

CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

PETROLOGY OF THE ALKALIC HAWI VOLCANIC SERIES
OF KOHALA VOLCANO, HAWAII

A thesis submitted in partial satisfaction of the
requirements for the degree of Master of Science in

Geology

by

Bruce Wayne Furst

January, 1982

The Thesis of Bruce Wayne Furst is approved:

Dr. Terry E. Davis

Dr. George C. Dunne

Dr. Peter W. Weigand, Chairperson

TABLE OF CONTENTS

	<u>Page</u>
Tables	v
Figures	vi
Appendices	vii
Photographs	viii
Abstract	ix
Introduction	1
Purpose	1
Location and General Setting	2
Evolution of Hawaiian Volcanoes	4
Kohala Volcano	7
Kohala Stratigraphy	7
Previous Petrologic Studies on Kohala	9
K-Ar Chronology	11
Nomenclature of Hawaiian Volcanic Rocks	12
Sample Collection	16
Petrography	16
Hawaiite	18
Mineralogy	18
Mugearite	21
Mineralogy	21
Benmoreite	22
Mineralogy	22
Benmoreite-Trachyte	23
Mineralogy	23
Inclusions	24
Implications of Alteration and Corrosion	24
Summary	25
Geochemistry	25
Methods	25
Accuracy and precision	27
Results	29
Normative Mineralogy	38
Intracone Comparison	49
Geographic Variation	49
Temporal Variation	50
Intra-Island Volcano Comparison	62
Inter-Island Volcano Comparison	62

TABLE OF CONTENTS

Continued

	<u>Page</u>
Sr-Isotope Tracer Study	71
Introduction and Previous Work	71
Results	72
Intra-Island Patterns	81
Inter-Island Patterns	81
Discussion	82
Variation Within the Hawi Volcanic Series	82
MgO-Variation Diagrams	82
Chemical Variation Based on Relative Stratigraphy	84
Mineralogical Variation	85
Origin of Alkalic Rocks	86
Differentiation from Tholeiite	86
Primary Alkalic Magma and its Relation to Tholeiite	91
Relation of Hawaiiite-Benmoreitic Suite Rocks to Alkalic Basalt	95
Crystal Fractionation Models	96
Contamination	104
Origins and Sources-Conclusions	107
Conclusions	108
Acknowledgments	112
References	113
Appendices	129

TABLES

	<u>Page(s)</u>
1. Petrographic Summary of Hawi Series, Kohala Volcano	19
2. Analysis of Some Rocks Used as Standards	28
3. Chemical Composition and Normative Mineralogy of the Hawi Volcanic Series	30-33
4. Averages for Different Rock Types of the Hawi Volcanic Series	34
5. Comparison of Compositional Variation Between Rock Types Relative to Position on Rift Zone	59
6. $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios vs. SiO_2 for Hawaiian Rocks	73
7. $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios of Hawi Volcanic Series	75

FIGURES

	<u>Page(s)</u>
1. Map of Hawaiian Archipelago	3
2. Topographic Map of the Island of Hawaii	5
3. Geologic Map of Kohala Volcano	8
4. Alkali-Silica Diagram of Tilley (1950)	14
5. Sample Locality Map for Kohala Volcano	17
6. MgO-SiO ₂ Comparative Diagram for This Study and Previous Works	36
7. Alkali-Silica Diagram for Hawi Volcanic Series	37
8. MgO-Variation Diagrams (a-l)	38-47
9. Rock Composition vs. Geographic Position (a-l)	51-58
10. Rock Composition and Stratigraphic Position	60-61
11. Comparison of Hawi Rock Chemistry to Other Hawaiian Alkalics (a-j)	63-69
12. K ₂ O/(K ₂ O + Na ₂ O) vs. ⁸⁷ Sr/ ⁸⁶ Sr	74
13. Sr Isotopes vs. Geographic Position	77
14. Sr Isotope Variation Diagrams (a-c)	78-80
15. Lateral Variation of ⁸⁷ Sr/ ⁸⁶ Sr Along Hawaiian Islands	83
16. MgO-SiO ₂ Diagram for Tholeiite and Alkalic Basalt with Mineral Composition	90
17. TiO ₂ vs. Al ₂ O ₃ Diagram	94
18. Crystal Fractionation Diagrams (a-e)	98-102
19. K ₂ O vs. K/Rb Diagram	105
20. K/Rb vs. ⁸⁷ Sr/ ⁸⁶ Sr Diagram	106

APPENDICES

	<u>Page(s)</u>
I. Previous Chemical Analyses of Alkalic Kohala Lavas	129
II. Sample Localities	130-132
III. Sample Petrography	133-137
IV. Instrumental Parameters for Geochemical Analysis	138
V. Dissolving Procedure for Atomic Absorption Analysis	139
VI. Partial Chemical Analyses	140
VII. Published Sr Isotope Ratios for Hawaiian Rocks	141-143
VIII. Crystal Fractionation Diagrams, Nonconclusive	144-146

PHOTOGRAPHS

	<u>Page</u>
1.(a) Fine-Grained Hawaiite (2.5X)	120
(b) Close-Up Hawaiite (10X)	120
2. Hourglass Extinction in Augite	121
3.(a) Fine-Grained Mugearite	121
(b) Coarse Mugearite	122
4.(a) Corroded Plagioclase	122
(b) Relict Kaersutite	123
5.(a) Benmoreite	123
(b) Benmoreite	124
6. Kaersutite With Opacite Rims	124
7.(a) Dunite Nodule (KV 15-1)	125
(b) Dunite Nodule (KV 11-2H)	125
(c) Dunite Nodule (KV 23-1)	126
8. Corroded Olivine	126
9. Corroded Clinopyroxene	127
10. Corroded Opaque	127
11.(a) Zircon(?) Polarized Light	128
(b) Zircon(?) Plane Light	128

ABSTRACT

PETROLOGY OF THE ALKALIC HAWI VOLCANIC SERIES OF KOHALA VOLCANO, HAWAII

by

Bruce Wayne Furst

Master of Science in Geology

Kohala Volcano is the northernmost and oldest volcano on the island of Hawaii. Early studies divided Kohala into two stratigraphic units; the Pololu and Hawi Volcanic Series. The Pololu is the older (1.3-0.3 m.y.a. K-Ar dates) and is composed of tholeiitic basalt. The Hawi is the alkalic basalt cap rock and is on the order of 0.25 to 0.066 m.y.a. (K-Ar dates). A hiatus or erosional unconformity separates the two units.

Rocks collected for this study were obtained from the alkalic cinder cones that lie along a N35°W trending line that approximates the major rift zone of Kohala. The mineralogy and whole-rock major-element analyses show a wide range of basalt types ranging from hawaiite through mugearite and benmoreite. The wide range in chemical composition (44-59% SiO₂, 0.9-5.0% MgO), the trends emphasized on variation

diagrams, mineralogical changes over the observed compositional range, corrosion and alteration effects, and the narrow range for Sr isotopes strongly suggest that fractional fusion or fractional crystallization is the main process controlling the composition of these lavas.

Qualitative analysis of MgO variation diagrams appears to indicate that clinopyroxene, along with plagioclase, olivine, opaques and kaersutite, control the evolution of the alkalic suite. A problem with this interpretation is that clinopyroxene is not a liquidous mineral phase at the low pressure expected where the fractionation is proposed to have taken place.

The Hawi Series cones line up along two separate loci which show slight compositional differences. Samples from the NW-SE locus appear to be slightly higher in CaO and TiO₂, and slightly lower in SiO₂ and alkalis than cones of an E-W trend. There also appears to be a general increase in FeO_T, MgO and CaO as the cinder cones get younger, possibly reflecting a zoned differentiating magma chamber beneath Kohala.

Strontium isotopic compositions of samples representative of the entire compositional range vary from 0.7031 to 0.7036 (initial ⁸⁷Sr/⁸⁶Sr). These low figures appear to preclude marine sediment or sea water contamination. There is no apparent intra-island Sr isotope variation for the island of Hawaii, nor is there any evidence for variation in Sr isotopes with geographic position. There does appear to be an inter-island variation for the Hawaiian Island chain, reflecting a heterogeneous mantle source for these basalts. Finally, Sr isotopes indicate that tholeiitic and alkalic Kohalan lavas may have a similar

source area.

Comparison of major element chemistry for Kohala with other alkalic Hawaiian volcanics show that Kohala is very enriched in P_2O_5 by about a factor of two over the average. Kohala also has higher amounts of CaO and Al_2O_3 , and lower amounts of MgO and Rb than most other Hawaiian alkalic volcanics.

The origin of the hawaiite-mugearite-benmoreite trend studied here may be separate from alkalic basalt. Fractionation of clinopyroxene from an alkalic basalt does not produce hawaiite, which has very different phenocryst assemblages and lower SiO_2 than this parental material. In addition, there has yet to be found on Kohala a true alkalic (olivine) basalt. The hawaiite-mugearite-benmoreite trend appears to represent a series of overlapping liquid lines of descent lavas.

INTRODUCTION

Purpose

The basalts of the Hawaiian Islands have been a source of much geological study. Detailed studies on the petrology, mineralogy and geochemistry of these lavas have yielded information bearing on the origin, evolution, compositional variations and age of these basalts, as well as intra-island and mantle heterogeneity. Important advances in the understanding of Hawaiian lavas were made after stratigraphic mapping (Stearns and Macdonald, 1946), petrographic studies (Macdonald, 1949a, b), and the recognition of the differences between tholeiitic and alkalic basalts by Tilley (1950).

Most petrologic research of the Hawaiian rocks have been confined to the tholeiitic suite, possibly due to their greater abundance and because the only active volcanoes, Mauna Loa and Kilauea, are entirely tholeiitic in nature. The thorough work done on these tholeiite volcanics and lack of much work on the alkali suite leaves major questions unanswered. Questions pertaining to the low-pressure fractionation scheme for alkalic rocks, the relation of alkalic rocks to tholeiitic rocks, the origin of the alkalic suite, and compositional variation (temporal, short- or long-term) have yet to be answered.

The alkalic rocks of Kohala Volcano on the island of Hawaii in particular, have been virtually unstudied. Previous studies show that Kohala tholeiites have an unusual composition; i.e., low K_2O content, highest Al_2O_3 and lowest TiO_2 of any tholeiite sequence studied (Macdonald and Katsura, 1964). Do these characteristics carry over to the alkalic suite? The lack of chemical analyses and the possible

unusual composition of Kohalan lavas make this volcano an interesting and focal study for the alkalic suite.

The purpose, then, of this study is to investigate the major-element, some trace-element and Sr-isotopic composition of the alkalic series rocks from Kohala Volcano. The data have been applied to give some insight into lava sources, differentiation models, mantle heterogeneity, temporal and compositional variations, and possible contamination. In addition, cinder cones were sampled to study distinct eruptions and possible temporal variations. Unfortunately, no discussion concerning the relative vertical relationships between eruptions within a particular cinder cone was possible. This was due to the thick grass cover and lack of dissection in all but one cone (11).

Location and General Setting

The Hawaiian Archipelago is situated in the central Pacific Ocean (Figure 1). From Kure Island in the northwest to the island of Hawaii in the southeast, the Archipelago measures approximately 2,400 km (1,500 mi). The last eight major islands in the southeast portion constitute the Hawaiian, or Windward Islands. The others are called Leeward Islands.

Each island in the Archipelago represents the top of a volcano. In the northwest, the volcano tops have been extensively eroded by stream, wave and wind erosion, and show little relief. In contrast, the southeast volcanoes, such as Mauna Loa and Mauna Kea on the island of Hawaii, attain altitudes in excess of 4,170 m (13,600 ft) above sea level.

