

## Geochemistry of the Hawi lavas, Kohala Volcano, Hawaii

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**Abstract.** Hawi lavas form the late stage alkalic cap on Kohala Volcano and range in composition from hawaiite to trachyte. New, detailed field mapping of Kohala and reinterpretation of previously published age data suggest that there was no significant eruption hiatus between the Hawi and underlying Pololu shield lavas as was previously suggested. Mineral and whole-rock chemical data are consistent with a crystal fractionation origin for the hawaiite to trachyte compositional variation observed within the Hawi lavas. Plagioclase, clinopyroxene, Ti-magnetite, olivine and apatite fractionation are needed to explain this variation. The clinopyroxene fractionation may have occurred at moderate pressure because it is virtually absent in these lavas and is not a near liquidus phase at pressures of less than 8 Kb. Plagioclase would be buoyant in the Hawi hawaiite magmas so a mechanism like dynamic flow crystallization is needed for its fractionation and to account for the virtual absence of phenocrysts in the lavas. Hawi lavas are distinct in Sr and Nd isotopic ratios and/or incompatible element ratios from the Pololu lavas. Thus they were derived from compositionally distinct sources. Compared to other suites of Hawaiian alkalic cap lavas, Hawi lavas have anomalously high concentrations of phosphorus and rare earth elements. These differences could be due to greater apatite content in the source for the Hawi lavas.

### Introduction

The chemical composition and character of eruptive products from the alkalic stage of development of a Hawaiian volcano are distinctly different from that of the underlying shield lavas. These late lavas are mildly alkalic and moderately to strongly evolved (hawaiite to trachyte) in contrast to the dominantly tholeiitic basalts of the shield. Volcanism is typically strombolian producing thick flows (i.e., 2–5 m vs. typically <1 m for the shield lavas) which are erupted from steep-sided, 50–100 m high cinder cones.

Macdonald and Katsura (1962, 1964) delineated two types of alkalic caps on Hawaiian volcanoes: the Haleakala and Kohala types. The Haleakala type is characterized by a basal transition zone of interbedded basalt and hawaiite overlying the tholeiitic shield lavas and is composed predominantly of hawaiites (>90%). In contrast, the Kohala type is characterized by an abrupt change in composition

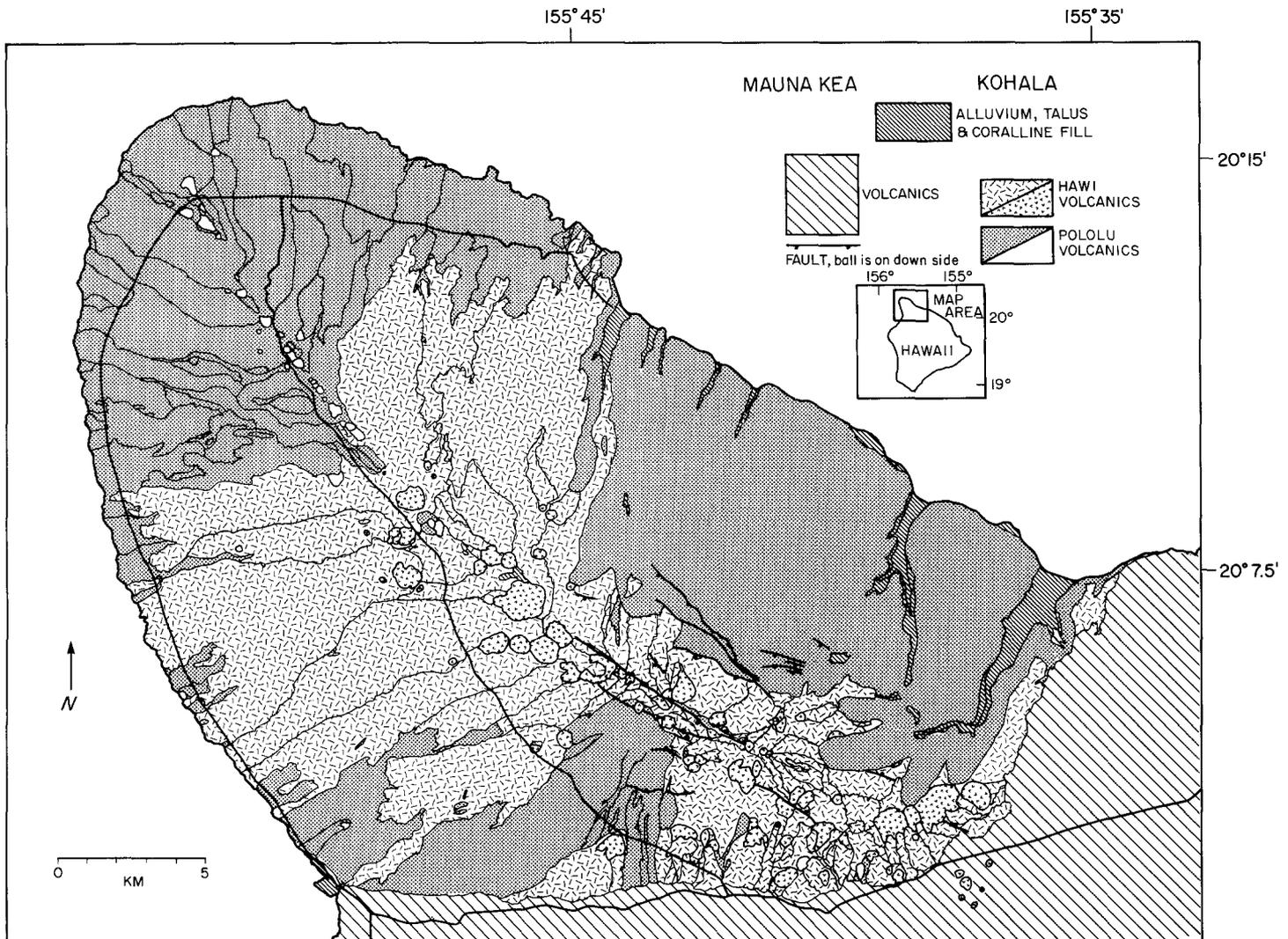
from basalt to mugearite (which was thought to be the dominant rock type of the cap, >90%), with a significant eruptional hiatus separating the two. On Kohala, for instance, an apparent age gap of about 100 Ka between shield and cap lavas was suggested (McDougall and Swanson 1972). The age and compositional gaps of the Kohala-type caps are difficult to reconcile with current models for the thermal history of a Hawaiian hotspot (e.g., Wise 1982). Why would the volcano stop erupting and then restart with a different composition?

Previous interpretations of the Kohala cap were based on reconnaissance mapping and limited chemical analyses (Stearns and Macdonald 1946; Macdonald and Katsura 1964; Malinowski 1977; Sibray 1977; Furst 1982). The purpose of this study is to re-examine the Kohala cap to determine: 1) the relative proportions of the rock types present; 2) the causes for the compositional variation among the cap rocks; and 3) the chemical and stratigraphic relationships of the shield lavas to the cap lavas. We mapped the western and northern portions of Kohala Volcano in detail as part of the U.S. Geological Survey's Big Island Map Project. The southern and eastern parts of Kohala were mapped by S.C. Porter (University of Washington). This paper combines the field and geochemical data from both studies.

### Regional geology

Kohala Mountain is the northernmost and oldest of the five volcanoes comprising the island of Hawaii (Fig. 1). Reconnaissance mapping by Stearns and Macdonald (1946) led to the subdivision of Kohala lavas into two stratigraphic units: the Pololu and the Hawi volcanic series. Pololu lavas constitute roughly 99 percent of the subaerial volume of the volcano and are dominantly tholeiitic in composition. The upper 100 meters of Pololu lavas exposed in Waipio Valley show a progressive up-section increase in alkalinity and incompatible element content (Feigenson et al. 1983). The overlying Hawi lavas form a cap of up to 153 m thick which thins abruptly away from the summit region, forming massive, relatively thick (2–5 m) flows ranging in composition from hawaiite to trachyte (Stearns and Macdonald 1946). In this study, aphyric lavas were found at and near the top of the Pololu section which have a composition intermediate between Pololu and Hawi lavas. They are termed here transitional Pololu.

Hawi volcanism was mildly explosive in nature, producing large, steep-sided cinder cones (which predominantly follow the trend of the pre-existing rift zones formed during Pololu activity) and voluminous lava flows (up to  $160 \times 10^6 \text{ m}^3$ ). Morphologically the Hawi lavas are distinguished by their hummocky surface and



**Fig. 1.** Geologic map of the northern portion of the island of Hawaii. Kohala Volcano is subdivided into two units: Pololu and Hawi lavas. Flows for each of these units are shown by the upper pattern in the boxes; cinder cones are shown by the lower pattern. Younger and coeval lavas from Mauna Kea abut Kohala on its southern flank. Major roads are shown by solid lines. Geology by M. Garcia, S. Porter and S. Spengler after H. Stearns (Stearns and Macdonald 1946)

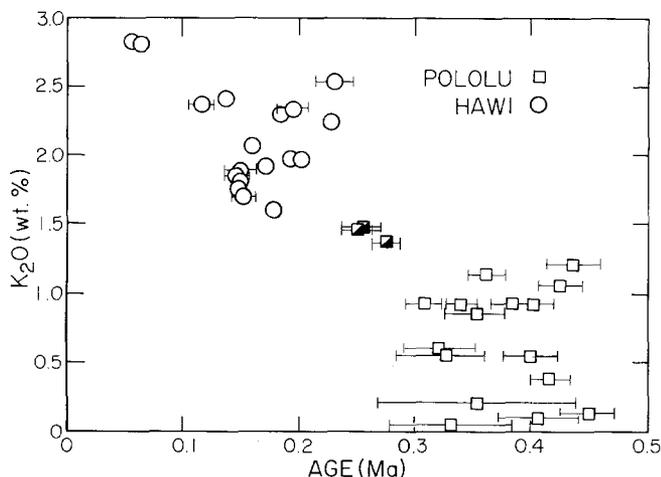
blocky flows in contrast to the relatively smooth surfaces of the pahoehoe and aa flows of the Pololu lavas. Pololu lavas are also commonly overlain by well developed reddish weathering surfaces, especially on the lower flanks of the volcano.

Reported potassium-argon age dates for 17 Hawi lavas range from 60 to 254 Ka (McDougall 1969; McDougall and Swanson 1972). The oldest reported age (254 Ka, HW-20; McDougall and Swanson 1972) is for a sample with a lower  $K_2O$  content (1.46 wt.%) than any other definitive Hawi sample collected in this study. Although this flow has the appearance of a Hawi flow (i.e., massive, thick and aphyric), it is overlain by a plagioclase-phyric Pololu flow. In addition it has a low  $P_2O_5$  content (0.83 wt.%) and lacks modal apatite, features that distinguish it from all other Hawi lavas. Thus sample HW-20 should be excluded from the Hawi age range. Recalculation of the ages of these old K-Ar age dates using the set of decay and abundance constants recommended by the IUGS Subcommittee on Geochronology (Dalrymple 1979) yields a new age range of 62–232 Ka for the Hawi. Pololu lavas now range from 260 to 455 Ka (using only samples with uncertainties of less than 30 Ka). This reduces the age gap between the two groups to only 28 Ka. Additional K-Ar age dating by G.B. Dalrymple (pers. comm., 1987) of lavas collected during this study from the uppermost Pololu section and of

transitional Pololu lavas has confirmed that the age gap separating Pololu from Hawi lavas lies within analytical uncertainty of the measurements (i.e., ages, 28 Ka vs. analytical,  $\pm 10$ –30 Ka). The common occurrence of soil horizons between Pololu and Hawi flows simply reflects a decrease (rather than cessation) in eruptive activity since large parts of Kohala (especially the lower flanks) remained uncovered for relatively long periods of time before being buried by the more episodic eruptions which typified Hawi activity.

