Garcia et al., 1989). However, H_2O and Cl contents are high compared to other Hawaiian submarine glasses, except those from Loihi. The depth of submarine eruption apparently was shallow enough to allow some S and CO_2 loss during eruption, but sufficiently deep to retain the more soluble volatiles, H_2O and Cl. High Cl and H_2O contents in Hawaiian shield-building lavas are distinctive of lavas from the early stages of shield development (Garcia et al., 1989). Reduced carbon, CO, was detected in the glasses of all three samples. Reduced carbon is common in Hawaiian basalts and is thought to be an indication of the moderately reduced state of Hawaiian magmas prior to storage in a shallow-level magma chamber (Byers et al., 1985).

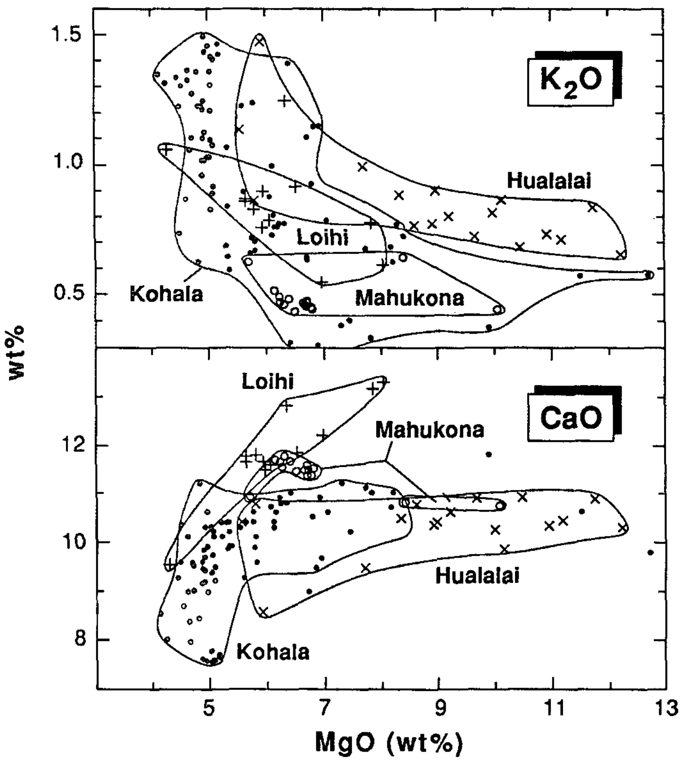

Figure 3. Plot of MgO vs. CaO and K_2O (in wt%) for glasses from Mahukona (open circles) and Loihi (plus signs) and whole rocks from Mahukona (solid circles), Hualalai (X), and Kohala (dots). Data for Loihi from Byers et al. (1985) and Garcia (unpublished); Kohala data from Garcia (unpublished); Hualalai data from Clague (1987).

The most distinctive feature of the Mahukonas lavas is their high $^3He/^4He$ ratios, which range from 11.6 to 21.0 times atmospheric. Among Hawaiian alkalic lavas, only those from preshield stage of Loihi Seamount have such primordial $^3He/^4He$ ratios (Kurz et al., 1983, 1987). Of the five measurements reported here, the two lowest $^3He/^4He$ ratios were obtained from glass samples with very low He contents (Table 1). The isotopic compositions of these samples may have been altered by posteruptive decay of Th and U in the glass. Assuming the age estimate given above, and using K/U of $\sim 10^4$ to scale the uranium contents, about 4×10^{-8} cm^3 (standard temperature pressure) of ^4He would have been produced within the glasses after eruption. Although all the measurements were made by crushing in vacuo, a small amount of leakage from the solid phases could readily lower the $^3He/^4He$ ratios obtained by crushing, because of the very small gas quantities in the glass. This is supported by the systematically higher ratios obtained in the glass with high total helium contents, and from the olivines, which have less Th and U. We therefore assume that the high $^3He/^4He$ ratios are representative of Mahukona, although to assume otherwise changes none of the conclusions.

Three of the same samples were also analyzed for Sr isotopes (Table 1). A narrow range of $^{87}Sr/^{86}Sr$ values was obtained on these samples (0.70367–0.70373). These values are within the range observed for lavas from the neighboring shield volcanoes (e.g., Hualalai—Clague, 1987; Kohala—Lanphere and Frey, 1987).