Consistent with the extensive erosion, the northwestern islands

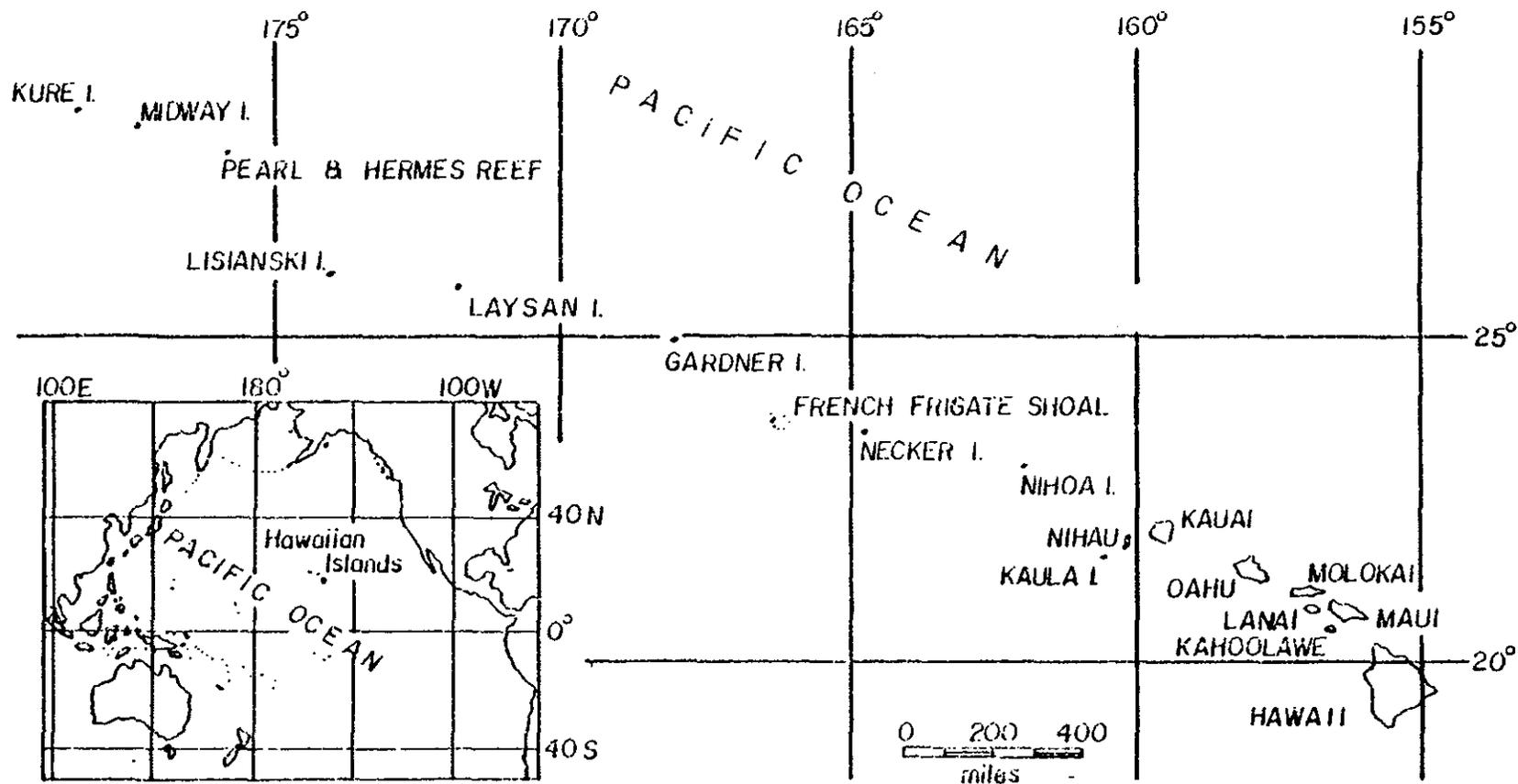


FIGURE 1 Map of the Hawaiian Archipelago

represent the older islands, as first noted by Dana (1890). McDougall (1964) obtained K-Ar ages on the Hawaiian Islands and showed a systematic decrease in age from Kauai (5.6 million years), to Hawaii (less than 0.7 million years). This age progression has been postulated to be the result of each island moving northwest over a "hot spot" (Dalrymple, 1971). Extinction of each volcano is due to drift away from the hot spot and subsequent cooling of the main magma chambers.

The island of Hawaii lies at the southeast end of the Hawaiian Archipelago, and consists of five major volcanic centers (Figure 2). Mauna Loa and Kilauea are still active, while the others are considered extinct (Kohala and Mauna Kea), or dormant (Hualalai).

EVOLUTION OF HAWAIIAN VOLCANOES

Hawaiian volcanoes progress through a succession of life stages (Stearns, 1940a), diagrammed below.

Rejuvenation Period

Principal Period

Erosional unconformity
 Old age, or postcaldera stage
 Mature, or caldera stage
 Youthful, or shield-building stage

The shield-building stage is the earliest and produces the bulk of the volcano. The lavas are tholeiitic and range from normal basalt to olivine basalt to oceanite (up to 50% olivine phenocrysts). Toward the end of the shield-building stage, most Hawaiian volcanoes collapse at the summits to form a large caldera. With continued eruption, the calderas begin to fill and there may be many cycles of collapse and

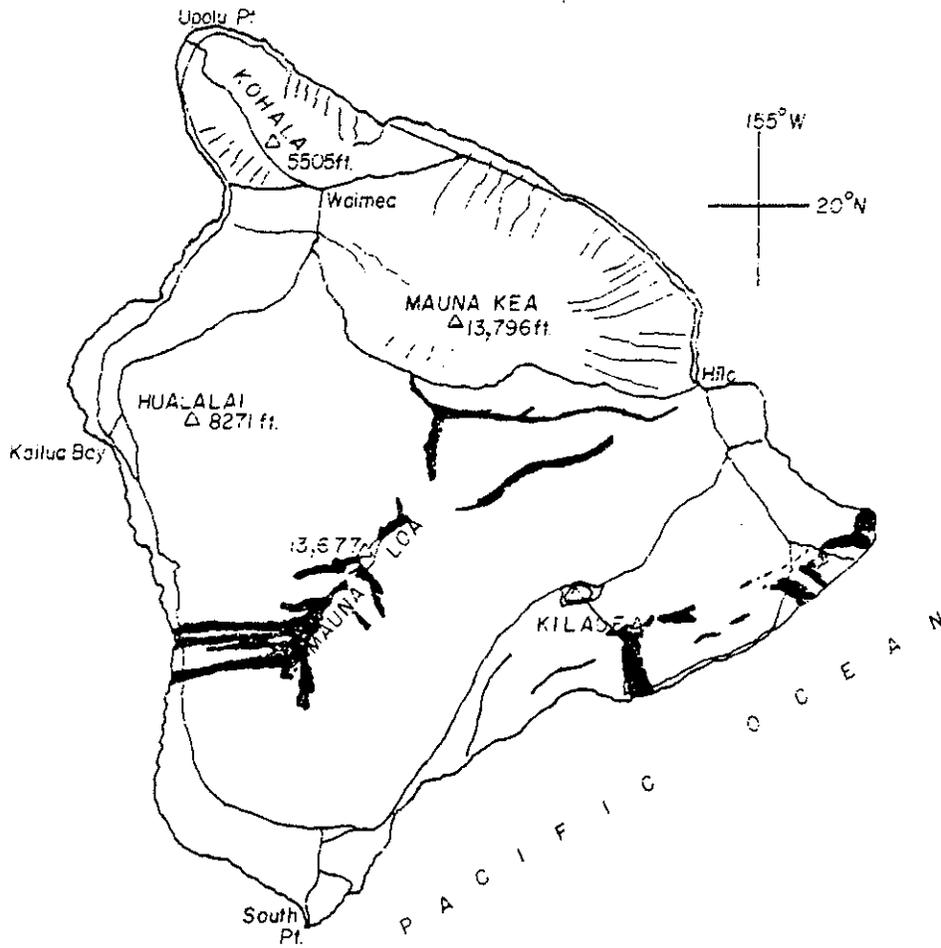


FIGURE 2 Map of island of Hawaii (with recent lava flows)

fill. The lava types of this caldera stage remain tholeiitic, although toward the end of this stage alkalic basalts may appear. The post-caldera stage consists of the production of a cap of alkalic lava which usually covers the caldera, and which makes up about 1 to 2 percent of the bulk of the volcano. The change in lava composition is identified by an increase in potassium and sodium, a decrease in silica, and an increase in the minerals augite and feldspar. There is also an increase in the gas content of the lava, causing more explosive eruptive activity and the production of cinder cones along the rift zones. The change in lava composition may occur gradually or abruptly. The first type of change is called the "Haleakala" type, and examples include Haleakala and Mauna Kea. In the other type, called the "Kohala" type, the eruptive cycle appears to go dormant for a period of time and then resumes with alkalic rocks only. Examples of this type are Kohala and West Maui (Stearns, 1946, and Macdonald and Abbott, 1970). The end of the principal period is marked by either a permanent end of activity or a long period of quiescence. In either case there is a great amount of erosion and dissection of the volcano. The rejuvenation period is marked by very explosive activity and radically different lava types, which include nephelinites and basanites such as those found in the Honolulu area of Oahu. These lavas are very silica deficient and are very high in alkalis. Phenocrysts of olivine are very small, while nepheline and melilite tend to substitute for feldspar.

It should be noted that not all Hawaiian volcanoes follow this life cycle. Some volcanoes, such as Mauna Loa and Kilauea are still in the late caldera stage, while others (Mauna Kea and Hualalai) have skipped

stages (Macdonald and Abbott, 1970).

KOHALA VOLCANO

Kohala Volcano forms a peninsula in the northern-most area of the island of Hawaii (Figure 2). The name Kohala means "whale" in Hawaiian (Washington, 1923). The elongate and oval shield is 36 km (22 mi) long, 24 km (15 mi) wide, and has an area of 864 km² (234 mi²). This elongate form was built around two major rift zones that trend N35°W and S65°E (Stearns and Macdonald, 1946). A possible, but poorly delineated, third rift zone may trend S50°W. The highly visible cinder cones studding the crest of Kohala mark the major N35°W rift zone. The summit contains a buried caldera, as evidenced by a series of curved faults (Macdonald and Abbott, 1970).

The shield has a maximum altitude of 1,694 m (5,505 ft) and is asymmetrical in cross-section. The western slope is quite gentle and has been only slightly dissected by stream-eroded valleys, while the eastern side of the shield has been truncated, with sea cliffs reaching heights of 431 m (1,400 ft), and it has also been dissected by a series of deep stream-cut canyons.

Kohala has followed the typical volcano life cycle closely. Abundant evidence is available for each stage up to the erosional unconformity stage. There is no evidence of the rejuvenation stage.

Kohalan Stratigraphy

Two stratigraphic units were recognized in the geologic mapping of Kohala by Stearns and Macdonald (1946): the Pololu and Hawi Volcanic Series (Figure 3). The older, tholeiitic Pololu Volcanic Series (Pololu V.S.) makes up the major portion of the volcano. The type



Fig. 3. Geologic map of Kohala Volcano. Numbers refer to cinder cone sample sites. Map after Stearns and Macdonald (1946). Scale 1/12,500.

locality is exposed on the northeast wall of Pololu Valley (Stearns and Macdonald, 1946). The rocks here are weathered, but the Pololu Series can still be distinguished from the Hawi because the former weathers to red-brown soils, whereas the latter weathers to gray soils. Pololu rocks generally contain olivine and feldspar phenocrysts, although some lavas are nonporphyritic. Augite appears as a phenocryst phase near the top of the series. About nine tholeiitic cinder cones are located at the northern end of the peninsula.

The Hawi Volcanic Series comprises the alkalic cap rock of Kohala. The type locality is at an altitude of 123 m (400 ft) in a quarry at the Kohala Sugar Company, 0.8 km east of Hawi in Kumakua Gulch. Hawi rocks are mostly intermediate members of the alkalic rock suite, mugearite and benmoreite, with less hawaiite, and minor basalt and trachyte. About 50 Hawi cinder cones stud the major rift zones of Kohala. They extend from just south of the southeastern-most tholeiite cones (Puu Hue), over the apex of Kohala, down the southeast part of Kohala and onto the plains between Kohala and Mauna Kea.

The Pololu and Hawi Volcanic Series are separated by an erosional unconformity on the eastern slopes, and a soil layer on the western slopes of Kohala (Stearns and Macdonald, 1946). For purposes of this study, petrologic discussions are limited to the Hawi Volcanic Series.

Previous Petrologic Studies on Kohala

Cohen (1880, according to Cross, 1915, p. 33) first classified Kohalan rocks into two groups. The first was "normal plagioclase basalts" rich in olivine; the second was a rock type transitional from basalt to augite andesite. Dutton (1884) was the first to note a

difference between Kohala and other volcanic centers of Hawaii. He thought Kohala lavas to be unique in that they are less ferruginous and more feldspathic compared to other Hawaiian lavas. He thought Kohalan lavas to be similar to andesites.