Among the dated Hawi lavas there is no correlation of rock type with eruptive age (Fig. 2). Furthermore, at localities where relative stratigraphic position could be determined, no consistent trend in composition with age was observed. Thus, the Hawi lavas were probably products of numerous discrete magma batches rather than products of a progressively fractionating, long-lived magma body.

There are approximately 88 mappable Hawi vents (this is a minimum estimate since some vents within the caldera complex were probably buried by later activity), which erupted over a time span of approximately 170 Ka. The continuity in ages for analyzed Hawi rocks (Fig. 2) suggests that volcanic activity was relatively constant and that an eruption occurred on average about once every 1900 years. This eruption frequency for Kohala is similar to the range estimated for Mauna Kea alkalic cap lavas (1250–



**Fig. 2.** K–Ar age dates for Kohala Volcano lavas versus whole-rock,  $K_2O$  wt.%. Horizontal lines give  $\pm 2$  sigma error for ages. For symbols without lines, the error is less than the size of the symbol. Data from McDougall (1969), McDougall and Swanson (1972), Lanphere and Frey (1987) and G.B. Dalrymple (unpubl.). Symbols for transitional Pololu lavas are half filled. For Hawi lavas there is no temporal variation in  $K_2O$  content

1500 years; West et al. 1988) but is a factor of 16 less than the estimate of Feigenson and Spera (1981). Their rate was based on a two-dimensional analysis and thus, is a minimum. The new ages provide a much better framework for estimating eruption rates than was previously available. With the revised eruption frequency and our new volume estimates for typical Hawi eruptive events ( $\sim 100 \times 10^6 \text{ m}^3$ ), an eruption rate of  $4 \times 10^4 \text{ m}^3$  of lava per year is derived. Adjusting for vesicularity of the lavas (approximately 10%), a value of  $3.6 \times 10^4 \text{ m}^3/\text{yr}$  of magma is obtained. This is much lower than the eruption rate for Kilauea Volcano (minimum of  $30 \times 10^6 \text{ m}^3/\text{yr}$  of tholeiite between 1956 and 1983; Dzurisin et al. 1984) or Hualalai Volcano ( $2 \times 10^6 \text{ m}^3/\text{yr}$  of alkalic basalt during the Holocene; Moore et al. 1979). The decrease in eruption rates from Kilauea to the late stage alkalic cap of Kohala clearly reflects the drift of Hawaiian volcanoes away from the locus of magma production.

### Petrography

Hawaiian late-stage cap rocks are characteristically aphyric ( $< 1$  vol.% phenocrysts). Petrographically, Hawi lavas can be distinguished from evolved Pololu lavas by: 1) the presence of modal apatite, which is a reflection of the anomalously high  $P_2O_5$  contents of these lavas (up to 2.35 wt.% in the mafic hawaiiites); and 2) the almost complete absence of modal clinopyroxene (even in the groundmass) in Hawi hawaiiites and mugearites. The modal abundance of apatite in Hawi lavas is quite constant (0.1–0.3 modal percent) regardless of the whole rock  $P_2O_5$  content.

Kohala hawaiiites are typically dark grey in color and generally glisten in hand sample because of the parallel to sub-parallel alignment of groundmass feldspar laths. They have a fine-grained, intergranular texture and are darker in color than the more evolved alkalic rocks on Kohala (which contain more groundmass plagioclase). In both hawaiiites and mugearites, rare subhedral to euhedral zoned phenocrysts of plagioclase are present. Euhedral to subhedral magnetites and olivines, whose rims are slightly altered to iddingsite, also occur as microphenocrysts and coarse groundmass grains. Apatite (0.1–0.3 modal percent) occurs in two forms; as tiny needles, colorless to light brown in color, and as rare, euhedral, pinkish-brown pleochroic microphenocrysts which are commonly found in contact with magnetite grains. Extremely rare, small, colorless to pale green needles of clinopyroxene occur in the groundmass.

Benmoreites are typically more porphyritic and lighter in color than the hawaiiites and mugearites and are distinguished by the presence of amphibole (kaersutite). Andesine is the predominate phenocryst phase with subordinate amounts of kaersutite, olivine, magnetite and rare microphenocrysts of augite. Phenocrysts of kaersutite are usually rounded with opacite reaction rims. Many amphiboles have completely opacitized. The groundmass is composed largely of untwinned, subhedral to anhedral grains of oligoclase. Apatite predominantly occurs as microphenocrysts in association with magnetite although it is also rarely found included in amphibole. Olivine grains are subhedral and are almost entirely altered to iddingsite. Biotite is also seen as an accessory phase in some samples. Anorthoclase is present as small groundmass grains.

### Mineral compositions

New analyses of phenocryst and groundmass olivine and magnetite grains were made using the Cameca microprobe at the University of Hawaii (see Garcia et al. 1986 for methods). These analyses in conjunction with other microprobe analyses of mineral phases observed in Hawi lavas (Sibray 1977; Malinowski 1977; Nicholls 1985, pers. comm.) form a large body of mineral compositional data for crystal fractionation modeling. Microprobe analyses of kaersutite and biotite can be found in Sibray (1977).

Hawi plagioclases have andesine compositions (Table 1). Sibray (1977) used long counting times (80–200 s) and up to 20 analyses per plagioclase grain to measure the SrO content of Kohala plagioclases by microprobe. Resulting distribution coefficients range from 3.5–4.5 in hawaiiites to 3.5–7.5 in benmoreites (Sibray 1977).

Olivines show a decrease in forsterite (Fo) content with increasing differentiation and range in composition from  $Fo_{74}$  in the hawaiiites to  $Fo_{46}$  in the benmoreites. The amount of Mn in olivine increases dramatically from about 0.60 to wt.% in hawaiiites up to 2.4 wt.% in benmoreites. The predominant opaque phase in Hawi lavas is titaniferous magnetite (21.5–24.7 wt.%  $TiO_2$ ). Magnetites found in the hawaiiites generally have higher titanium and magnesium contents and lower manganese contents than those in the more differentiated Hawi lavas. Pyroxenes are either absent or too small for analysis by microprobe in hawaiiites and most mugearites. Sibray (1977) analyzed a groundmass augite in a mugearite ( $En_{43}Fs_{13}Wo_{44}$ ) and a microphenocryst in a benmoreite ( $En_{31}Fs_{23}Wo_{46}$ ). Their compositions are similar to values reported for augites in evolved alkalic lavas on Maui (Fodor et al. 1975).

Apatite compositions are similar over a wide range in rock composition (Table 2). However, many of the apatites in the highly evolved rocks occur as inclusions in magnetite and amphibole; thus their composition could reflect the chemistry of the magma at an earlier stage of differentiation. This is further suggested by the similar Sr contents of apatites found as inclusions in Sr-poorer benmoreites and the groundmass apatites in the Sr-rich hawaiiites and mugearites (Sibray 1977). The distribution coefficient of Sr in apatite is 2.3 for hawaiiites (Sibray 1977). The fluorine content of the apatite is greater in the core than the rim indicating normal zoning (J. Nicholls 1986, pers. comm.).

### Whole rock analytical methods

Great effort was taken to collect only the freshest, least altered rocks available from a given flow unit. Major element analyses of these rocks (Table 3) were performed using X-ray fluorescence spectroscopy and  $CO_2$  analyses using a CHN analyzer at the US Geological Survey's Branch of Analytical Chemistry at Lakewood, Colorado.  $Na_2O$  abundances were also determined by INAA (precision  $< 2\%$ ; Chen and Frey 1985). The average deviation of  $Na_2O$  values obtained by XRF and INAA for the same crushed powder was 2%. Based on replicate analyses of USGS standard rocks BCR-1 and BHVO-1, the precision for the major elements is better

**Table 1.** Microprobe analyses of minerals in Hawi lavas used in modeling calculations for hawaiites (H), mugearites (M) and benmoreites (B)

	Olivine			Opaque			Plagioclase <sup>a</sup>			Clinopyroxene*
	H	M	B <sup>a</sup>	H	M	B	H	M	B	
SiO <sub>2</sub>	37.30	35.56	34.60	—	—	—	56.30	59.30	60.40	47.70
TiO <sub>2</sub>	—	—	—	24.68	23.84	21.50	—	—	—	2.42
Al <sub>2</sub> O <sub>3</sub>	—	—	—	2.08	0.87	0.94	27.40	24.90	25.10	7.98
NiO	0.14	0.10	0.04	—	—	—	—	—	—	—
FeO	25.30	32.44	41.10	67.86	70.45	72.96	1.01	1.02	0.38	6.38
MnO	0.60	1.06	2.41	0.85	1.13	1.70	—	—	—	0.12
MgO	35.10	30.85	20.90	3.24	2.49	1.95	—	—	—	13.80
CaO	0.53	0.50	0.32	—	—	—	8.96	7.70	5.98	19.80
Na <sub>2</sub> O	—	—	—	—	—	—	5.88	6.51	6.99	0.70
K <sub>2</sub> O	—	—	—	—	—	—	0.42	0.57	0.80	—
P <sub>2</sub> O <sub>5</sub>	—	—	—	—	—	—	—	—	—	—
Total	98.97	100.51	99.37	98.76	98.78	99.05	99.97	100.00	99.65	98.90

\* From Mahood and Baker (1986) for a hawaiite magma at 1150° C and 8 kb

<sup>a</sup> From Sibray (1977)**Table 2.** Microprobe analyses of apatite grains in Hawi lavas, Kohala Volcano, Hawaii

Rock Type	Hawaiite		Mugearite		Benmoreite		Trachyte
	H-4-74 <sup>b</sup>	H-84-3 <sup>a</sup>	H-22-74 <sup>b</sup>	H-84-25 <sup>a</sup>	H-28-74 <sup>b</sup>	H-84-62 <sup>a</sup>	H-84-61 <sup>a</sup>
SiO <sub>2</sub>	—	0.14	—	0.17	—	0.08	0.17
FeO	—	0.77	—	0.95	—	0.53	0.97
MnO	—	0.08	—	0.10	—	0.13	0.13
MgO	—	0.49	—	0.48	—	0.43	0.38
SrO	0.40	—	0.40	—	0.39	—	—
CaO	52.70	53.88	53.80	53.36	53.50	53.27	53.18
P <sub>2</sub> O <sub>5</sub>	40.5	40.92	41.20	40.53	41.10	40.80	40.02
F	4.64	3.75	3.59	3.45	4.20	2.00	3.68
Cl	0.48	—	0.44	—	0.30	—	—
Total	98.87	99.89	98.30	99.09	98.60	97.24	98.53
Trace elements (ppm)							
La	—	—	—	475 <sup>n</sup>	—	790 <sup>n</sup>	490 <sup>n</sup>
Ce	—	—	—	530 <sup>n</sup>	—	1990	1025
Pr	—	—	—	110 <sup>n</sup>	—	140 <sup>n</sup>	173 <sup>n</sup>
Nd	—	—	—	635 <sup>n</sup>	—	920	865

Analysts: <sup>a</sup> J. Nicholls (University of Calgary)<sup>b</sup> Sibray (1977)

The symbol "n" denotes analyses near the detection limit

than 1% for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, FeO, CaO, K<sub>2</sub>O, and TiO<sub>2</sub>, 2% for MgO and 5% for N<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub> (T.L. Wright 1986, pers. comm.). Samples were selected for trace element analyses (Table 4) by INAA and XRF on the basis of freshness as determined by petrographic analysis of thin sections (degree of alteration of mineral phases) and low whole-rock volatile content (loss on ignition at 900° C). REE, Hf, Ta, Th, Sc, Na, Cr and Co abundances were determined by INAA at MIT. Chen and Frey (1985) reported that the average standard deviations for five replicate INAA analyses of an alkalic lava from Haleakala ranged from 1 to 3% for Sc, Co, Na, La, Sm, 4 to 6% for Nd, Eu, Tb, Cr and 7 to 12% for Hf, Ta, Th, Lu and Yb. Abundances of V, Cr, Ni, Y, Zn, Ba, Zr, Rb, Nb and Sr were determined by X-ray fluorescence at the University of Massachusetts. Analytical precision of XRF analysis at the University of Massachusetts is 0.6–1.0% for Rb,

Sr, Zr and Zn, 2.0–3.5% for V and Nb, and about 25–30% for Ni and Cr (due to the low concentration of these elements in this standard) for replicate analysis of standard BCR-1 (Rhodes 1983).