DISCUSSION

The high $^3He/^4He$ ratios of the Mahukona alkalic lavas indicate that they probably formed during the preshield stage rather than during postshield alkalic volcanism. On all other Hawaiian volcanoes, the postshield alkalic lavas are characterized by lower ratios (~8 times atmosphere; Kurz et al., 1983). Also, the $^{87}Sr/^{86}Sr$ ratios of the Mahukona alkalic lavas are somewhat higher than ratios for other postshield alkalic lavas (e.g., Frey et al., 1990). The $^3He/^4He$ and $^{87}Sr/^{86}Sr$ ratios of the Mahukona samples are intermediate between those of Loihi and Mauna Loa (Fig. 4). Data from the three volcanoes form a negative correlation of $^3He/^4He$ with $^{87}Sr/^{86}Sr$. Variations in $^{87}Sr/^{86}Sr$ from Hawaiian basalts are generally attributed to mixing of mantle source components (e.g., West et al., 1987), and the He data provide additional limits on the nature of the source components. In particular, the $^3He/^4He$ ratios from Loihi Seamount are the highest of any volcanic rocks (Kurz et al., 1983) and indicate that they are derived from a relatively undegassed, more primitive mantle source. The $^{87}Sr/^{86}Sr$ ratios from Loihi Seamount are lower than those assumed for bulk silicate earth (0.7035 ±0.0001 vs. 0.7050 ±0.0005; Zindler and Hart, 1986); this indicates that estimates of bulk-earth Sr values are too high or that the mantle sources having bulk-earth isotopic composition are not primitive with reference to He. The samples from Mahukona are interesting because they also have high $^3He/^4He$ ratios, and are similar in isotopic composition to alkalic basalts from Loihi Seamount. Therefore, the mantle source of the Mahukona lavas is also relatively primitive with reference to He.

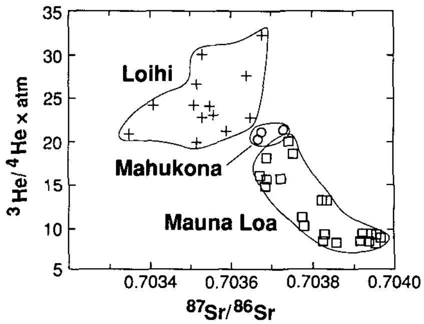

Figure 4. Plot of $^{87}Sr/^{86}Sr$ vs. $^3He/^4He$ time atmosphere (atm) for lavas from Mahukona, Loihi, and Mauna Loa. Symbols as in Figure 3 except Mauna Loa (square). Loihi data from Kurz et al. (1983), Mauna Loa data from Kurz and Kammer (1989).

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The trend shown in Figure 4, with Mahukona having intermediate $^3He/^4He$ ratios between the Mauna Loa and Loihi samples, could be explained by a temporal evolution of Hawaiian volcanoes. Previous studies have shown that $^3He/^4He$ ratios in Hawaiian basalts are related to age and hence to the evolutionary stage of the volcanoes (Kurz et al., 1983, 1987; Kurz and Kammer, 1989). Similar temporal trends have also been observed in major elements, trace elements, stable isotopes, and volatiles (Garcia et al., 1989). Kurz et al. (1983) suggested that Loihi Seamount had the highest $^3He/^4He$ ratios because it is the smallest, least-evolved Hawaiian volcano, and is most representative of the hotspot source simply because it is in the early stages of shield building. This hypothesis is supported by data from Haleakala and Mauna Loa, where stratigraphic sampling shows that the isotopic composition of the basalts can be correlated with age. For example, the Mauna Loa samples with highest $^3He/^4He$ ratios shown in Figure 4 are older than the samples with lower $^3He/^4He$ ratios (Kurz et al., 1987; Kurz and Kammer, 1989). The Mahukona samples may be intermediate between Loihi and Mauna Loa in He isotopes because they were erupted at a stage of evolution intermediate between these other two volcanoes. This is supported by the relative volumes of the volcanoes. Therefore, the isotopic data are consistent with the hypothesis that Mahukona is a Hawaiian volcano that became extinct shortly after its preshield stage. However, it is impossible to rule out simple mixing (unrelated to evolution) as an explanation for the trend in Figure 4.

Why did Mahukona become extinct before reaching sea level? There is no simple answer to this question, but some observations are worth noting. Mahukona is not unique in missing some of the stages of growth of a typical Hawaiian volcano. For example, Koolau and Lanai volcanoes are missing the postshield lavas (see Clague and Dalrymple, 1987, for a thorough review). Mahukona is part of a western chain of volcanoes that progressively decrease in size from Oahu to Mahukona (Fig. 1). Perhaps the plume component that was supplying the western chain decreased in size, causing the premature extinction of Mahukona. Vogt and Smoot (1984) noted large variations in the size of the Geisha Seamounts in the western Pacific. They proposed a model of "arrested evolution" to explain the size variations which they attributed to fluctuations in the "potency" of the plume and/or to variable plate thickness. In Hawaii, the plate thickness is nearly constant. Therefore, fluctuations in the size of Hawaiian volcanoes may be related to the dynamics of the hotspot plume.

The nature of the plume under Hawaii is poorly known, but some inferences can be made about its behavior. The recognition of the paired sequence of volcanoes in the southern part of the Hawaiian chain indicates that for the past 4 m.y. it has produced two distinct chains of volcanoes. There are no apparent structural weaknesses in oceanic crust near the Hawaiian Islands that would control the location of the two independent chains, so their origin must be controlled by subcrustal processes. Griffith (1986) has shown that rising, thermally driven diapirs may entrain the surrounding material. In experiments where the plume ascends through a horizontally deflected medium, the plume bifurcates (Richards and Griffith, 1989). Although simplistic, this model may be representative of the upper mantle processes and might be a mechanism for generating the two parallel chains of volcanoes that form the Hawaiian Islands. However, the model is based on laboratory experiments, which are sensitive to differences in the temperature and density between the plume and the material it intrudes; these differences are unknown for the Hawaiian hotspot. Nonetheless, it is an attractive model that should be more fully evaluated by future research.

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