Lyons (1896) made petrographic and chemical analyses of Kohalan rocks from the area of Waimea (Appendix I). He found Kohala lavas to contain much feldspar and very little "chrysolite". Rocks analyzed were quartz normative.

Harker (1904) noted that feldspar makes up as much as 70% of some Kohalan rocks. He also found that the feldspar is oligoclase with subordinate orthoclase, and olivine is more abundant than augite. Apatite was observed in unusually high concentrations, up to 3 modal percent.

The work of Cross (1915) was the first major study done on Kohala. Of importance was the observation that it is the late-stage Kohalan lavas that are different from the "normal" Hawaiian basalts. He concluded this from the petrographic work done on samples collected in the western area of Mahukona. These samples contain feldspar, olivine, magnetite, and apatite. The feldspar is labradorite (phenocrysts) and andesine (microlites), with irregular patches of orthoclase.

Iddings (1913) classified Kohala lavas as hawaiites (andesine andesites) and "kohalaite" (oligoclase andesites). In the porphyritic samples, phenocrysts of plagioclase may be more calcic than normative plagioclase. Iddings described potassium-oligoclase as a result of mixing K-feldspar with oligoclase.

Washington (1923) presented four chemical analyses (Appendix I) of Kohala lavas collected along the Waimea-Kohala road. He recognized two

major groups of lavas: basalts and andesites. Andesites were described as "Kohalaite" with aphyric oligoclase, augite, magnetite and apatite.

The reconnaissance mapping of Stearns and Macdonald (1946) of the island of Hawaii opened the door to modern-day work. They divided the Kohalan shield into two stratigraphic lithologic units—an older, tholeiitic Pololu Volcanic Series, and a younger capping alkalic Hawi Volcanic Series. The Hawi V.S. was described as being composed mostly of mugearites with some hawaiiite and trachyte.

K-Ar Chronology

Kohala is the oldest shield volcano on the island of Hawaii (McDougall and Swanson, 1972). Difficulties have arisen with the dating of the tholeiitic Pololu series as these lavas are quite young, have very low K_2O (0.069-0.077 weight percent; McDougall and Swanson, 1972), and are aphyric. Therefore, there has been very little radiogenic Ar produced, and that which is made may be lost by diffusion (McDougall, 1964). K-Ar ages determined for the Pololu V.S. are summarized as follows with the number of age determination in parenthesis.

McDougall (1964)	Less than 0.8 m.y.
Evernden et al. (1964)	0.43 m.y. (1)
Dalrymple (1971)	0.46 \pm 0.36 to 1.28 \pm 0.46 m.y. Best age is the mean 0.7 \pm 0.15 m.y. (5)
McDougall and Swanson (1972)	Range 0.33 to 0.45 m.y. (9)

Dalrymple's (1971) samples were collected from the lowest part of the Waipio Valley and probably represent some of the oldest exposed Kohalan lavas.

Ages for the Hawi V.S. have been determined mostly on samples of mugearite. Younger ages may be found if age determinations are done on samples of trachytes as well as some other late differentiated samples from cinder cones instead of flows. Also, the oldest Hawi lavas may not have been sampled, as these may be ponded in a grabben at the summit of Kohala (Macdonald and Abbott, 1970). Age determinations for the Hawi V.S. rocks are summarized below.

McDougall (1969)	0.14-0.20 m.y. (3)
McDougall and Swanson (1972)	0.06-0.25 m.y. (9 mugearites)
Malinowski (1977)	0.082 ± 0.006 m.y. (1 flow, 3 analyses)

In summary, the Pololu V.S. erupted from approximately 1.3 to 0.3 m.y.b.p., and the Hawi V.S. erupted from about 0.25 to 0.066 m.y.b.p. The Pololu-Hawi hiatus appears to have lasted anywhere from 0.5 m.y.b.p. (Dalrymple, 1971) to less than 0.2 m.y.b.p. (McDougall and Swanson, 1972).

NOMENCLATURE OF HAWAIIAN VOLCANIC ROCKS

Hawaiian lavas can be divided into three rock suites: tholeiitic, alkalic and nephelinitic (Macdonald, 1968; Macdonald and Katsura, 1964). The tholeiitic and alkalic suites appear to be chemically and petrographically different. Variation within each rock suite is principally due to crystal fractionation (Macdonald, 1968).

Hawaiian tholeiites are characterized by olivine and pigeonite and/or hypersthene + augite + Ca-plagioclase. Tholeiites are silica-saturated, low in alkalies and high in Ca, Fe and Mg. Alkalic basalts are principally composed of olivine, Ca-augite and intermediate

plagioclase. Compositionally, they are silica-undersaturated, high in alkalis, Al and P, and lower in Ca, Fe and Mg than tholeiites.

Nephelinitic suite rocks are characterized by a lack of olivine and replacement of plagioclase by nepheline (and possibly leucite). They are silica-undersaturated and have high Mg and Ca, with low Al. Nepheline is always in the norm.

There has been a long history of debate concerning the definition and usage of the terms tholeiite and alkalic basalt. Hawaiian tholeiites and "andesites" (feldspar-rich alkalic basalt) differ from the normal use. Thus, various types of classification schemes have been suggested by many authors (Macdonald and Katsura, 1964; Yoder and Tilley, 1962; Tilley, 1950; Kennedy, 1933). By far the best criterion appears to be the alkali-silica diagram proposed by Tilley (1950). Most rocks can easily be assigned to the tholeiitic or alkalic suite, despite complete gradation between these two suites. Figure 4 shows the separation of alkalic from tholeiitic basalt. Since this thesis is primarily concerned with alkalic volcanics, discussion will be limited to that division. The following criteria can be used to distinguish various rocks of the alkalic suite—groundmass olivine, augite (and titanian-augite), and alkali feldspar (interstitial and subhedral). Macdonald and Katsura (1964) proposed a classification based on modal composition. Rocks of the alkalic suite can be subdivided as follows:

- a) alkalic basalt - containing less than 5% modal olivine and less than 5% nepheline.
- b) alkali olivine basalt - containing 5% or more modal olivine and less than 5% normative nepheline.

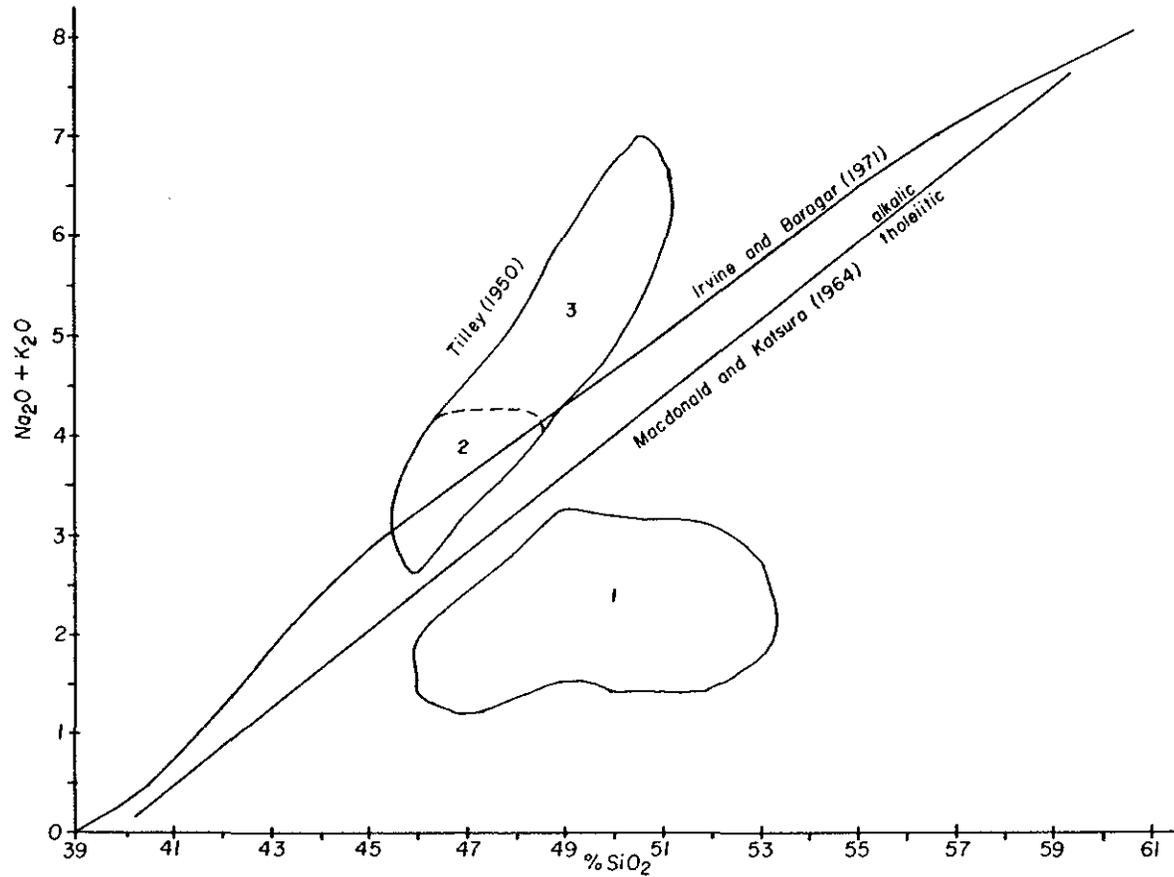


Fig. 4. Alkali vs. silica diagram of Tilley (1950). Field 1-Mauna Loa and Kilauea tholeiites; 2-olivine basalts from Hualalai; 3-mugearites from Mauna Kea. Also included are the field boundaries of Irvine and Baragar (1971) and Macdonald and Katsura (1964).

- c) ankaramite - containing very abundant phenocrysts of olivine and augite, with less than 30% total feldspar.
- d) hawaiiite - a rock of moderate to high color index and frequently basaltic habit, in which normative and modal feldspar is andesine and soda/potash ratio is greater than 2:1.
- e) mugearite - a rock similar to hawaiiite but in which the feldspar is oligoclase.

Two important terms missing from the above classification are:

- f) benmoreite - a light gray color rock with a chemical composition transitional between mugearite and trachyte (Tilley et al., 1965).
- g) trachyte - a fine-grained, generally light-colored rock composed predominantly of potassium feldspar, with minor amounts of ferromagnesian minerals. Trachyte can also be composed entirely of black glass (from Macdonald and Abbott, 1970).

Variation in "definition" of each basalt type is necessary. For example, it has been noted by Beeson (1976) on East Molokai, and Keil et al. (1972) on Maui, that even though some mugearites may compositionally approach the average mugearite (from Macdonald, 1968), plagioclase composition may be andesine. In several instances in this paper there is a distinct disagreement between petrography and chemical composition. The classification used in these cases is reflected in combining terms such as mugearite-hawaiiite. For purposes of this thesis, classification will be based on relative composition, mode and norm composition, plagioclase composition, soda to potash ratio, color and texture are used. Where conflict occurs, it is weighed against the other factors; i.e., if most factors indicate a hawaiiite and one says mugearite, the rock is called a hawaiiite. Chemical variation diagrams and petrography were weighed most. The point here is that there must

be elasticity in the "definitions" of rock terms of Hawaiian basalts.

SAMPLE COLLECTION

Sample collection was limited to the alkalic suite cinder cones on Kohala. Rocks were collected from a wide geographic area (Figure 5). Samples were labeled as follows: KV 1-1A: Kohala Volcano, cinder cone number, sample locality number, individual macroscopic hand sample. Some 59 samples were collected from 26 cinder cones. One other sample, number 15, was collected from a flow from a nearby cinder cone (Figure 5). Sample locality descriptions can be found in Appendix II.

Due to the nature of the extensive and thick grass cover, exposures of any kind were sampled. Unfortunately, no stratigraphic sequence could be derived for an individual cinder cone due to the cover. The number of samples for a cone varied, depending on the exposure of rock. At Cone 11, Puu Kawaiwai, multiple samples were collected horizontally along a single horizon composed of lava blocks and cinders for 40 meters. The purpose here was to check for any change in composition in the flow. This was the only cone where this was possible, due to the excavation of the cone. A gap in sampling exists along the Kohala Summit cones due to extensive rain forest.