### Petrogenesis

The isotopic variation among Hawi lavas is small (Fig. 3). Nine out of ten samples are within analytical error for Sr isotopes and five out of six for Nd isotopes (Hofmann et al. 1987; Lanphere and Frey 1987). The isotopic variation does not correlate with the age or composition of the lavas. Thus, given the small and apparently random variation in isotopic composition, the observed chemical variation (i.e., hawaiite

**Table 3.** Major element analyses of representative Pololu and Hawi lavas from Kohala Volcano, Hawaii<sup>a</sup>

	Pololu formation						Hawi formation	
	P-84-11	P-84-9	P-85-44	P-85-45	T-85-17	T-85-16	H-84-11	H-84-3
SiO <sub>2</sub>	48.70	51.80	47.80	45.80	47.70	47.30	47.60	49.30
TiO <sub>2</sub>	1.88	2.28	3.36	2.98	3.83	3.52	3.02	2.63
Al <sub>2</sub> O <sub>3</sub>	10.40	14.00	14.00	14.50	14.90	16.70	15.90	16.60
FeO	11.64	10.77	12.02	12.46	12.55	11.66	11.75	10.68
MnO	0.17	0.17	0.18	0.18	0.22	0.19	0.23	0.23
MgO	15.90	6.91	7.06	7.80	5.10	4.99	4.59	3.94
CaO	8.66	11.00	10.70	10.50	7.99	7.66	7.56	7.04
Na <sub>2</sub> O	1.61	2.24	2.77	2.66	3.59	4.11	4.85	5.00
K <sub>2</sub> O	0.25	0.32	0.80	0.76	1.34	1.47	1.59	1.76
P <sub>2</sub> O <sub>5</sub>	0.17	0.22	0.50	0.39	0.77	0.93	2.28	1.96
LOI	0.04	0.01	0.20	1.49	1.01	0.01	0.01	0.09
CO <sub>2</sub>	<0.01	<0.01	<0.01	0.16	0.02	<0.01	<0.01	<0.01
Total	99.38	99.72	99.39	99.68	99.02	98.54	99.37	99.23
Normative mineralogy								
Ne	0.0	0.0	0.0	0.0	0.0	1.5	2.2	1.1
Hy	7.2	19.8	5.8	6.9	9.4	0.0	0.0	0.0
D.I. <sup>b</sup>	15.1	20.9	26.1	23.9	37.4	42.5	48.6	51.8

<sup>a</sup> See text for methods and analytical uncertainty<sup>b</sup> Differentiation Index (normative quartz, albite, orthoclase and nepheline)**Table 3.** (continued)

Hawi formation									
H-84-64	H-84-67	H-84-25b	H-84-2	H-85-25	H-84-10	H-84-21	H-84-79	H-84-62	H-84-61
49.30	49.80	51.70	52.80	53.80	54.50	53.80	55.00	57.10	58.50
2.57	2.67	2.18	2.03	1.69	1.74	1.92	1.46	1.46	1.17
16.60	17.10	16.90	17.20	17.40	17.40	17.20	17.60	17.80	17.50
10.77	10.32	9.52	9.26	8.24	8.41	8.14	8.51	6.84	5.92
0.24	0.22	0.24	0.24	0.25	0.25	0.19	0.24	0.17	0.18
3.45	4.00	3.29	3.10	2.80	2.62	2.44	2.27	1.54	1.49
6.14	7.12	5.93	5.59	4.81	4.77	5.14	4.40	3.46	2.87
5.01	4.43	5.32	5.60	6.03	6.00	5.60	5.47	6.02	6.34
1.79	1.82	2.02	2.12	2.27	2.35	2.56	2.75	3.07	3.41
1.97	1.63	1.57	1.47	1.23	1.22	1.30	1.03	0.89	0.72
0.40	0.01	0.35	0.01	0.40	0.01	0.57	0.23	0.76	1.06
<0.01	0.02	0.02	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
97.84	99.14	99.04	99.42	98.92	99.27	98.86	98.97	98.35	98.10
Normative mineralogy									
0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0
7.4	5.8	1.6	0.3	0.0	0.3	2.7	9.0	10.5	7.6
51.2	48.3	55.9	59.9	63.8	64.7	62.5	62.6	69.0	73.8

to trachyte) was modeled with the simplest possible mechanism, fractional crystallization.

The relative abundances of rock types in a suite of rocks is the classic test for fractional crystallization. Hawi lavas show a strong negative correlation between the differentiation index and the number of mappable flow units of a given differentiation index (Fig. 4). Roughly 85% of the area covered by Hawi lavas have been remapped and chemi-

cally analyzed. Hawaiiite flows cover approximately 70% of the area, mugearites 26%, and bermoreites and trachytes 4%. No basalts were identified. Based on field observations, the average thickness of hawaiiite flows is 3 m, mugearite flows is 5 m and bermoreite and trachyte flows is 7 m. This yields relative volume abundances of 57% hawaiiite, 35% mugearite and 8% bermoreite and trachyte. These new data are in sharp contrast to estimates by Macdonald (1963)

**Table 4.** Trace element analyses of representative Pololu and Hawi lavas from Kohala Volcano, Hawaii<sup>a</sup>

	Pololu formation				Transitional		Hawi formation	
	P-84-11	P-84-9	P-85-44	P-85-45	T-85-17	T-85-16	H-84-11	H-84-3
Rb	3.6	3.8	3.9	8.4	25.3	31.4	28.0	35.9
Sr	222.7	281.9	511.9	492.2	685.4	1193.9	1854.4	1720.5
Ba	68.5	65.4	278.8	219.4	395.3	526.6	611.6	663.3
Sc	27.0	33.5	28.7	29.2	20.2	12.9	9.1	7.6
Cr	965.0	344.0	285.2	135.6	16.3	1.6	1.4	1.5
Co	74.1	41.7	71.6	71.3	53.1	55.5	15.7	13.6
Ni	690.3	102.0	138.4	149.6	35.0	10.1	14.3	8.7
V	221.1	275.1	283.5	277.8	215.7	147.8	53.2	37.9
Zr	106.7	138.5	273.3	208.6	365.3	347.9	337.4	373.8
Nb	8.6	9.2	28.6	21.2	40.7	48.4	52.0	55.3
Hf	2.6	3.4	6.5	5.1	8.2	7.6	7.7	8.2
Ta	0.45	0.49	2.98	1.69	2.82	3.94	2.93	3.19
Th	0.4	0.8	2.6	1.0	3.4	3.0	3.2	4.2
La	7.33	8.25	25.14	20.33	36.0	42.8	55.6	57.1
Ce	18.7	24.2	64.5	50.45	90.5	100.5	149.5	143.2
Nd	13.4	16.5	38.5	31.4	50.9	53.7	88.3	82.9
Sm	3.85	4.92	9.26	7.81	11.92	12.19	20.15	18.35
Eu	1.39	1.78	2.90	2.54	3.68	3.70	6.22	5.64
Tb	0.67	0.81	1.20	1.12	1.62	1.46	2.35	2.13
Yb	1.67	2.08	2.56	2.16	3.02	2.74	3.66	3.36
Lu	0.23	0.30	0.37	0.31	0.44	0.36	0.50	0.49
Y	20.5	26.4	34.4	28.9	40.8	37.3	55.6	51.7

<sup>a</sup> See text for methods and analytical uncertainty**Table 4.** (continued)

Hawi formation									
H-84-64	H-84-67	H-84-25b	H-84-2	H-85-25	H-84-10	H-84-21	H-84-79	H-84-62	H-84-61
31.4	31.9	42.1	47.0	42.6	53.2	53.5	59.3	67.8	81.6
1650.0	1538.5	1775.2	1747.0	1650.2	1615.2	1115.0	945.2	781.7	647.7
731.7	726.9	817.4	816.4	790.9	823.2	710.6	816.4	621.6	579.7
7.5	8.3	6.3	5.8	4.8	4.8	5.6	5.0	4.0	3.5
3.8	1.2	nd	nd	2.6	nd	2.1	4.3	5.4	2.3
13.3	16.3	9.7	8.2	nd	6.8	9.8	8.6	1.7	4.7
5.0	17.2	19.7	11.3	4.4	15.5	11.7	nd	12.0	11.5
36.8	56.3	27.0	17.6	9.4	12.5	34.1	nd	12.3	14.9
417.8	435.4	446.5	458.8	532.8	531.5	586.4	801.3	694.1	743.7
59.4	63.5	64.1	64.5	77.7	74.4	75.1	81.4	88.6	93.0
9.1	9.1	9.6	10.1	11.1	11.0	12.2	16.3	14.2	15.7
3.41	3.52	3.60	3.84	5.7	4.1	4.2	4.7	5.0	5.5
4.2	4.1	4.6	4.5	5.0	4.8	6.3	6.9	7.5	8.4
61.9	89.4	62.8	63.5	72.4	65.1	67.3	72.4	85.7	63.5
149.6	140.3	150.7	155.1	176.9	163.5	144.9	174.7	137.9	146.9
85.8	87.5	78.4	80.3	91.7	79.3	71.6	80.5	84.5	64.8
19.74	18.82	17.89	17.57	18.6	16.6	15.3	16.4	16.1	12.6
5.89	5.77	5.50	5.47	5.4	5.0	4.2	4.8	3.8	2.8
2.29	2.33	2.19	2.11	2.07	1.94	1.83	1.84	2.45	1.46
3.41	4.63	3.77	3.59	4.06	3.6	3.1	3.9	3.3	3.8
0.56	0.64	0.52	0.49	0.53	0.50	0.46	0.57	0.46	0.57
56.9	77.4	53.5	51.7	51.4	49.0	41.5	47.4	43.4	43.5

of rock-type distribution for Hawi lavas (i.e., 1% hawaiite, 58.5% mugearite, 0.5% trachyte and 40% alkalic basalt). These new rock-type abundances represent the most thorough characterization of the alkalic stage of a Hawaiian volcano and are consistent with a crystal fractionation model for the Hawi lavas.