PETROGRAPHY

The Hawi Volcanic Series consists of hawaiites, mugearites, benmoreites and trachyte rock types. Petrographic examination of these rocks were made with a Leitz polarizing microscope. Plagioclase determinations were made by the "a-normal" method where possible, otherwise the Michel-Levy method was used. Phenocrysts are described as crystals

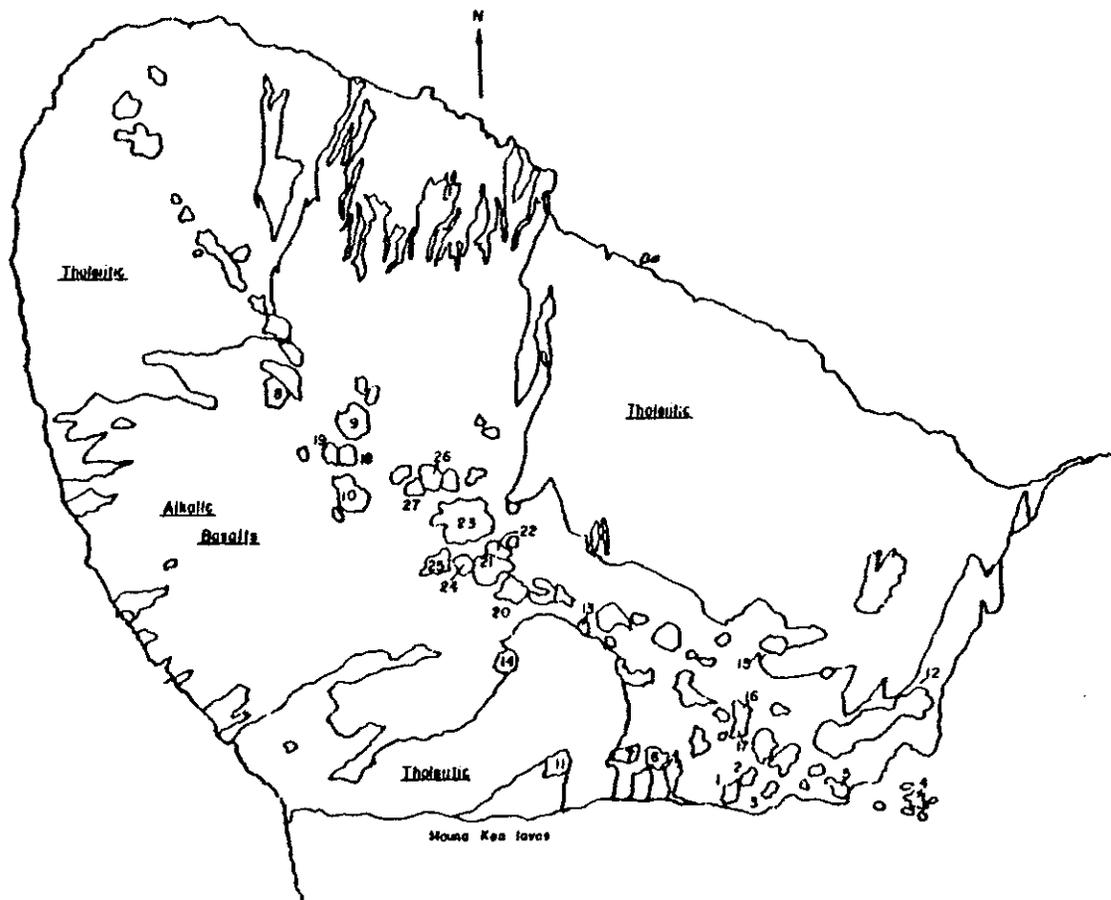


Fig. 5. Sample locality map for Kohala Volcano. Numbers refer to cinder cone sample sites. Map after Stearns and Macdonald (1946). Scale 1/12,500.

about 10 times larger than those of the groundmass. These may have formed under intratelluric conditions. Microphenocrysts are crystals slightly larger than the groundmass and may have formed during magma ascent. Groundmass is defined as almost indistinguishable crystals that formed probably after lava extrusion. A summary of the petrographic data can be found in Table 1. Modal percentages are estimates. Separation of samples into each rock type was difficult due to the transitional nature of many samples. A summarized description of each rock type follows. Individual descriptions can be found in Appendix III.

Hawaiite

The most characteristic features of hawaiites are their textural qualities and modal composition. Hawaiites are fine to coarse grained. The coarse samples display intergranular texture with larger grains of olivine, plagioclase and opaque minerals, with some microphenocrysts of clinopyroxene filling the interstices between plagioclase. In addition, groundmass is much darker in color than any other alkalic series rocks found in this study. In some cases there were localized flow textures. These textures are exemplified in Photographs 1a and 1b.

Mineralogy - In many hawaiites there are inclusions of opaques in olivine phenocrysts, thus indicating that opaque phases crystallized prior to olivine. Several crystals of olivine show jackets of clinopyroxene(?) indicating pyroxene formation after olivine. Some olivine cores are corroded. Some rims are slightly altered to iddingsite. Olivine is also found in the groundmass. Clinopyroxene is, for the most part, confined to the groundmass. The composition of the

TABLE 1

Petrographic Summary of Hawi Series, Kohala Volcano

	<u>Olivine</u>	<u>Augite</u>	<u>Plagioclase</u>	<u>Opauques</u>	<u>Apatite</u>	<u>K-feldspar</u>	<u>Other*</u>
<u>HAWAIIITE (21)**</u>							
Mode average	6	6	63	13	-	-	
Mode range	2-10	Up to 12	50-70	8-18	1-4	1	
Phenocrysts (%)	1-2	0-2	5-15	1-3	-	0.5-2	
Size range-mm	0.02-0.69	0.01-0.15	0.05-1.83	0.04-0.39	0.04-0.36	-	
Shapes	anh-euh	subh	subh-euh	anh-subh	subh-euh	subh	
<u>MUGEARITE (12)</u>							
Mode average	4	-	68	17	2	-	
Mode range	1-9	15-20	50-75	15-20	1-4	0.5-3	b tr-1
Phenocrysts (%)	1-2	-	-	3-4	3-4	-	
Size range-mm	0.08-0.50	0.01-0.05	0.07-0.10	0.13	0.36	-	0.20
Shapes	anh-euh	subh-euh	subh-euh	anh-euh	anh-euh	anh	subh
<u>BENMOREITE (4)</u>							
Mode average	1	4	80	11	1	-	k-3
Mode range	0.5-2	1-8	70-90	10-12	-	-	k 0.5-6
Phenocrysts (%)	-	-	Up to 30%	-	-	-	2
Size range-mm	0.10	0.30-0.90	0.09-0.50	0.30	-	-	0.90
Shapes	anh-subh	subh	subh	anh-subh	subh	-	subh-euh
<u>BENMOREITE-TRACHYTE (2)</u>							
Mode average	2	-	80	9	-	-	k 0.5-1
Mode range	1-3	7-8	75-85	7-10	-	-	b 0.5-1
Phenocrysts (%)	1-2	1-2	5-6	5-6	-	-	k 0.6-.27
Size range-mm	0.01-0.24	0.03-0.07	0.18-1.38	-	-	-	b 0.07
Shapes	anh	subh	subh-euh	anh	-	-	any-subh

*Other minerals - k=kaersutite, b=biotite

**Number of samples is indicated in parenthesis.

anh=anhedral

subh=subhedral

euh=euhedral

clinopyroxene is augite (extinction $40-60^{\circ}$, $2V > 60^{\circ}$, slight green to brownish pleochroism). In Sample 8-2, one augite crystal displayed hourglass extinction, or zoning (see Photograph 2). This zoning indicates compositional differences between different sectors, which result from conditions of relatively slow cooling (Strong, 1969). Plagioclase occurs as macro- and microphenocrystic laths and as acicular needles. Many of the macrophenocrysts are obscured with some core alteration and corrosion. They are also concentrically zoned. In a few cases up to five zones were observed. Composition averages An_{41} (andesine), but ranges from An_{28} to An_{51} . Zoning is regular; i.e., more calcic cores and more sodic rims. Groundmass plagioclase composition overlap that of the phenocrysts, and range from An_{32} to An_{42} . Anomalous feldspar was also observed as lath-shaped, untwinned, but regularly concentrically zoned crystals. Extinction of $2-3^{\circ}$ was observed. This anomalous feldspar also occurs as splotchy interstitial material. Macdonald (1942b) suggests that this material is potash oligoclase and is typical of some Hawaiian andesites. Opaques are found predominantly sprinkled through the groundmass. Some phenocryst opaque crystals have corroded cores. Apatite has hexagonal shapes and was slightly brownish in color. Relief was higher than other minerals in sections. Trace amounts of biotite and possibly amphibole were also observed.

Optical data on one crystal in Sample 24-2 indicates that zircon is present. The properties of rather high relief, euhedral shape, parallel extinction, slow elongation, high birefringence and a uniaxial positive sign were observed. Photographs 11a and 11b are of this mineral. Electron microprobe work will be done in the future to

confirm the petrographic observations. If confirmation is made, this is the first reported occurrence of zircon in Hawaiian basalts. Zircon has been reported in other basalt localities from India (Deshmukh, according to Poldervaart, 1968), and from various localities in the United States and one in South Africa (Poldervaart, 1956). Normally, zirconium is concentrated in the pyroxene phase (Poldervaart, 1956). Zircon formation in basalts is usually thought to be a late-stage product (Poldervaart, 1968, 1956).

Mugearite

Mugearite textures are mostly fine-grained with fairly equant grain size. Many samples are vesicular. Mugearites are definitely lighter in color than hawaiites, due to increased plagioclase content. Localized flow textures were also evident (pilotaxitic texture). See Photographs 3a and 3b.

Mineralogy - Olivine is the dominant phenocryst phase. Most olivine is completely altered to red translucent iddingsite. Opaque inclusions were observed in many crystals. Cores of many olivine crystals are corroded and in some cases there are jackets of different material (clinopyroxene?) with different extinction angles (core-parallel, jackets -67°). Clinopyroxene occurs as microphenocrysts, but mostly as a groundmass phase. It is unaltered and clear to slightly green. Plagioclase occurs as laths and acicular needles. Laths are zoned and twinned. Composition ranges from An_{23} to An_{39} (cores and rims, respectively), by the a-normal method. One twinned and zoned phenocryst gave $An_{38-50-38}$. A groundmass determination yielded An_{21} . Potash-oligoclase again occurs as laths and interstitial phases. These are

untwinned but zoned. Opaques are mostly confined to the groundmass. Apatite has high relief and is rounded in shape. Apatite content peaks in rocks that are slightly transitional to hawaiiite. Biotite displays light-brown to dark-brown pleochroism.

Benmoreite

Benmoreite is easily distinguishable from mugearite by the appearance of amphibole (kaersutite), relict mineral skeletons and corrosion of plagioclase cores (see Photographs 4a and 4b). These rocks were also lighter in appearance (see Photographs 5a and 5b).

Mineralogy - All olivine shows complete alteration to iddingsite. Rims of the olivine crystals show effects of corrosion. Clinopyroxene is lath-shaped and sometimes displays slightly light to slightly darker green pleochroism. Some crystals have corroded cores with rims of opaque material. The cores may be olivine, as these have parallel extinction. Most clinopyroxene is in the groundmass. Plagioclase macrophenocrysts are zoned and corroded. Composition ranges from An_{22} to An_{28} (oligoclase). In one case a zoned crystal was observed to have a more sodic core than rim; An_{22-24} . These crystals may be xenocrysts. Some opaque grains show signs of corrosion. In some cases, small grains of opaques formed outlines of pre-existing minerals (relicts). Apatite was round and light brown in color. The modal percentage of apatite drops off sharply in the benmoreites. Amphibole has corroded cores and heavy oxide rims, opacite (Photograph 6). There is good amphibole cleavage, third order birefringence, 17° extinction and light to darker yellow-brown pleochroism. These data indicate that the amphibole is either basaltic hornblende or kaersutite. Electron

microprobe analyses by Sibray (1977) on some Kohalan benmoreites indicate that the amphibole is kaersutite.

Benmoreite-Trachyte

These samples are similar to benmoreites, but appear to have higher plagioclase content (and higher alkalis), with a lack of apatite, as well as smaller and less amphibole. Textures are slightly vesicular, relatively fine-grained, slightly porphyritic (plagioclase). Cores of plagioclase phenocrysts were reabsorbed.

Mineralogy - Olivine occurs as microphenocrysts completely altered to iddingsite. Clinopyroxene occurs as microphenocrysts, but was mostly found in the groundmass. Microphenocrysts appear to have jackets of material with a different extinction angle. Plagioclase was observed as subhedral laths and squares. Many zoned crystals are altered and have inclusions of sericite(?). Groundmass plagioclase looks fibrous in some instances. Composition normally ranges from An₂₁ to An₂₄. One large phenocryst yielded An₄₄ (a xenocryst?). Opaques are microphenocrystic and also occur in the groundmass. Some opaque material seems related to amphibole alteration and breakdown. Amphibole displays yellow-brown pleochroism and has heavy iron oxide rims. Biotite has light-brown to dark-brown pleochroism (high-Ti type) and has $v > r$ dispersion.

Inclusions

Three dunite nodules were discovered in samples collected for this study. All host rocks were hawaiites. A reaction relationship between host basalt and nodule was not observed (see Photographs 7a, 7b and 7c). The olivine crystals are anhedral and generally unaltered. Many have

kink banding. Olivine composition was determined to be approximately Fo_{88} via the optic angle method (Deer et al., 1966). Opaque minerals were observed in trace amounts and were anhedral to subhedral. In Sample 11-2H there is a trace of biotite, displaying light to dark yellow-brown pleochroism.

Implications of Alteration and Corrosion

Alteration and corrosion of minerals yield insight into crystallization history. Alteration of olivine rims in hawaiites and mugearites, and complete alteration of olivine to iddingsite in benmoreites suggest that benmoreite olivines are subjected to longer periods of alteration, perhaps as reaction in a magma chamber at shallow depths (more available water). Iddingsite alteration is the result of hydrothermal effects (Deer et al., 1966) and shows up in the whole range of alkalic suite rocks studied here, although it is more intense in the benmoreite phases. There is also corrosion of olivine (Photograph 8) and clinopyroxene (Photograph 9) cores.

Alteration of cores and intermediate zones of macrophenocrystic plagioclase laths was observed in several samples. Intermediate zones are dusted in several instances, cores are both embayed and dusted. This usually occurred in the mugearite-benmoreite, benmoreite and benmoreite-trachytic rock types (see Photograph 4a).

Amphibole in these same rocks shows alteration as thick "iron oxide" (opacite) rims. There are also relict structures where iron oxide rims are all that is left of amphibole crystals (see Photograph 4b). This would seem to occur during a period of oxygen enrichment, as would be expected in a late-stage magma chamber.

Opaques show more alteration and corrosion effects in the benmoreite rock types. Larger grains show embayment on some otherwise subhedral surfaces (see Photograph 10).

Summary

In reviewing the petrography, several points are worth noting: (1) most of these rocks are relatively fresh; alteration is generally on the mineral level due to oxidation and hydrothermal effects, (2) there is a notable increase in plagioclase and Ab content from hawaiite to benmoreite, (3) there is a significant lack of clinopyroxene as a phenocryst phase in any of these rocks and in some places it is lacking in the groundmass, and (4) hydrous phases such as amphibole appear in the benmoreites.

GEOCHEMISTRY

Methods

Samples selected for geochemical analysis were screened for freshness by petrographic analysis. Factors considered included general appearance of the slide (mottling and clarity) and alteration of the major minerals.

Fresh samples were then crushed and powdered in a Spex Shatterbox for 10 minutes. Powdered samples were then subjected to X-ray diffraction to determine the content of the zeolite minerals chabazite, phillipsite and analcime. Results were negative.

Pressed sample discs made with boric acid backings were analyzed in a Norelco vacuum-path X-ray spectrometer for Si, Ti, Fe_T, Ca and K. Parameters used for each element are listed in Appendix IV.

Samples were dissolved using standard procedures (Appendix IV) and

were analyzed on an Instrument Laboratories atomic absorption spectrophotometer for Al, Mn, Mg, Na, Rb and Ni. Blank solutions were run at the same time as the standards for atomic absorption. Results for these solutions were below detection in all cases. Phosphorus was analyzed on a spectrophotometer using Shapiro's (1975) method.

U.S. Geological Survey standard rocks were analyzed before, during and after analysis of the unknowns and were used in calculating calibration curves to determine content of the unknowns. Standards chosen varied with oxides analyzed so that standard values bracketed those of the unknowns. Standards used were AGV-1, BD-1, BCR-1, W-1, JB-1, QMC-1, PCC-1, BHVO-1, JG-1, G-2 and BCR-1.

Abundances of Sr and Sr-isotopic composition were determined in nine samples from the Hawi Volcanic Series, and one from the Pololu Volcanic Series. The alkalic rocks analyzed were selected on the following criteria: (1) geographic spread, (2) unique/typical observed major-element composition, (3) freshness as determined by petrographic inspection, (4) good total summation of chemical analysis, and (5) cinder cones with two or more lava flows. The Pololu tholeiite is from the north wall of the Waipio Valley (P. Weigand, personal communication).

Selected rocks were first ground in a Spex Shatterbox for 10 minutes. One hundred to one hundred fifty milligrams of sample were then weighed into Teflon beakers and then subjected to an acid test. HCl (2.5N) was added to the sample and heated to see if any carbonate was present (i.e., effervescence). None of the samples tested contained carbonate. The samples were then spiked with ^{84}Sr and digested using

hydrofluoric and quartz-distilled nitric acids. Sr was separated on a 15 cm Dowex ion-exchange column in the chloride form, and then analyzed on an Avco 35 cm, 90⁰ solid source mass spectrometer at California State University, Los Angeles.

Accuracy and Precision

Table 2 shows a comparison between accepted values for three rock standards and values determined in this study. The three standards chosen are close in composition to the study samples. There is excellent agreement between accepted and determined values for those standards. Analytical precision for this study is also listed in Table 2, and is represented by the coefficient of variation, where:

$$C_v = \frac{100s}{\bar{x}}$$

where C_v = coefficient of variation, s = standard deviation, and \bar{x} = average value for each element.

In addition, the HIGS series of the interlaboratory Hawaiian volcanic rocks (Macdonald et al., 1973) were analyzed. Comparison between the literature and this study results is listed in Table 2. Agreement in some cases is poor. It is possible that the analyses cited by Macdonald et al. (1973) are inaccurate.

During mass spectrometer runs, the interlaboratory NBS SrCO₃ standard was analyzed four times. The accepted value is $^{87}\text{Sr}/^{86}\text{Sr} = 0.7101$. A combined result of 0.7102 ± 0.0006 was obtained. All errors are reported as one sigma standard deviation. $^{87}\text{Sr}/^{86}\text{Sr}$ values have been normalized to the $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194 to correct for

TABLE 2
Analyses of Some Rocks Used as Standards

	AGC-1		BCR-1		BHVO-1		HIGS-3		HIGS-5		HIGS-8		Cv
	This Study	Lit. 1	This Study	Lit. 1	This Study	Lit. 2	This Study	Lit. 3	This Study	Lit. 3	This Study	Lit. 3	
SiO ₂	59.04	59.00	54.87	54.50	49.98	50.27	59.33	61.98	40.05	35.78	49.43	47.30	0.30
TiO ₂	1.18	1.04	2.36	2.20	2.68	2.73	0.56	0.39	2.51	2.84	2.85	3.01	0.70
Al ₂ O ₃	17.25	17.25	13.64	13.61	13.91	13.84	17.91	17.48	11.11	11.46	14.62	14.28	2.40
FeO _T	6.12	6.11	12.47	12.11	10.74	10.86	4.85	4.42	14.02	15.93	11.35	12.18	1.00
MnO	0.10	0.10	0.18	0.18	0.18	0.17	0.36	0.32	0.23	0.22	0.16	0.15	3.00
MgO	1.56	1.53	3.48	3.46	7.24	7.08	0.36	0.38	10.49	10.21	7.57	7.44	2.70
CaO	4.60	4.90	6.93	6.92	11.40	11.46	1.46	0.82	12.92	13.07	8.74	8.71	1.80
Na ₂ O	4.24	4.26	3.33	3.27	2.22	2.19	7.03	8.32	5.12	5.56	3.53	3.67	3.70
K ₂ O	2.87	2.89	1.70	1.70	0.54	0.52	4.60	5.04	2.11	1.98	1.38	1.38	1.30
P ₂ O ₅	0.50	0.49	0.35	0.36	0.29	0.28	0.19	0.16	1.07	1.08	0.67	0.63	5.10
Rb (ppm)	60.09	67.00	56.60	46.60	17.76	8.10	139.63	-	83.71	-	43.17	-	17.69
Ni (ppm)	16.59	18.50	19.11	15.80	118.10	112.00	15.46	-	239.48	-	230.78	-	5.20

- References: 1. Flanagan (1973).
 2. Analyses compiled from Flanagan (1976), and Weigand (unpublished data).
 3. Macdonald et al. (1973), average, no trace element data.

instrumental fractionation. Duplicate samples were prepared for three samples to test for external precision of the analyses. Samples 1-1E and Pol. 16 were analyzed twice with completely different sample concentrates, while 6-3 was analyzed twice with samples from the same Sr concentrate.

Results

Partial chemical analyses of all 60 samples were performed by XRF. Examination of these data showed that 20 samples could be eliminated from further analysis because of compositional similarities and geographical proximity to other samples. The partial analyses of these 20 samples are found in Appendix VI. Table 3 lists 40 new chemical analyses of the Hawi Volcanic Series made in this study. Strontium abundances are listed in Table 8, arranged by sample number.

Low summations may reflect the fact that these analyses are anhydrous; also total iron is reported as FeO which lowers the totals slightly. Water in Hawaiian alkalic rocks (from Muir and Tilley, 1961; Macdonald and Katsura, 1964; Macdonald, 1968; Macdonald and Powers, 1968; Hlava, 1974, Malinowski, 1977; and Sibray, 1977) are listed below.

Alkalic Basalt	1.13% \pm 1.48
Hawaiite	1.06% \pm 0.42
Mugearite	0.71% \pm 0.34
Benmoreite	1.77% \pm 1.31
Trachyte	0.67% \pm 0.37

Thus, the addition of water would bring all totals closer to 100%.

Table 4 is a summary of the average chemical composition of the various rock types of the Hawi Volcanic Series. As mentioned earlier,

TABLE 3

Chemical Composition and Normative Mineralogy of Hawi Volcanic Series

	<u>1-1A</u>	<u>1-1C</u>	<u>1-1D</u>	<u>1-1E</u>	<u>2-1A</u>	<u>2-1B</u>	<u>3-1B</u>	<u>3-2B</u>	<u>4-1</u>	<u>5-2</u>
SiO ₂	50.26	53.49	55.48	50.51	49.17	51.38	53.85	50.70	41.52	50.30
TiO ₂	1.91	1.65	1.55	2.61	2.77	2.35	1.80	2.60	3.45	2.61
Al ₂ O ₃	20.75	19.69	18.40	16.91	17.35	16.90	18.21	16.77	19.31	17.88
FeO _T	10.20	8.58	6.73	10.81	11.33	9.70	8.28	10.52	14.44	10.70
MnO	0.23	0.23	0.24	0.24	0.24	0.23	0.23	0.23	0.26	0.24
MgO	1.91	1.52	2.64	3.96	3.98	3.99	2.75	4.08	4.27	3.51
CaO	2.35	3.10	4.17	6.89	5.68	6.72	4.18	6.97	4.86	5.89
Na ₂ O	4.62	5.20	5.71	4.77	4.38	4.78	5.74	5.06	2.67	4.41
K ₂ O	2.52	2.56	2.48	1.91	1.93	1.91	2.25	1.88	1.21	1.91
P ₂ O ₅	<u>0.94</u>	<u>0.90</u>	<u>0.99</u>	<u>1.81</u>	<u>1.81</u>	<u>1.66</u>	<u>0.99</u>	<u>1.76</u>	<u>1.92</u>	<u>1.58</u>
TOTAL	95.96	96.92	98.39	100.42	98.64	99.61	98.28	100.56	93.89	98.76
Rb	34	51	45	39	44	40	37	41	13	31
Ni	12	17	8	12	17	14	7	15	26	10
<u>CIPW Norms</u>										
Qz	8.1	7.0	2.0	-	1.3	-	0.6	-	7.6	2.1
Co	8.7	5.0	1.1	-	2.1	-	1.1	-	9.9	1.6
Or	15.5	15.5	14.8	11.2	11.6	11.3	13.5	11.0	7.6	11.4
Ab	40.6	45.2	48.9	40.0	37.4	40.4	49.2	42.4	24.0	37.6
An	5.7	9.7	14.4	18.9	16.5	19.0	14.5	17.3	12.2	19.0
Di	-	-	-	2.6	-	2.8	-	4.5	-	-
Hy	6.6	4.5	8.3	8.0	14.3	11.0	9.1	2.6	17.6	12.2
Ol	-	-	-	3.3	-	0.9	-	6.7	-	-
Mt	8.8	7.7	5.1	6.9	7.3	6.2	6.2	6.6	9.5	7.3
Hm	-	-	-	-	-	-	-	-	-	-
Il	3.8	3.2	3.0	4.9	5.3	4.5	3.5	4.9	6.9	5.0
Ap	2.3	2.2	2.4	4.2	4.3	3.9	2.4	4.1	4.8	3.8
Rock Type	M	M-B	M-B	H-M	M	H-M	M-B	H-M	H	H