Hawi lavas show a well-defined trend in major element variation from hawaiite to trachyte. Figure 5 shows the observed major element variation in Hawi lavas, using  $K_2O$  as a measure of the degree of differentiation ( $K_2O$  is the most incompatible major element oxide analyzed). These variation diagrams allow qualitative constraints to be

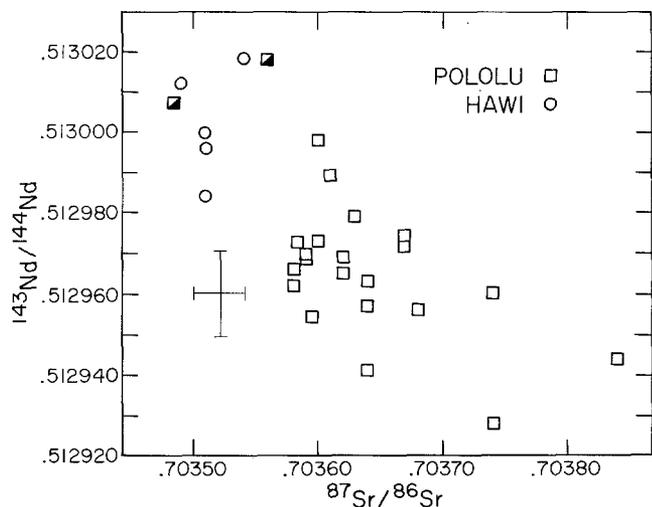


Fig. 3.  $^{143}\text{Nd}/^{144}\text{Nd}$  versus  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios in Kohala Volcano lavas. Lines gives  $\pm 2$  sigma error for isotopic ratios. Data from Hofmann et al. (1987). Transitional Pololu lavas shown by half filled squares

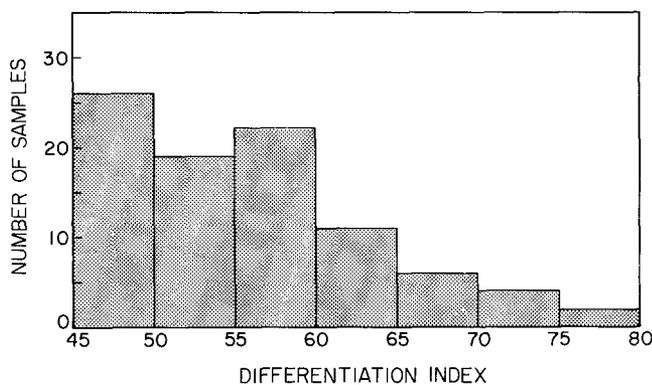


Fig. 4. Histogram of differentiation index (normative orthoclase + albite + nepheline) for Hawi lavas. The general decrease in abundance of Hawi lavas with differentiation index is consistent with a crystal fractionation model for the cause of compositional variation among the Hawi lavas

placed on possible fractionating phases.  $\text{P}_2\text{O}_5$ ,  $\text{CaO}$ ,  $\text{FeO}$ ,  $\text{TiO}_2$  and  $\text{MgO}$  contents decrease strongly,  $\text{Na}_2\text{O}$  and  $\text{SiO}_2$  contents increase, and  $\text{Al}_2\text{O}_3$  content slightly increases (up to about 3%  $\text{K}_2\text{O}$ ) as differentiation proceeds. The continual decrease in  $\text{FeO}$  and  $\text{TiO}_2$  contents with differentiation indicates that an iron-titanium-rich phase, presumably titaniferous magnetite (which is a common microphenocryst in Hawi lavas) has fractionated. The decrease in  $\text{P}_2\text{O}_5$  content throughout the series indicates that apatite fractionation also occurred. The decrease in  $\text{MgO}$  content indicates that olivine and/or clinopyroxene fractionation was important while the drop in  $\text{CaO}$  observed could be due to clinopyroxene, apatite, and/or plagioclase fractionation. A plot of  $\text{CaO}/\text{Al}_2\text{O}_3$  vs.  $\text{K}_2\text{O}$  shows a negative trend which shallows somewhat at higher  $\text{K}_2\text{O}$  contents. A change in slope at about 2.3 wt.%  $\text{K}_2\text{O}$  is also noted for other major elements in Fig. 5. The slope changes can be explained by initially greater amounts of clinopyroxene and apatite fractionation in hawaiites and mugearites followed by relatively

greater amounts of plagioclase fractionation in the derivation of the more evolved mugearites and benmoreites.

### Major Element Least-Squares Modeling

Computer modeling of the major element variation was carried out using the least-squares mixing equations of Bryan et al. (1969). The fractionation calculations were broken up into four intermediate steps, using rocks which had been analyzed for both major and trace element content. Plagioclase, apatite and magnetite were used in the fractionation calculations because of their clear fingerprints on the variation diagrams and their occurrence as microphenocrysts in the lavas. Olivine phenocrysts are found in most Hawi rocks and were also used in the calculations.

Clinopyroxene (cpx) fractionation was also considered (despite its nearly complete absence in Hawi lavas) because the marked decrease in the  $\text{CaO}/\text{Al}_2\text{O}_3$  ratio could not be explained by fractionation of apatite and plagioclase alone (Hofmann et al. 1987). In addition, a small but consistent decrease in Sc content with increasing  $\text{K}_2\text{O}$  is observed for Hawi lavas (Fig. 6). Since cpx is not a near liquidus phase at low pressure in hawaiites (as evidenced by the virtual absence of cpx phenocrysts in these lavas and experimental, 1-atmosphere run products on rocks of hawaiitic composition [Thompson 1974]), cpx fractionation probably occurred at moderate pressures. Additional evidence for higher pressure crystal fractionation is that Hawi lava compositions cross the low-pressure normative nepheline/hypersthene thermal divide as differentiation proceeds from hawaiite to benmoreite.

In the modeling calculations a moderate-pressure cpx composition calculated from 8 Kb experimental runs by Mahood and Baker (1986) was used. The use of other compositions (e.g. Salt Lake Crater pyroxenite 68SAL-7 cpx which was used by Feigenson et al. 1983), had only minor effects on the modeling results. The use of amphibole and other accessory minerals found in the evolved lavas does not improve the quality of fit. Table 5 shows the results of the least-squares calculations using both the four-phase observed assemblages and a five-phase (observed-plus-cpx) assemblages. Note that for three of the four differentiation steps, there is a large improvement in the calculated residual when using the five-phase assemblage. In particular the calculated differences in  $\text{CaO}$  and  $\text{P}_2\text{O}_5$  are greatly improved, because for the four-phase assemblage the program compensates for the large observed decrease in  $\text{CaO}$  by fractionating out excess apatite. The triangular symbols in the variation diagrams (Fig. 5) are the calculated least-square compositions using the five-phase assemblage. The small magnitude of the residuals from these calculations suggests that fractionation of the observed mineral assemblage and variable amounts of cpx is a viable explanation for the observed chemical variation. The relatively high  $\text{Na}_2\text{O}$  residual in the last two differentiation steps is thought to be due to Na loss in the benmoreite (H-84-62). It was collected from the interior of a 30 m thick flow. Similar flows in Kenya have been shown to have lost Na during cooling (Baker and Henage 1977). This sample was the freshest benmoreite available and of the major elements only Na seems to have been affected. Similar results were observed by Baker and Henage (1977) on thick evolved lavas in Kenya.

Figure 7 shows the relative proportions of fractionating phases required to derive several evolved Hawi lavas from

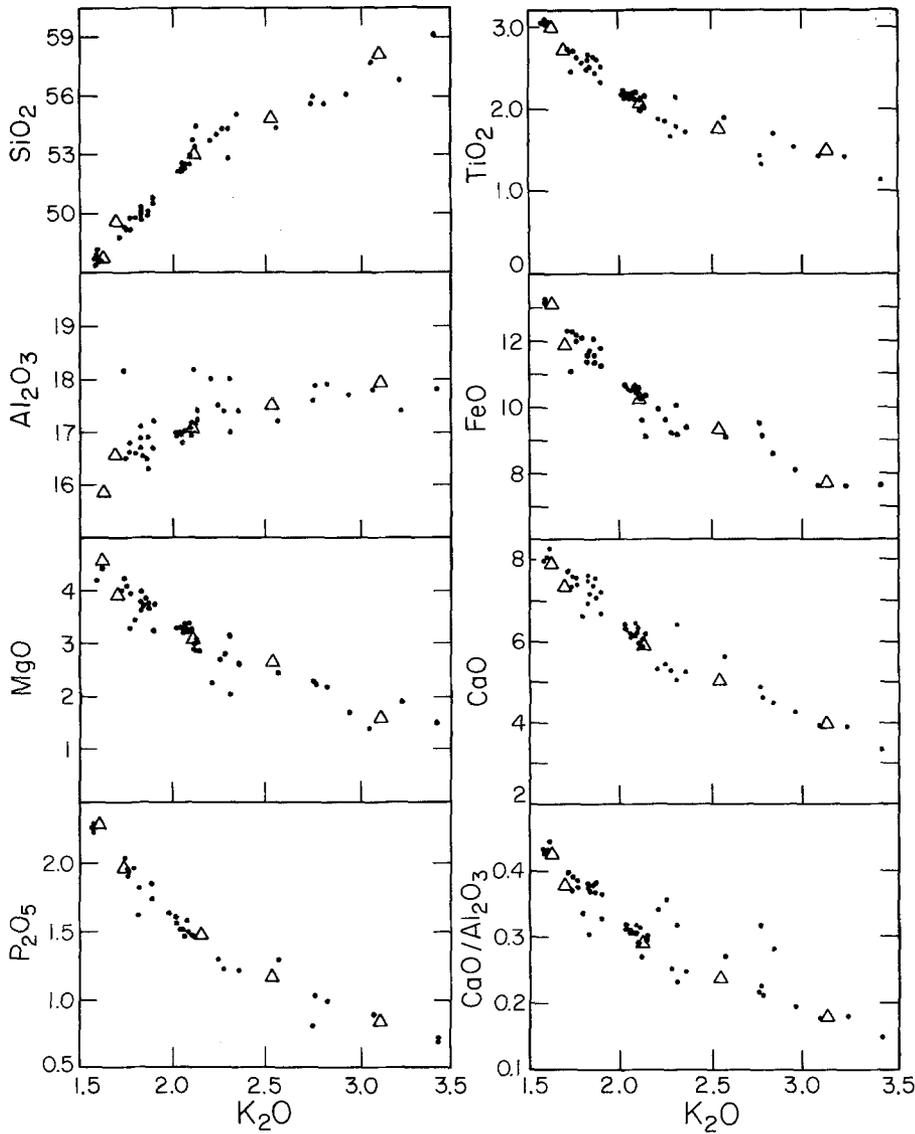


Fig. 5. Major element variation diagrams for Hawi lavas. Triangles show the average compositions used in the least-squares modeling. Note the well defined trends for these nearly aphyric lavas for all oxides except  $Al_2O_3$ . Oxides are plotted against  $K_2O$  because it is the most incompatible of the major elements. All values are in weight%