TABLE 3 (Continued)

	<u>6-1</u>	<u>6-2</u>	<u>6-3</u>	<u>7-2</u>	<u>8-1-2B</u>	<u>8-1-2C</u>	<u>8-2</u>	<u>9-1</u>	<u>11-1A</u>	<u>11-2E</u>
SiO ₂	53.51	59.00	58.94	53.20	46.97	50.56	48.68	48.47	48.68	48.93
TiO ₂	1.94	0.90	0.98	1.97	3.66	2.57	3.18	3.12	2.93	2.83
Al ₂ O ₃	18.99	18.51	18.02	17.60	18.87	17.32	17.22	16.62	16.28	16.72
FeO _T	7.56	5.15	5.34	8.90	13.02	10.78	11.07	12.09	11.88	11.49
MnO	0.25	0.18	0.20	0.23	0.20	0.23	0.19	0.21	0.22	0.24
MgO	2.96	0.89	1.00	3.18	4.40	3.83	4.64	3.83	3.98	4.29
CaO	4.96	2.11	2.27	5.32	6.12	6.55	7.59	7.58	7.56	7.16
Na ₂ O	5.04	6.05	6.17	5.15	3.02	4.76	3.78	4.02	4.52	4.74
K ₂ O	2.27	3.67	3.59	2.14	1.57	1.88	1.60	1.47	1.56	1.62
P ₂ O ₅	<u>0.90</u>	<u>0.45</u>	<u>0.47</u>	<u>1.27</u>	<u>0.90</u>	<u>1.69</u>	<u>1.57</u>	<u>1.79</u>	<u>1.85</u>	<u>1.88</u>
TOTAL	98.38	96.91	97.00	98.96	98.74	100.16	99.51	99.19	99.41	99.89
Rb	43	74	78	41	27	40	27	23	34	33
Ni	8	15	11	10	14	7	12	8	10	12
<u>CIPW Norms</u>										
Qz	2.2	5.3	4.4	1.2	4.2	-	0.4	1.4	-	-
Co	1.4	1.9	1.0	0.2	3.2	-	-	-	-	-
Or	13.6	22.3	21.8	12.7	9.4	11.0	9.5	8.7	9.3	9.5
Ab	43.2	52.6	53.6	43.8	25.7	40.0	32.0	34.1	38.2	40.0
An	19.0	7.7	8.4	18.2	24.7	20.2	25.3	23.0	19.5	19.5
Di	-	-	-	-	-	0.9	1.7	2.4	4.8	3.0
Hy	9.3	2.3	2.6	10.8	15.7	9.9	14.9	12.4	7.5	4.5
Ol	-	-	-	-	-	2.2	-	-	3.3	6.8
Mt	5.5	4.7	5.0	6.3	8.0	7.0	6.6	7.9	7.6	7.1
Hm	-	0.3	0.1	-	-	-	-	-	-	-
Il	3.7	1.8	1.9	3.8	7.0	4.8	6.0	5.9	5.6	5.4
Ap	2.2	1.1	1.1	3.0	2.2	4.0	3.7	4.2	4.4	4.4
Rock Type	M	B-T	B-T	M	H	H-M	H	H	H	H

TABLE 3 (Continued)

	<u>11-2H</u>	<u>12-1A</u>	<u>13-1</u>	<u>14-1</u>	<u>14-2</u>	<u>17-1</u>	<u>18-1</u>	<u>19-1</u>	<u>19-2</u>	<u>21-1</u>
SiO ₂	48.05	55.98	45.33	47.30	52.39	55.70	48.23	47.99	48.94	48.17
TiO ₂	2.91	1.26	3.51	3.36	2.05	1.48	3.57	3.13	2.96	2.85
Al ₂ O ₃	16.65	17.93	17.34	16.96	18.06	18.65	17.31	16.80	16.70	17.80
FeO _T	12.03	7.49	12.84	12.98	9.66	6.37	11.67	12.90	11.86	11.80
MnO	0.23	0.23	0.21	0.20	0.23	0.23	0.18	0.24	0.23	0.25
MgO	4.42	2.19	4.45	4.28	2.82	1.32	5.03	4.02	3.99	3.61
CaO	7.50	3.95	7.32	6.91	5.00	2.73	8.01	6.69	7.20	5.63
Na ₂ O	4.58	5.23	2.34	2.56	5.18	5.52	3.76	3.97	4.35	4.00
K ₂ O	1.56	2.87	0.97	1.26	2.04	2.65	1.15	1.67	1.70	1.59
P ₂ O ₅	1.99	0.83	1.03	1.02	1.22	0.53	0.76	1.98	1.93	1.62
TOTAL	99.94	97.95	95.34	96.83	98.65	95.17	99.66	99.38	99.86	97.33
Rb	34	57	10	17	33	23	20	35	28	23
Ni	13	14	42	39	6	14	14	13	11	11
<u>CIPW Norms</u>										
Qz	-	4.4	6.7	7.2	1.8	7.4	-	1.5	-	4.3
Co	-	1.0	1.7	1.3	1.2	3.1	-	1.0	-	3.2
Or	9.1	17.2	6.0	7.6	12.2	16.4	6.8	9.9	10.0	9.6
Ab	38.6	45.0	20.6	22.2	44.2	48.9	31.8	33.6	36.7	34.5
An	20.2	14.4	30.9	28.4	16.9	10.6	26.9	20.3	20.9	17.7
Di	3.2	-	-	-	-	-	6.3	-	1.7	-
Hy	3.5	7.5	16.6	16.0	9.8	3.4	10.8	14.9	12.2	13.2
Ol	8.0	-	-	-	-	-	2.2	-	0.8	-
Mt	7.3	6.1	8.2	8.3	7.2	5.7	6.7	8.2	7.6	8.1
Hm	-	-	-	-	-	0.2	-	-	-	-
Il	5.5	2.4	7.0	6.6	3.9	2.9	6.8	6.0	5.6	5.5
Ap	4.7	2.0	2.5	2.5	2.9	1.3	1.8	4.7	4.6	3.9
Rock Type	H	M-B	H	H	M	B	H	H	H	M

TABLE 3 (Continued)

	<u>21-2A</u>	<u>21-2B</u>	<u>21-3</u>	<u>22-1</u>	<u>23-1</u>	<u>23-2</u>	<u>24-1</u>	<u>24-2</u>	<u>26-1</u>	<u>27-1</u>
SiO ₂	54.44	50.26	46.95	49.89	45.63	44.15	44.96	48.87	48.20	52.12
TiO ₂	1.04	2.54	2.92	2.65	3.07	3.14	3.19	2.81	2.79	2.43
Al ₂ O ₃	20.05	17.69	17.87	17.72	18.07	18.58	18.38	17.38	17.98	17.84
FeO _T	6.33	10.85	12.41	11.25	13.14	13.38	13.38	11.75	11.72	9.06
MnO	0.26	0.24	0.24	0.24	0.25	0.25	0.27	0.25	0.24	0.24
MgO	0.95	3.83	3.48	3.20	3.78	3.75	3.88	3.15	2.70	2.61
CaO	2.01	6.13	5.39	5.81	5.01	5.03	5.47	6.11	4.86	4.69
Na ₂ O	5.70	4.35	3.92	4.48	3.41	3.32	3.37	4.45	4.51	4.76
K ₂ O	2.93	1.82	1.66	1.83	1.67	1.34	1.26	1.73	1.79	2.12
P ₂ O ₅	0.33	1.70	1.55	1.65	1.78	2.01	1.81	1.78	1.36	0.94
TOTAL	97.04	99.41	96.51	98.72	95.80	94.94	95.97	98.29	96.16	96.82
Rb	32	35	17	33	29	22	10	32	21	30
Ni	12	16	11	10	63	17	12	14	12	14
<u>CIPW Norms</u>										
Qz	5.6	2.1	3.8	2.8	6.1	7.1	6.1	1.9	3.5	4.1
Co	4.9	1.5	3.6	1.8	6.0	7.7	6.1	1.2	3.1	1.4
Or	18.3	10.8	10.1	10.9	10.2	8.3	7.7	10.3	10.9	13.4
Ab	51.1	36.8	34.2	38.2	29.9	29.4	29.5	38.0	39.4	41.4
An	8.3	19.3	17.2	18.2	13.7	12.4	15.9	19.4	15.8	17.7
Di	-	-	-	-	-	-	-	-	-	-
Hy	2.5	13.6	13.0	11.3	14.7	14.8	15.2	11.2	9.5	8.1
Ol	-	-	-	-	-	-	-	-	-	-
Mt	6.4	7.1	8.7	8.0	8.9	9.2	9.0	8.4	9.0	7.0
Hm	-	-	-	-	-	-	-	-	-	-
Il	2.1	4.8	5.7	5.1	6.0	6.2	6.3	5.4	5.5	4.7
Ap	0.8	4.0	3.8	3.9	4.4	5.0	4.4	4.3	3.3	3.2
Rock Type	B	H-M	H-M	H-M	H	H	H	H-M	M	M

TABLE 4

Averages for Different Rock Types of the Hawi Volcanic Series

	<u>Hawaiite</u>	<u>Hawaiite- Mugearite</u>	<u>Mugearite</u>	<u>Mugearite- Benmoreite</u>	<u>Benmoreite</u>	<u>Benmoreite- Trachyte</u>
SiO ₂	47.31	50.24	50.55	54.70	55.07	58.97
TiO ₂	3.18	2.56	2.39	1.57	1.26	0.94
Al ₂ O ₃	17.32	17.40	18.40	18.56	19.35	18.27
FeO _T	12.30	11.01	10.03	7.77	6.35	5.25
MnO	0.22	0.24	0.24	0.23	0.25	0.19
MgO	4.20	3.62	2.94	2.28	1.14	0.95
CaO	6.80	6.18	4.74	3.82	2.37	2.19
Na ₂ O	3.70	4.61	4.64	5.47	5.61	6.11
K ₂ O	1.46	1.87	2.04	2.54	2.79	3.63
P ₂ O ₅	1.59	1.65	1.26	0.93	0.43	0.46
TOTAL	98.08	99.38	97.23	97.87	94.62	96.96
Rb	25	35	34	48	28	76
Ni	20	12	11	8	13	13
Qz	1.74	0.60	3.59	3.49	6.19	4.72
Co	1.09	0.50	2.95	2.09	3.82	1.41
Or	8.63	11.05	12.06	15.01	16.49	21.45
Ab	31.31	39.01	39.26	46.28	47.47	51.70
An	23.36	19.89	15.29	12.88	8.95	7.86
Hy	15.08	12.70	9.90	7.23	2.84	2.37
Mt	7.79	7.21	7.38	6.18	5.80	4.73
Hm	-	-	-	-	0.08	0.21
Il	6.04	4.86	4.54	2.98	2.39	1.79
Ap	3.77	3.91	2.98	2.20	1.02	1.09
TOTAL	98.81	99.73	97.96	98.35	95.05	97.32
Number of Samples	15	8	8	4	2	2

there is a great deal of intergradation between the various alkalic basalt rocks. In order to "classify" each rock, all the MgO variation diagrams were reviewed to see where it placed in relation to others as well as in relation to the "average basalt type" of Macdonald (1968). In addition, petrographic criteria were applied. Where there was a good correlation between all criteria, the label "hawaiite", "mugearite", etc. was applied with confidence. In several cases there appeared to be no definite choice and terms like "hawaiite-mugearite" were applied. Geochemistry was the main criterion used in such cases.

Compositions determined in this study are well within the range of those determined in previous works. For example, Figure 6 shows a comparison for silica and magnesia for this study and all previous analyses of Hawi rocks. In general, hawaiites have the highest amounts of TiO_2 , FeO_T , MgO, CaO and P_2O_5 , and the lowest SiO_2 , Al_2O_3 , Na_2O and K_2O . Benmoreites and benmoreite-trachytes have the opposite relationships with mugearite transitional. P_2O_5 seems to be higher in the rocks transitional between hawaiite and mugearite. MnO shows no real variation with rock type. Rb is highest in the benmoreite-trachyte rocks and lowest in hawaiites. Ni content stays generally the same throughout the hawaiite to benmoreite-trachyte series except for a few hawaiites (KV 13-1, 14-1, 23-1), which have significantly higher amounts.

Tilley (1950) showed that alkalic basalts could be distinguished from tholeiites by using the alkali-silica diagram. All values determined in this study lie above the tholeiite-alkalic divide (Macdonald and Katsura, 1964; Irvine and Baragar, 1974), see Figure 7, and

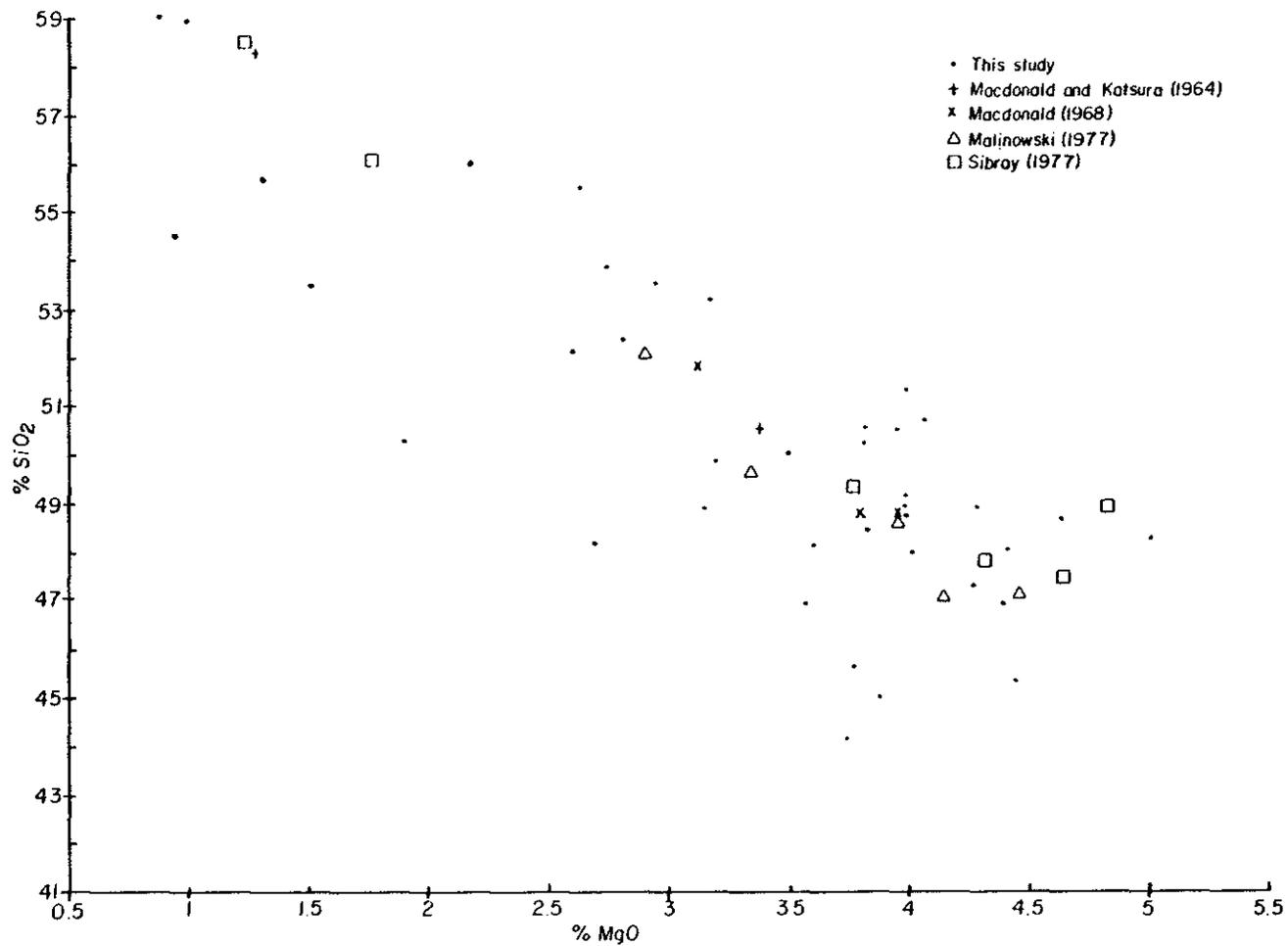


Fig. 6. MgO versus SiO₂ comparison diagram between Hawi rocks of this study and all previous modern-day chemical analyses.

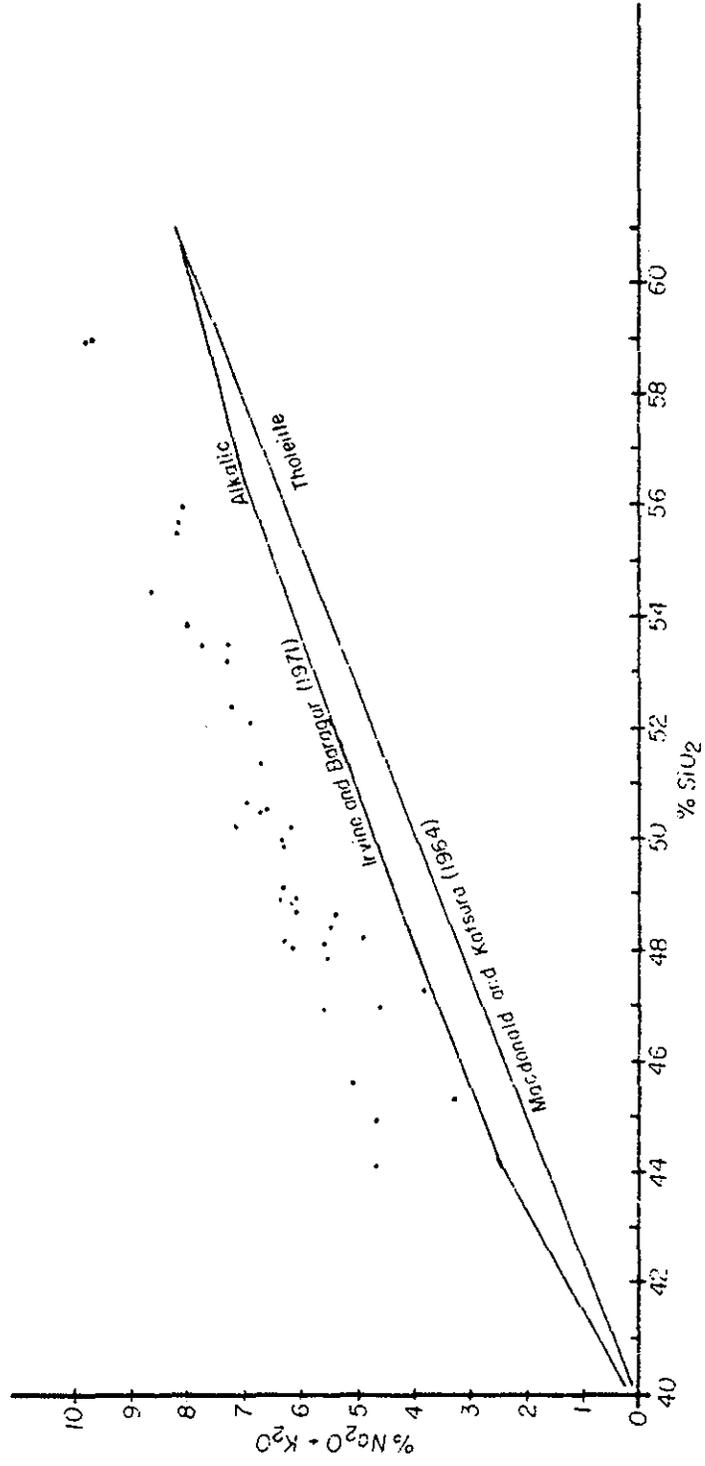


Fig. 7. Alkali-silica diagram for Hawi rocks of this study.

therefore are considered to belong to the alkalic suite using this criterion.

According to Wright (1974), oxide/oxide variation diagrams are the best way of presenting all chemical data for a given suite of igneous rocks. The plots permit comparison of analyses. MgO is chosen as the best oxide for comparisons due to its wide range in basaltic rocks and its change in content during crystal fractionation.

Figures 8a through 8l are MgO-variation plots for analyses in this study. SiO₂, Al₂O₃, Na₂O, K₂O and Rb show negative slopes, while TiO₂, FeO_T and CaO show positive correlations with MgO. P₂O₅, MnO and Ni show no real variation relative to MgO.

Normative Mineralogy - Normative mineralogy calculated for the 40 new chemical analyses are listed in Table 3; averages for different rock types are listed in Table 4.

Since oxidation states of iron were not analytically distinguished, Fe₂O₃ and FeO were calculated from FeO_T in order to calculate normative mineralogy. Values of ferrous and ferric iron from Macdonald (1968) and Macdonald and Katsura (1964) for Hawaiian alkalic suite rocks were plotted on a FeO/Fe₂O₃ versus MgO diagram. The resultant least squares relationship was then used to compute an "N" value for each rock type:

Hawaiite	N = 1.55
Mugearite	N = 1.45
Benmoreite	N = 0.625
Trachyte	N = 0.45

Then each FeO_T value was used to calculate FeO and Fe₂O₃ as follows:

$$\text{Fe}_2\text{O}_3 = \frac{\text{FeO}_T}{N + 0.898} \text{ and } \text{FeO} = \text{FeO}_T - 0.898(\text{Fe}_2\text{O}_3)$$

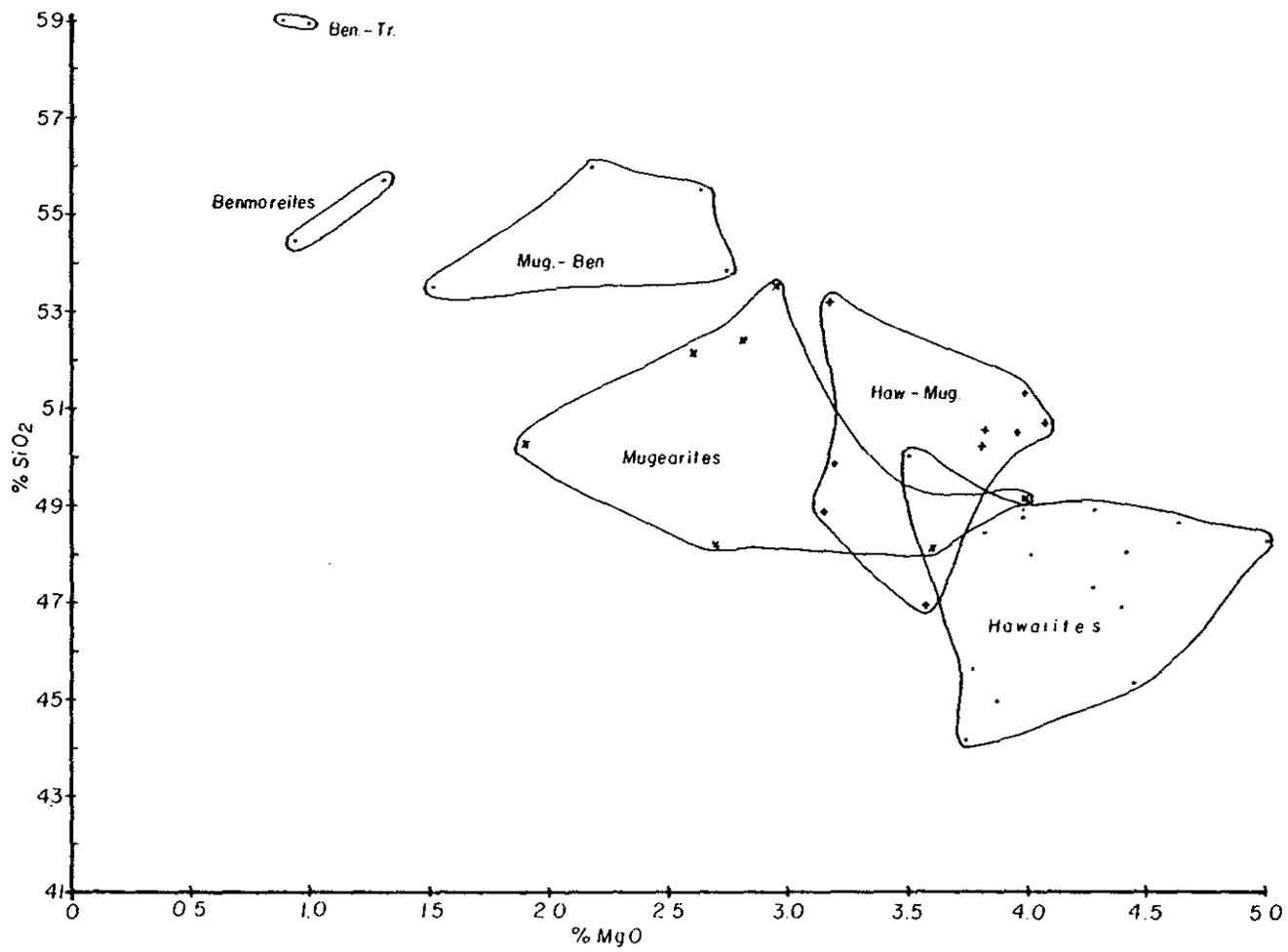


Fig. 8a. Magnesia - silica diagram for Hawi V.S.