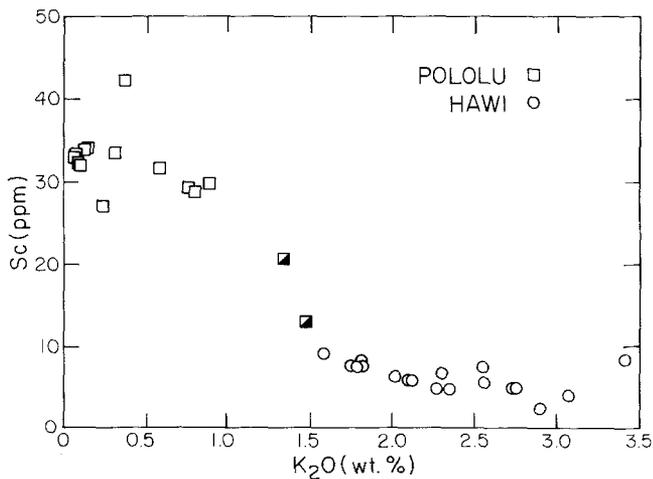


Fig. 6.  $K_2O$  versus Sc variation for Kohala lavas. Data from Hofmann et al. (1987), Lanphere and Frey (1987) and this study. The low Sc abundance in even the least fractionated Hawi lavas indicate substantial cpx fractionation prior to the formation of these lavas (Hofmann et al. 1987)

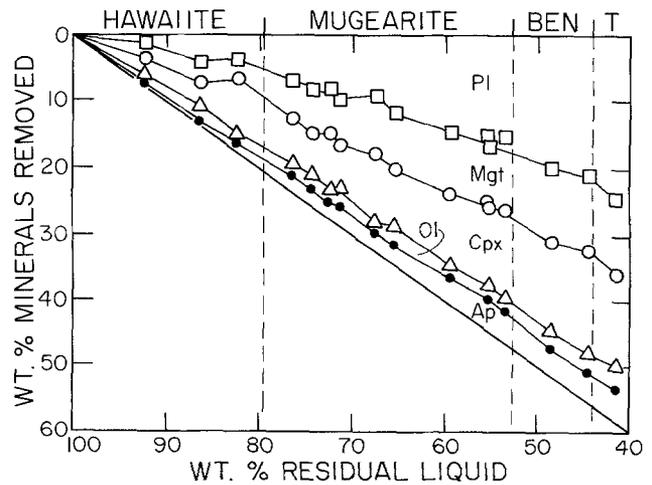
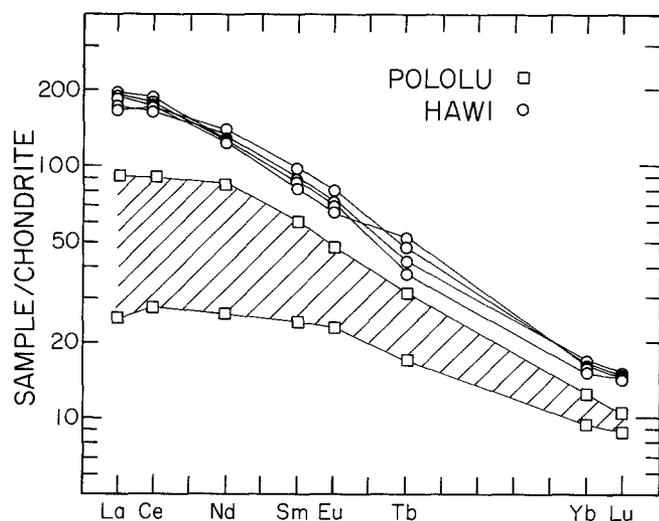
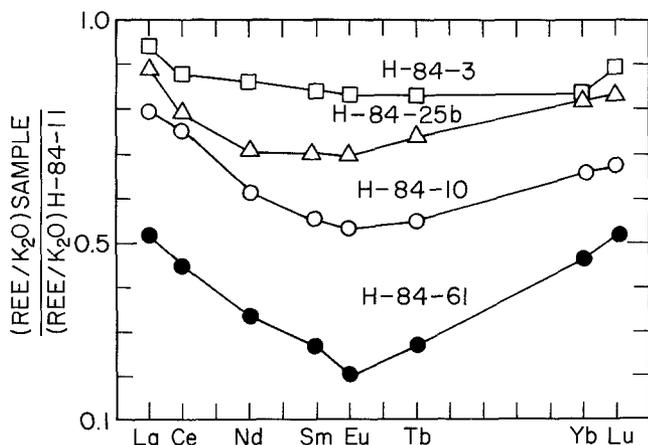


Fig. 7. Proportions of mineral phases fractionated as a function of weight percent residual liquid in sequential modeling of a trachyte from a mafic hawaiite (sample H-84-11). Weight percent of each mineral removed is shown by the vertical distance between symbols. Dashed vertical lines separate different rock types. Ben - benmoreite; T - trachyte



**Fig. 8.** Rare earth element abundances in Kohala Volcano lavas normalized to chondritic average. Field for Pololu lavas includes all analyzed samples (data from Feigenson et al. 1983; Hofmann et al. 1987; Lanphere and Frey 1987; this study). Note narrow range and crossing patterns for Hawi lavas

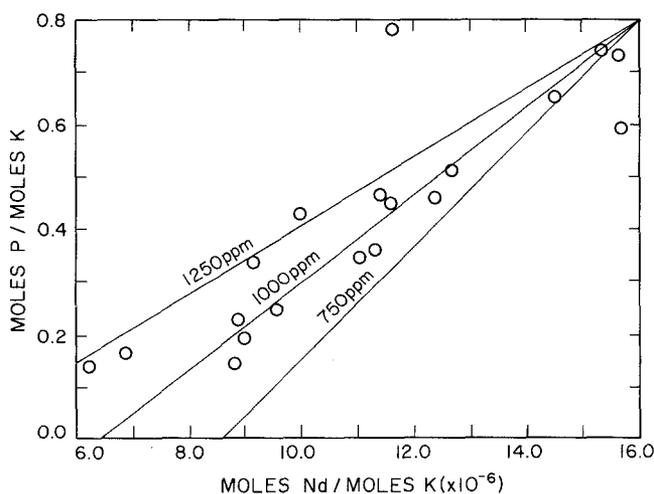
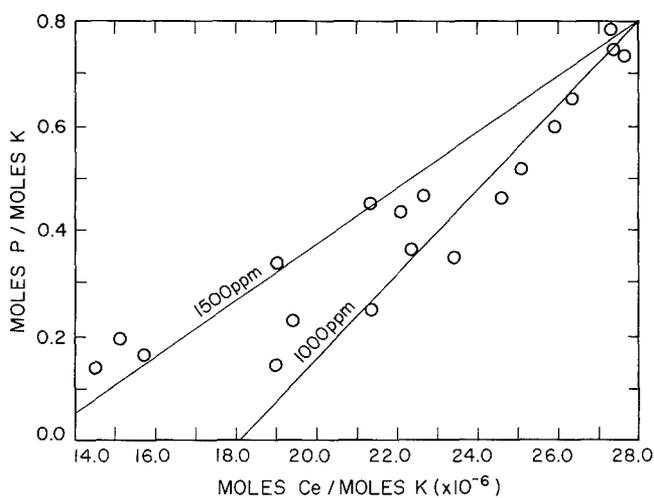
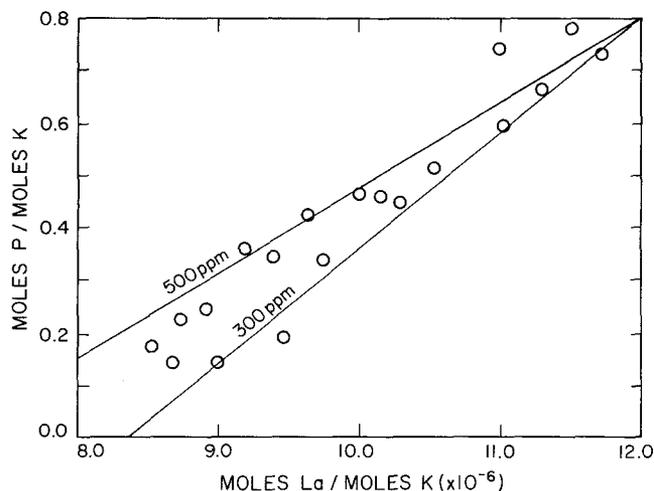


**Fig. 9.** Variation in rare earth element abundances of selected Hawi lavas normalized for fractionation (dividing by whole rock  $K_2O$  content) and compared to the most mafic Hawi lava (H-84-11). Symbols: *square*, hawaiiite (D.I. - 51.8); *triangle*, mugearite (D.I. - 56.9); *open circle*, mugearite-benmoreite (D.I. - 64.7); *solid circle*, benmoreite-trachyte (D.I. - 73.8). See text for explanation

the most primitive observed Hawi composition, H-84-11. Overall, plagioclase is the dominant fractionating phase followed in importance by cpx, then magnetite and much smaller amounts of apatite and olivine. The ratio of plagioclase to cpx fractionation increases with decreasing percent residual liquid.

### Trace elements

Trace elements can be used as an independent test of the major element modeling. Throughout the Hawi suite, the highly incompatible trace elements (Zr, Nb, Ta, Th) all show varying degree of uniform enrichment while the ferromagnesian compatible trace elements generally decrease with differentiation. The low content of Ni in the hawaiiites



**Fig. 10.** Molar ratio diagrams illustrating the variation in light REE vs. P (both normalized for fractionation by dividing by K) for Hawi lavas. *Lines* show the variations predicted for removing apatite with different concentrations of La, Ce and Nd. *Open circles* show the observed variation in Hawi lavas, which is broadly consistent with the crudely measured REE concentrations in Hawi apatites (Table 2). Mafic hawaiiites plot in the upper right corner of each plot; trachytes in the lower left corner

**Table 5.** Major element, crystal fractionation calculations for Hawi lavas

Parent	Hawaiiite		Mugearite		Mugearite		Benmoreite	
	H-84-11		H-84-25b		H-84-10		H-84-62	
Daughter	Mugearite		Mugearite		Benmoreite		Trachyte	
	H-84-25b		H-84-10		H-84-62		H-84-61	
# of Components	4	5	4	5	4	5	4	5
Residuals <sup>a</sup>								
SiO <sub>2</sub>	0.02	-0.01	0.09	0.00	0.05	0.02	0.01	0.01
TiO <sub>2</sub>	-0.09	-0.13	0.02	-0.03	-0.04	-0.25	-0.05	-0.05
Al <sub>2</sub> O <sub>3</sub>	-0.13	0.01	-0.17	0.00	-0.18	-0.07	0.00	0.00
FeO	0.04	0.05	0.00	0.01	0.02	0.08	0.02	0.02
MnO	-0.02	-0.01	-0.01	-0.01	-0.01	0.06	-0.04	-0.04
MgO	-0.04	0.02	-0.03	0.00	-0.07	-0.05	-0.02	-0.02
CaO	0.22	0.03	0.13	0.00	0.18	0.02	0.00	0.00
Na <sub>2</sub> O	0.08	0.18	-0.15	-0.05	0.42	0.24	-0.18	-0.18
K <sub>2</sub> O	-0.01	0.02	0.05	0.01	-0.18	-0.20	-0.01	-0.01
P <sub>2</sub> O <sub>5</sub>	-0.28	0.03	-0.17	0.00	-0.23	-0.03	0.00	0.00
$\sum r_2$	0.120	0.054	0.109	0.004	0.336	0.178	0.036	0.036
Fractionation assemblage in percent								
Plag	10.7	9.0	10.2	6.8	12.1	10.3	8.3	8.2
Cpx	-	5.0	-	3.0	-	2.6	-	0.1
Ti-Magnetite	5.7	5.8	3.5	3.2	2.9	3.6	2.3	2.3
Olivine	4.5	2.7	2.3	1.2	3.9	2.1	0.4	0.4
Apatite	3.1	2.6	1.7	1.3	1.7	1.2	0.6	0.6
Residual melt	76.1	74.7	82.5	84.6	79.3	80.0	88.7	88.7

<sup>a</sup> Residuals are the difference between the observed and calculated daughter compositions

(5–9 ppm) suggests that the Hawi lavas had undergone extensive olivine and/or cpx fractionation prior to eruption of these least evolved Hawi lavas. The low abundance of Cr (<4 ppm) and Sc (<10 ppm) in the hawaiiites is indicative of fractionation of clinopyroxene and/or optional of Cr-rich spinel. The low abundance of cobalt in Hawi lavas (2–16 ppm) is consistent with either cpx fractionation (partition coefficient,  $D_c$  = 6–11) or appreciable amounts of olivine fractionation ( $D_o$  = 2.8–5.2).

The decrease in Sc content from hawaiiite to trachyte (9–3.5 ppm) requires the fractionation of either cpx or magnetite; both have partition coefficients for Sc greater than one. The strong depletion in Sr from hawaiiite to trachyte (1850–650 ppm) can be accounted for by both apatite ( $D_a$  = 2.2–2.4) and plagioclase ( $D_p$  = 3.5–5.0) fractionation. The decrease in V (56.3–10 ppm) is predominantly controlled by opaque fractionation and to a much lesser degree by cpx fractionation ( $D_c$  = 13,  $D_o$  = 1.3).

The Hawi lavas all show strong light REE enrichment (Table 4 and Fig. 8) which is typical of ocean island alkalic basalts (e.g., Schilling and Winchester 1969; Zielinski and Frey 1970). Unlike other Hawaiian alkalic suites the Hawi lavas show a decrease in abundance of REE, especially the middle rare earths (Nd, Sm, Eu) as differentiation proceeds which leads to crossing REE patterns (see Fig. 8). Hofmann et al. (1987) suggested that cpx fractionation could lower the rare earth element contents in evolved Hawi lavas. However, the alkalic lavas found on Mauna Kea show strong evidence of roughly similar amounts of cpx fractionation in their petrogenesis (based on computer modeling of major element data and their similar low Sc contents), and their

REE content increase with differentiation (West et al. in review). The decrease in middle REE concentration in Hawi lavas is probably due to the fractionation of apatite, which preferentially incorporates middle rare earth elements (Lanphere and Frey 1987). This is illustrated in Fig. 9, which is a plot of normalized REE abundances of Hawi lavas divided by the REE abundances of a Hawi mafic hawaiiite using K<sub>2</sub>O content as the normalization divisor to account for different degrees of fractionation. The resulting curves are mirror images of REE distribution coefficients for apatite co-existing with hawaiiite (Watson and Green 1981). Apatite fractionation would also help explain the lack of a negative europium anomaly in the hawaiiite and mugearite REE patterns despite extensive plagioclase fractionation. The decrease in europium abundance expected by the fractionation of plagioclase is masked by the concomitant decrease in the other middle rare earth abundances due to apatite fractionation (which has a low relative  $D$  for Eu). Only the most evolved Hawi lavas, such as sample H-84-61, show a slight Eu anomaly, consistent with the higher relative proportions of plagioclase fractionation calculated for the most evolved lavas.

An additional, quantitative check on the absolute amount of the rare earth elements removed from the melt can be made using molar ratio plots. If the variation in phosphorus and rare earth element contents (excluding europium) are predominantly controlled by apatite fractionation, then a plot of P/K vs. REE/K delineates the amount of rare earth element removed. Figure 10 shows the variation anticipated for removal of various concentrations of La, Ce and Nd in apatite. The trends of the data are broadly

**Table 6.** Matrix of partition coefficient values for the fractionating mineral assemblage to produce the observed trace element variation in Hawi lavas

Element	Olivine		Plagioclase		Opaque		Apatite		Clinopyroxene	
	H-M	M-BT	H-M	M-BT	H-M	M-BT	H-M	M-BT	H-M	M-BT
Sc	0.22	0.40	0.05	0.10	3.00	5.20	0.10	0.10	6.60	6.60
V	0.10	0.20	0.10	0.10	13.00	13.00	0.10	0.20	1.30	1.30
Sr	0.01	0.01	3.50	5.00	0.10	0.20	2.20	2.40	0.10	0.10
La	0.01	0.01	0.20	0.30	0.40	0.80	4.20	8.40	0.10	0.10
Ce	0.01	0.01	0.18	0.25	0.50	1.20	5.60	14.00	0.30	0.30
Nd	0.01	0.01	0.16	0.20	0.60	1.30	10.00	13.80	0.60	0.60
Sm	0.01	0.01	0.11	0.15	0.70	1.40	11.00	14.20	1.00	1.00
Eu	0.01	0.01	1.00	1.60	0.40	0.90	5.00	7.00	0.90	0.90
Tb	0.01	0.01	0.11	0.15	1.00	2.00	8.90	12.80	1.10	1.10
Yb	0.01	0.01	0.11	0.05	0.50	1.00	4.20	6.50	0.80	0.80
Ba	0.01	0.01	1.05	3.20	0.50	0.80	0.40	0.50	0.01	0.01

<sup>a</sup> Calculations broken up into two differentiation steps utilizing the average composition of hawaiites (H), mugearites (M) and benmoreites/trachytes (BT)

consistent with the amounts crudely measured by electron microprobe (Table 2).

The bulk distribution coefficient for 11 trace elements in several Hawi lavas was determined using log-log plots following the method of Allegree et al. (1977) using Rb as the highly incompatible element. A matrix of mineral partition coefficients was then calculated using the relative percentages of fractionating minerals derived from least-squares modeling (Table 5). The solution to this matrix is unfortunately underdetermined due to the contribution of several mineral partition coefficient values on the determination of the bulk *D*. For elements which are predominantly controlled by a single mineral phase (i.e., the rare earths in apatite), the effect of other fractionating phases is minimal and a good value can be calculated. For certain elements (Sr and Ba), distribution coefficient values for Hawi lavas were used (Sibray 1977). For other elements, values were constrained to be within the range of values obtained by experimental studies (Dudas et al. 1971; Goodman 1972; Green and Pearson 1985; Hart and Brooks 1974; Higuchi and Nagasawa 1969; Nagasawa and Schnetzler 1970; Schnetzler and Philpotts 1970; Watson and Green 1981) and those determined for other alkalic series (Villemant et al. 1981; Worner et al. 1983).

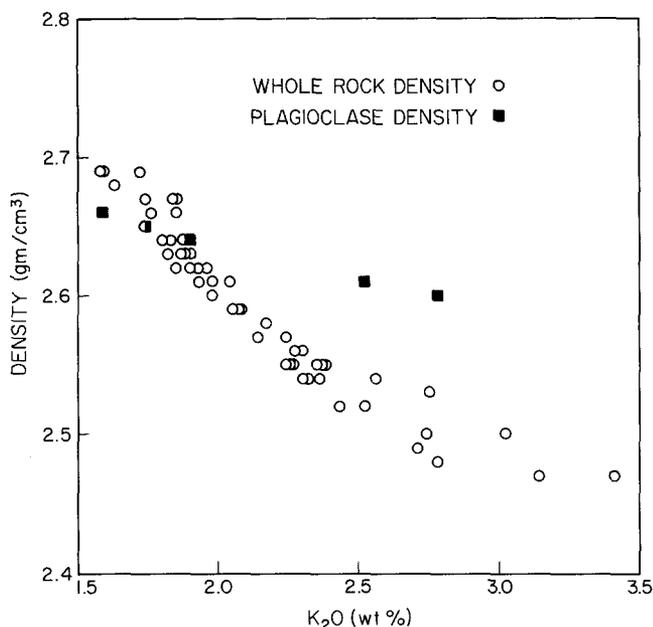
A matrix of partition coefficients for the fractionating mineral assemblage that would produce the observed trace element variation was calculated for each rock type (Table 6). Many elements that normally behave incompatibly within basaltic suites have relatively high bulk distribution coefficients. In the case of the rare earth elements this behavior is due to apatite fractionation; for other typically "hydromagmatophile" elements (e.g., Hf), it is due to the fractionation of titanomagnetite (Villemant et al. 1981). The coefficients determined for REE in apatite in the hawaiite to mugearite differentiation step are very similar to experimental values obtained by Watson and Green (1981) on a nepheline-normative hawaiite. The partition coefficient for Sc in cpx (6.6) is intermediate between literature values for rocks of basaltic to andesitic composition (1.7–3.2) and values for rocks of dacitic to rhyolitic composition (18–28). The need for a mineral with a high partition coefficient

for Sc is further evidence that cpx fractionation played an important role in the petrogenesis of Hawi lavas (Hofmann et al. 1987). Opaque fractionation alone could not create the observed decrease in Sc content.

### Magmatic conditions

Temperatures of Hawi magmas can be estimated using the empirical equation relating apatite solubility to absolute temperature and silica content (Harrison and Watson 1984). The resulting temperatures range from 1100° C for the hawaiites to 1000° C for the benmoreites. Temperatures calculated from the composition of plagioclase and the co-existing melt using the equations of French and Cameron (1981) yield results of about 1120° C for hawaiite and 1080° C for benmoreite. The hawaiite temperatures are similar to measured values of 1070–1090° C in hawaiite lavas from Etna (Sparks et al. 1977).

The density variation of Hawi magmas as a function of composition was calculated for 1100° C and 1 atmosphere using the equations of Bottinga and Weill (1970). The density of the magmas range from 2.69 g/cm<sup>3</sup> for hawaiite to 2.47 g/cm<sup>3</sup> for benmoreite while the density of plagioclase found in these magmas range from only 2.66 g/cm<sup>3</sup> in hawaiites to 2.59 g/cm<sup>3</sup> in benmoreites (calculated using the experimental data of Grundy and Brown (1967) extrapolated to 1100° C). Thus plagioclase found in Hawi hawaiites has a lower density than the magma from which it crystallized (Fig. 11). Since fractionation of the Hawi lavas occurred at higher than atmospheric pressure, this density contrast would be even greater and the cross-over in densities would shift to more evolved compositions due to the greater compressibility of liquids than of plagioclase. Therefore, lavas of hawaiite and moderately evolved mugearite composition (which show geochemical evidence of plagioclase fractionation) did not differentiate by simple gravitational settling. Dynamic flow crystallization (Irving 1980) or some other mechanism for fractionation of a buoyant to neutrally buoyant phase such as plagioclase is needed to explain crystal fractionation in the Hawi lavas. Such



**Fig. 11.** Densities of Hawi lavas and coexisting plagioclase versus  $K_2O$  content (an indicator of differentiation). Whole-rock densities were calculated for 1 atm and at  $1100^\circ C$  using the equations of Bottinga and Weill (1970). Plagioclase densities were extrapolated from values determined by Grundy and Brown (1967). Note that plagioclase would be buoyant in hawaiiite magmas

a fractionation mechanism may explain the nearly aphyric nature of the Hawi lavas.

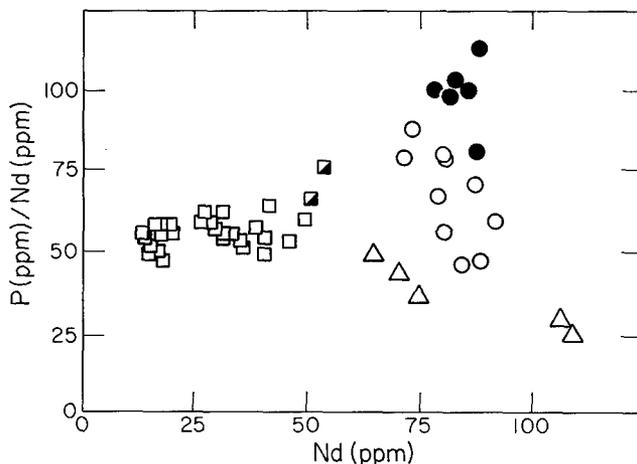
### Relationship of Hawi and Pololu lavas

Feigenson et al. (1983) proposed that all Kohala lavas could be related by a simple model of batch partial melting followed by fractional crystallization. New Sr isotope and trace element analyses show that the Hawi lavas were derived from a more depleted source than the shield-building Pololu tholeiitic lavas (Hofmann et al. 1987; Lanphere and Frey 1987). However, the differences in Sr isotope ratios are small for some of the upper Pololu alkalic basalts (0.70359 vs. 0.70357) and for the transitional Pololu lavas there is no difference (Fig. 3). Attempts to model the transitional or mafic upper Pololu alkalic lavas with the Hawi hawaiiites by crystal fractionation failed due to the large residuals for  $P_2O_5$  and the difference in ratios of highly incompatible elements (e.g., La/Nb, Ba/Nb and P/Nd) between the Hawi and Pololu lavas. Furthermore, modeling without assimilation requires 41% fractionation for the transitional Pololu to Hawi hawaiiite model although many incompatible elements (Rb, Zr, Nb, Hf, Th) are present in about the same concentration in the two lavas (Table 4). Also, the Hawi lava has 55% more Sr than the transitional lava despite the dominance of plagioclase in the fractionating assemblage (Table 7). Therefore, despite the similarity of the upper Pololu lavas with the Hawi lavas in Sr and Nd isotope ratios, there is a clear distinction in the composition of the parental magmas for the Pololu and Hawi lavas.

Lanphere and Frey (1987) pointed out the discontinuity of the MgO vs.  $P_2O_5$  trends for the Hawi and Pololu lavas and indicated that this discontinuity precluded a simple ge-

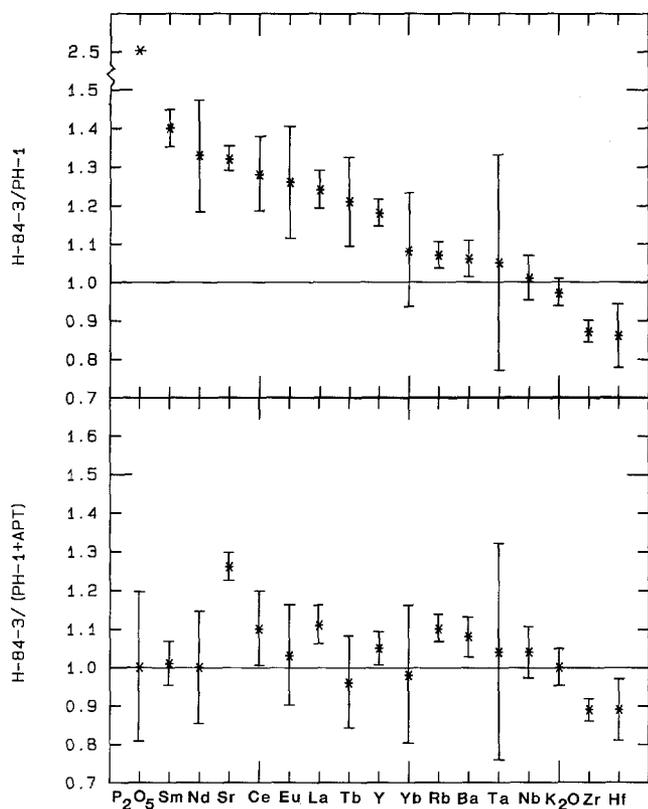
**Table 7.** Least-squares calculations attempting to relate the least differentiated Hawi hawaiiite (H-84-11) to a transitional Pololu lava and a mafic, upper Pololu lava with and without apatite assimilation. Note the reduction of the residuals (observed-calculated in weight%) for the apatite assimilation models

Parent	Transitional		Mafic Upper Pololu		
	Pololu T-85-16		P-85-45		
Daughter	Hawaiiite		Hawaiiite		Transitional
	H-84-11		H-84-11		T-85-16
SiO <sub>2</sub>	0.08	0.00	0.11	0.00	0.02
TiO <sub>2</sub>	0.04	0.01	-0.08	0.34	-0.14
Al <sub>2</sub> O <sub>3</sub>	-0.11	0.00	-0.07	0.01	-0.02
FeO	-0.01	0.00	0.03	-0.12	0.05
MnO	-0.01	-0.04	-0.03	-0.03	0.00
MgO	-0.07	0.00	-0.12	0.06	-0.04
CaO	-0.18	0.00	-0.19	-0.02	-0.02
Na <sub>2</sub> O	-0.22	-0.07	-0.34	0.00	-0.12
K <sub>2</sub> O	0.40	0.14	-0.10	0.11	-0.12
P <sub>2</sub> O <sub>5</sub>	0.42	-0.01	-0.82	0.03	-0.15
$\sum r^2$	0.422	0.026	0.758	0.148	0.076
Fractionation assemblage in percent					
Plag	26.6	10.1	17.3	11.4	12.7
Cpx	5.5	5.0	20.4	6.2	20.6
Opaque	6.6	3.8	5.2	4.5	3.5
Olivine	2.9	0.6	5.5	1.9	4.0
Apatite	-	-2.2	-	-1.4	-
Residual melt	58.9	82.7	53.2	77.0	59.7



**Fig. 12.** P (ppm)/Nd (ppm) versus Nd (ppm) for Pololu and Hawi lavas. Symbols: Pololu lavas as in Fig. 2; Hawi - hawaiiites, solid circle; mugearites, open circle; benmoreites and trachytes, triangle. Data from Feigenson et al. (1983), Lanphere and Frey (1987) and Tables 3 and 4. Note the high P/Nd ratio of the hawaiiites compared to the Pololu lavas and the decreasing P/Nd ratio from hawaiiite to trachyte which is due to apatite fractionation

netic relationship between these lavas. However, Hofmann et al. (1987) rebutted this interpretation by indicating that if the Hawi lavas were derived from a source enriched in phosphorus then Hawi lavas should have high P/Ce and P/Nd ratios (these ratios show little variation with fractionation in oceanic basalts worldwide; Hofmann et al. 1987). Their results showed similar P/Ce ratios for Hawi and Pololu lavas. Unfortunately, their sample suite did not include



**Fig. 13.** a Relative enrichment of various incompatible elements in a typical Hawi hawaiite (H-84-3) versus a typical Mauna Kea Volcano hawaiite (PH-1; F.A. Frey unpubl. data) of roughly similar degree of differentiation (based on similar  $K_2O$ , Ba, Nb and Rb contents). Note break in scale for  $P_2O_5$ . Vertical lines show  $\pm 2$  sigma error; b As above except with 2.9 g of apatite subtracted from 100 g of a Hawi hawaiite to bring the  $P_2O_5$  value to that of the Mauna Kea hawaiite. The trace elements in the fractionated apatite were calculated using the distribution coefficients calculated in this study (Table 6)

the more mafic Hawi lavas. These less differentiated Hawi lavas have P/Nd ratios up to twice those of Pololu lavas (Fig. 12). The high ratios are not due to accumulation of apatite because all of the Hawi lavas have about 0.2 vol.% apatite microphenocrysts (although the bulk rock  $P_2O_5$  content ranges from 0.72–2.35 wt.%). The low P/Nd ratios of the more fractionated Hawi lavas (Fig. 12) are due to apatite fractionation (see Table 5 and Fig. 7). Thus, it appears that the Hawi magmas were derived from a  $P_2O_5$ -enriched source.

#### High phosphorus contents in Hawi lavas

The Hawi hawaiites are unique among the Hawaiian alkalic cap lavas because of their high phosphorus content (up to 2.35 wt.% vs. a maximum of about 1.2 wt.% in other Hawaiian alkalic suites).  $P_2O_5$ -enriched alkalic lavas have, however, been dredged from Koko Seamount in the Emperor Seamount Chain (Clague 1974) and are found around the margins of the Snake River Plain (Leeman et al. 1976; up to 2.55 wt%  $P_2O_5$ ).

The high  $P_2O_5$  content of Hawi lavas is not related to apatite accumulation since the modal apatite content is low ( $\sim 0.2$  vol.%) over a wide range in whole rock  $P_2O_5$

content. In addition, the high  $P_2O_5$  contents are probably not due to lower degrees of partial melting as suggested by Hofmann et al. (1987) since no similar enrichment of highly incompatible elements (i.e., Rb, Zr, Ba) is observed (Fig. 13a). Compared to hawaiites from other Hawaiian volcanoes with similar incompatible element concentrations (K, Nb and Ba), Hawi hawaiites are enriched in REE content in the same relative order as their partition coefficient values in apatite (Watson and Green 1981). The gross differences in REE content between hawaiites from Kohala and Mauna Kea (see Fig. 13a) can be explained by removing 2.9 wt.% apatite from a Hawi hawaiite (H-84-3) to match the  $P_2O_5$  content of a Mauna Kea hawaiite with similar incompatible element abundances (i.e. K, Nb, Ta; Fig. 13b). Modeling using a hawaiite from Haleakala (HO-10, C.-Y. Chen unpublished data) in place of the Mauna Kea hawaiite yields similar results. The Mauna Kea and Haleakala hawaiites do not contain modal apatite and  $P_2O_5$  is highly incompatible in these lavas. Thus, their low  $P_2O_5$ , Sr and middle REE contents relative to the Hawi hawaiites is not due to apatite fractionation. The high P, Sr and middle REE contents of the Hawi lavas could be generated by the complete melting of apatite from an apatite-bearing source. Estimating the absolute amount of apatite in the source for the Hawi lavas is difficult due to the large amount of fractionation which even the least differentiated hawaiites have undergone. However, least-squares fractionation calculations require 1.4–2.2% apatite assimilation (Table 7). Why the source region for Hawi lavas should contain more apatite than the source regions for other alkalic products from Hawaiian volcanoes has yet to be resolved. However, studies of other Hawaiian volcanoes suggest source phosphorus content varies from one volcano to another (e.g., Clague 1987).

Alternatively, the observed enrichments could arise from assimilation. Exley and Smith (1982) noted positive P-anomalies in the hygromagmatophile element abundance patterns of some continental, primary alkali basalts which they related to assimilation. In their model, the source for the apatite is earlier magmas that crystallized at depth. These trapped magmas fractionated clinopyroxene at depth producing residual magmas enriched in phosphorus (Exley and Smith 1982). Upon protracted crystallization, apatite eventually crystallized in these residual magmas. These apatite-rich differentiates were then preferentially assimilated into the ascending liquids due to the high  $P_2O_5$  concentrations required for apatite saturation in basic magma at upper mantle P–T conditions (see Watson 1980). The similarity in composition of Hawi and Mauna Kea hawaiites when apatite is subtracted from the Hawi hawaiite is consistent with an assimilation model. Furthermore, the presence of apatite-bearing, mantle-derived xenoliths at Salt Lake Crater on Oahu (Clague et al. 1985) indicates that apatite may be available in the mantle under Hawaiian volcanoes. The lack, however, of a concomitant enrichment in other highly incompatible elements in Hawi hawaiites and the need to invoke this process for only Kohala Volcano are factors that make an assimilation model problematic.

#### Summary

The new field, petrographic, mineral chemistry and whole-rock major and trace element data presented here for Kohala lavas provide a more realistic framework for interpre-

tation of the petrogenic history of Kohala Volcano. The Hawi alkalic cap lavas conformably overlie the shield-building Pololu basalts. There is no discernible age gap between these lavas. The Hawi eruptions occurred about once every 1900 years producing typically  $100 \times 10^6 \text{ m}^3$  flows. During this waning stage of Hawaiian shield volcanism approximately  $4 \times 10^4 \text{ m}^3/\text{yr}$  of lava was erupted. Compositions of lava in the alkalic cap range from hawaiiite to trachyte with a corresponding decrease in volume with degree of differentiation. The compositional variation of Hawi lavas can be explained by crystal fractionation of plagioclase, cpx, Ti-magnetite, olivine and apatite. Cpx is not present in these nearly aphyric lavas nor is it expected based on experimental work. The absence of cpx, the nearly aphyric nature of the lavas, and the fact that plagioclase would float in some Hawi magmas indicates that some mechanism like dynamic flow crystallization at moderate pressures is needed to explain the fractionation of the Hawi lavas.

Although the uppermost Pololu lavas are similar to the Hawi lavas in Sr and Nd isotopic ratios they have distinct incompatible element ratios. Furthermore, the Hawi lavas have anomalously high  $\text{P}_2\text{O}_5$  contents (even compared to alkalic lavas from other Hawaiian alkalic lavas). Thus, the Hawi lavas were derived from distinct sources. The source for Hawi lavas is enriched in apatite compared to both the sources for the underlying Pololu lavas and lavas from other Hawaiian shield volcanoes.

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## References

- Allegre CJ, Treuil M, Minster J, Minster B, Albarede F (1977) Systematic use of trace elements in igneous processes; Part 1: Fractional crystallization processes in volcanic suites. *Contrib Mineral Petrol* 60:57-75
- Baker BH, Henage LF (1977) Compositional changes during crystallization of some peralkaline silicic lavas of the Kenya rift valley. *J Volcanol Geotherm Res* 2:17-28
- Bottinga Y, Weill DF (1970) Densities of liquid silicate systems calculated from partial molar volumes of oxide components. *Am J Sci* 269:169-182
- Bryan WB, Finger FW, Chayes F (1969) Estimating proportions in petrographic mixing equations by least squares approximation. *Science* 163:926-927
- Chen C-Y, Frey FA (1985) Trace element and isotopic geochemistry of lavas from Haleakala Volcano, East Maui, Hawaii. *J Geophys Res* 90:8743-8768
- Clague DA (1974) The Hawaiian-Emperor seamount chain: Its origin, petrology, and implications for plate tectonics. PhD Dissertation, Univ California, San Diego, 319 p
- Clague DA (1987) Petrology of West Molokai Volcano. *Geol Soc Am Abst Prog* 19:366
- Clague DA, Garcia MO, Frey FA (1985) Hornblende xenoliths from Salt Lake Crater, Hawaii: Evidence for metasomatism of the suboceanic mantle. *Am Geophys Union EOS* 66:1144
- Dalrymple GB (1979) Critical tables for conversion of K-Ar ages from old to new constants. *Geology* 7:558-560
- Dudas MJ, Schmitt RA, Harward ME (1971) Trace element partitioning between volcanic plagioclase and dacitic pyroclastic matrix. *Earth Planet Sci Lett* 11:440-446
- Dzurisin D, Koyanagi RY, English TT (1984) Magma supply and storage at Kilauea Volcano, Hawaii, 1956-1983. *J Volcanol Geotherm Res* 21:177-206
- Exley RA, Smith JV (1982) The role of apatite in mantle enrichment processes and in the petrogenesis of some alkali basalt suites. *Geochim Cosmochim Acta* 46:1375-1384
- Feigenson MD, Spera FJ (1981) Dynamical model for temporal variation in magma type and eruption interval at Kohala Volcano, Hawaii. *Geology* 9:531-533
- 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
- Fodor RV, Keil K, Bunch TE (1975) Contributions to the mineral chemistry of Hawaiian rocks: IV. Pyroxenes in rocks from Haleakala and West Maui volcanoes, Maui, Hawaii. *Contrib Mineral Petrol* 50:173-195
- French WJ, Cameron EP (1981) Calculation of the temperature of crystallization of silicates from basaltic melts. *Mineral Mag* 44:19-26
- Furst BW (1982) Petrology of the alkalic Hawi Volcanic Series of Kohala Volcano, Hawaii. MS Thesis, California State Univ, Northridge, 147 pp
- Garcia MO, Frey FA, Grooms DG (1986) Petrology of volcanic rocks from Kaula Island, Hawaii: Implications for the origin of Hawaiian phonolites. *Contrib Mineral Petrol* 94:461-471
- Goodman RJ (1972) The distribution of Ga and Rb in coexisting groundmass and phenocryst phases of some basic volcanic rocks. *Geochim Cosmochim Acta* 36:303-318
- Green TH, Pearson NJ (1985) Rare earth element partitioning between clinopyroxene and silicate liquid at moderate to high pressure. *Contrib Mineral Petrol* 91:24-36
- Grundy HD, Brown WL (1967) Preliminary single-crystal study of the lattice angle of triclinic feldspars at temperatures up to 1200°C. *Schweiz Mineral Petrog Mitt* 47:21-30
- Harrison MT, Watson EB (1984) The behavior of apatite during crustal anatexis: Equilibrium and kinetic considerations. *Geochim Cosmochim Acta* 48:1467-1477
- Hart SR, Brooks C (1974) Clinopyroxene matrix partitioning of K, Rb, Cs, Sr and Ba. *Geochim Cosmochim Acta* 38:1799-1806
- Henderson P (1982) *Inorganic Geochemistry*, Pergamon Press, Oxford
- Higuchi H, Ngasawa H (1969) Partition of trace elements between rock-forming minerals and the host volcanic rocks. *Earth Planet Sci Lett* 7:281-287
- Hofmann AW, Feigenson MD, Raczek I (1987) Kohala revisited. *Contrib Mineral Petrol* 95:114-122
- Irving AJ (1980) Petrology and geochemistry of composite ultramafic xenoliths in alkalic basalts and implications for magmatic processes within the mantle. *Am J Sci* 280A:389-426
- Lanphere MA, Frey FA (1987) Geochemical evolution of Kohala Volcano, Hawaii. *Contrib Mineral Petrol* 95:100-113
- Leeman WP, Vitaliano CJ, Prinz M (1976) Evolved lavas from the Snake River Plain; Craters of the Moon National Monument, Idaho. *Contrib Mineral Petrol* 56:35-60
- Macdonald GA (1963) Relative abundance on intermediate members of the oceanic basalt-trachyte association - a discussion. *J Geophys Res* 68:5100-5102
- Macdonald GA, Katsura T (1962) Relationship of petrographic suites in Hawaii. In: Macdonald GA, Kuno H (eds), *Crust of the Pacific Basin*. Geophysical Monograph 6, Am Geophys Union, Washington DC, pp 187-195

- Macdonald GA, Katsura T (1964) Chemical composition of Hawaiian lavas. *J Petrol* 5:82–103
- Mahood GA, Baker DR (1986) Experimental constraints on depths of fractionation of mildly alkalic basalts and associated felsic rocks: Pantelleria, Strait of Sicily. *Contrib Mineral Petrol* 93:251–264
- Malinowski MM (1977) Geology of the Kawaihae Quadrangle, Kohala Mountain, Island of Hawaii. MS Thesis, Univ Hawaii, 130 pp
- McDougall I (1969) Potassium-argon ages of lavas from the Hawi and Pololu Volcanic Series, Kohala Volcano, Hawaii. *Bull Geol Soc Am* 80:2597–2600
- McDougall I, Swanson DA (1972) Potassium-argon ages of lavas from the Hawi and Pololu Volcanic Series, Kohala Volcano, Hawaii. *Bull Geol Soc Am* 83:3731–3738
- Moore RB, Clague DA, Rubin M, Bohrsen WA (1987) Hualalai Volcano: A preliminary summary of geologic, petrologic, and geophysical data. In: Decker RW, Wright TL, Stauffer PH (eds) *Volcanism in Hawaii*, US Geol Surv Prof Paper 1350:571–585
- Nagasawa H, Schnetzler CC (1971) Partitioning of rare earth, alkali and alkalic earth elements between phenocrysts and acidic igneous magma. *Geochim Cosmochim Acta* 35:953–968
- Rhodes JM (1983) Homogeneity of lava flows: Chemical data for historic Mauna Loa eruptions. *J Geophys Res* 88:869–879
- Schilling JG, Winchester JW (1969) Rare earth contribution to the origin of Hawaiian lavas. *Contrib Mineral Petrol* 23:27–37
- Schnetzler CC, Philpotts JA (1970) Partition coefficients of rare-earth elements and barium between igneous matrix material and rock forming mineral phenocrysts – II. *Geochim Cosmochim Acta* 34:331–340
- Sibray S (1977) Mineralogy, petrology and geochemistry of some lavas from Kohala Volcano, Hawaii. MS Thesis, Univ New Mexico, 113 pp
- Sparks RSJ, Pinkerton H, Macdonald R (1977) The transport of xenoliths in magmas. *Earth Planet Sci Lett* 35:234–238
- Stearns HT, Macdonald GA (1946) Geology and groundwater resources of the island of Hawaii. *Hawaii Div Hydrogr Bull* 9, 362 pp
- Thompson RN (1974) Primary basalts and magma genesis I. Skye, Northwest Scotland. *Contrib Mineral Petrol* 45:317–341
- Villemant B, Jaffrezic H, Joron JL, Treuil M (1981) Distribution coefficients of major and trace elements: Fractional crystallization in the alkali basalt series of Chaîne de Puys. *Geochim Cosmochim Acta* 45:1997–2016
- Watson EB (1980) Apatite and phosphorus in mantle source regions: An experimental study of apatite/melt equilibria at pressures to 25 kbar. *Earth Planet Sci Lett* 51:322–335
- Watson EB, Green TH (1981) Apatite/liquid partition coefficients for the rare earth elements and strontium. *Earth Planet Sci Lett* 56:405–421
- West HB, Garcia MO, Frey FA, Kennedy A (submitted) Evolution of alkalic cap lavas, Mauna Kea Volcano, Hawaii. *Contrib Mineral Petrol*
- Wise WS (1982) A volume-time framework for the evolutions of Mauna Kea Volcano, Hawaii. *Am Geophys Union EOS* 63:1137
- Worner G, Beusen JM, Duchateau N, Gijbels R, Schmincke H-U (1983) Trace element abundances and mineral/melt distribution coefficients in phonolites from the Laacher See Volcano (Germany). *Contrib Mineral Petrol* 84:152–173
- Zielinski RA, Frey FA (1970) Gough Island: Evaluation of a fractional crystallization model. *Contrib Mineral Petrol* 29:242–254

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