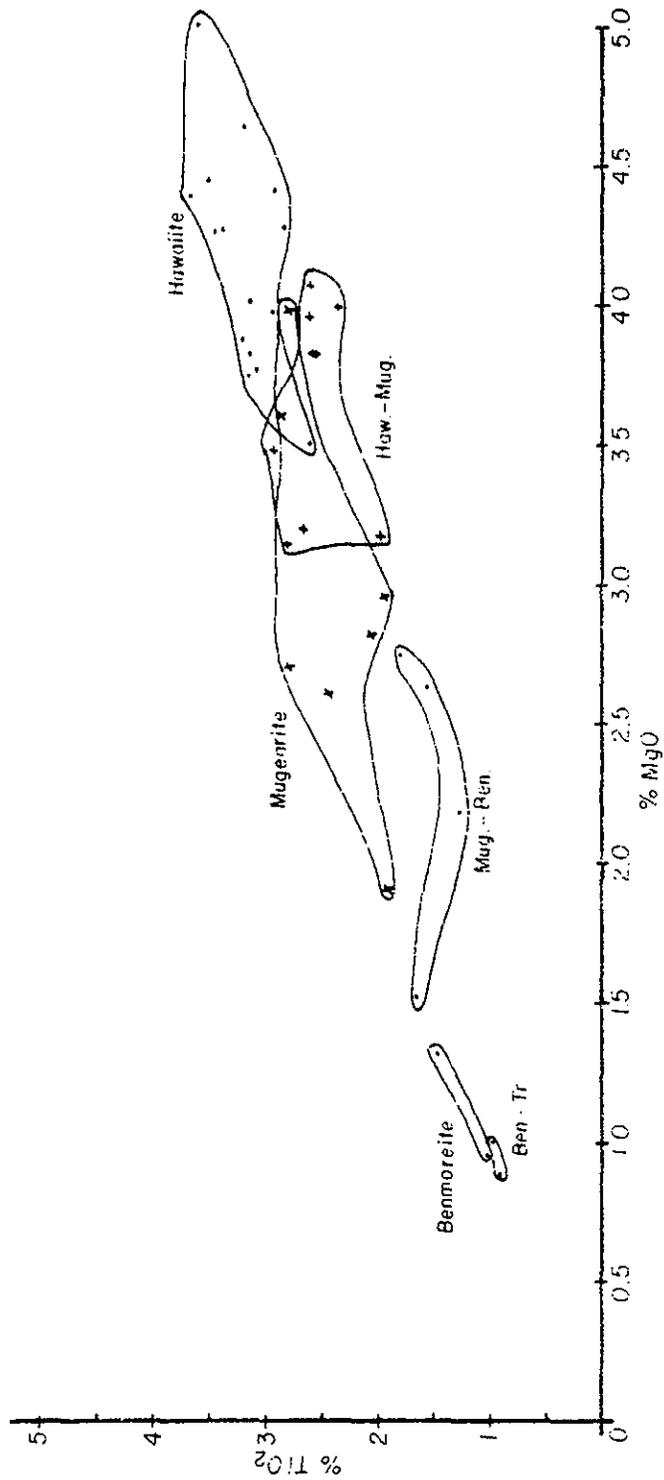


Fig. 8b. Magnesia - titania diagram for Hawi V.S.

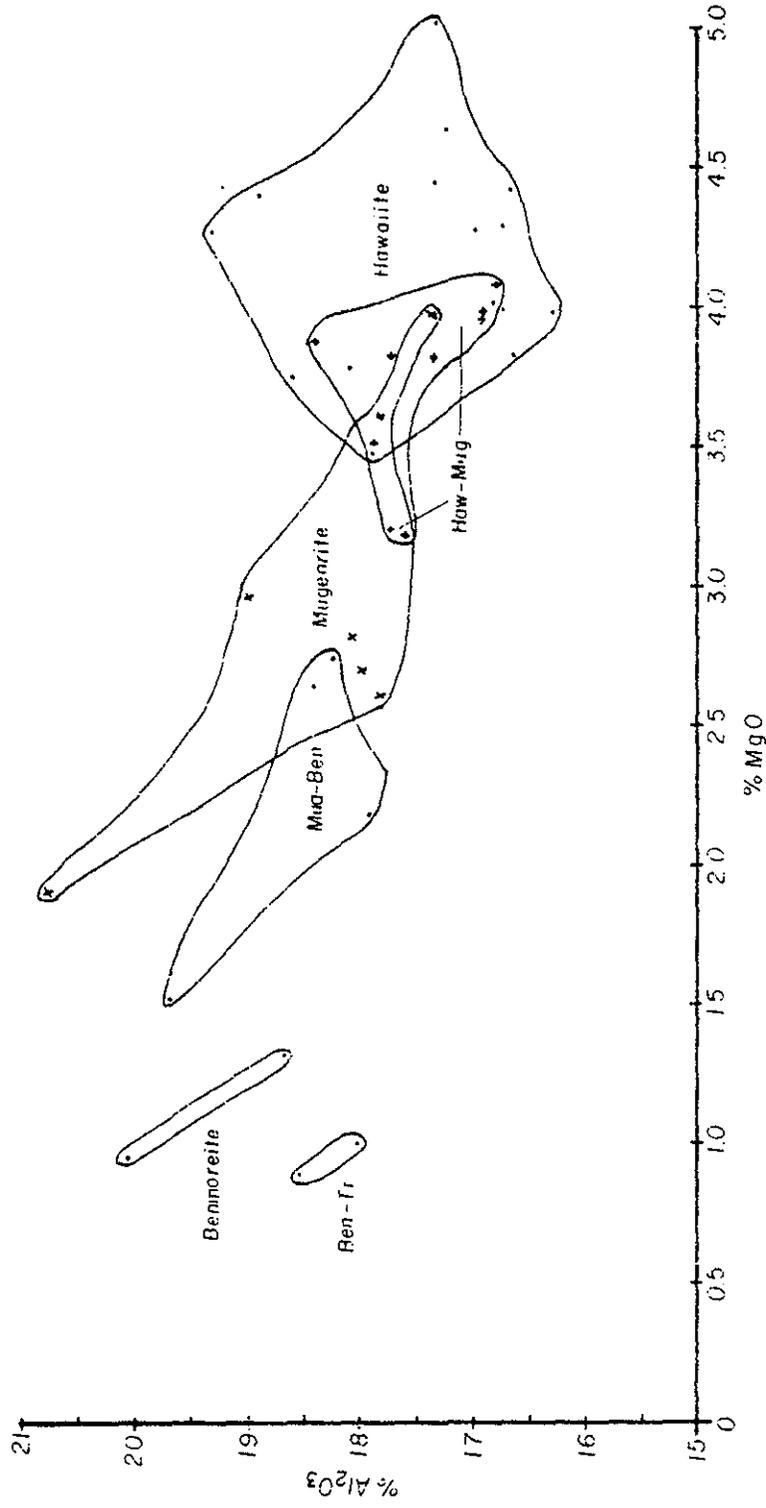


Fig. 8c. Magnesia - alumina diagram for Hawi V.S.

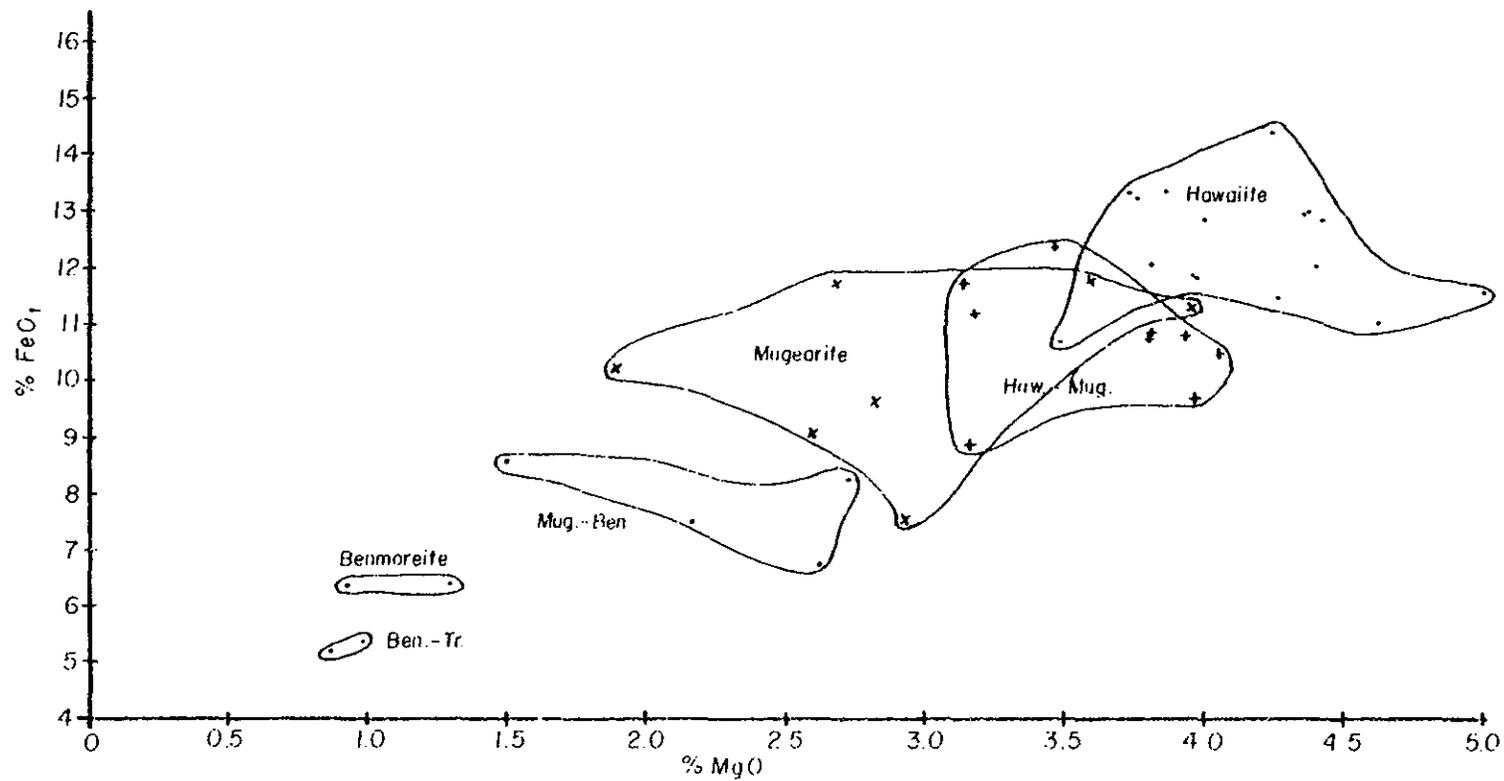


Fig. 8d. Magnesia - iron diagram for Hawaii V.S.

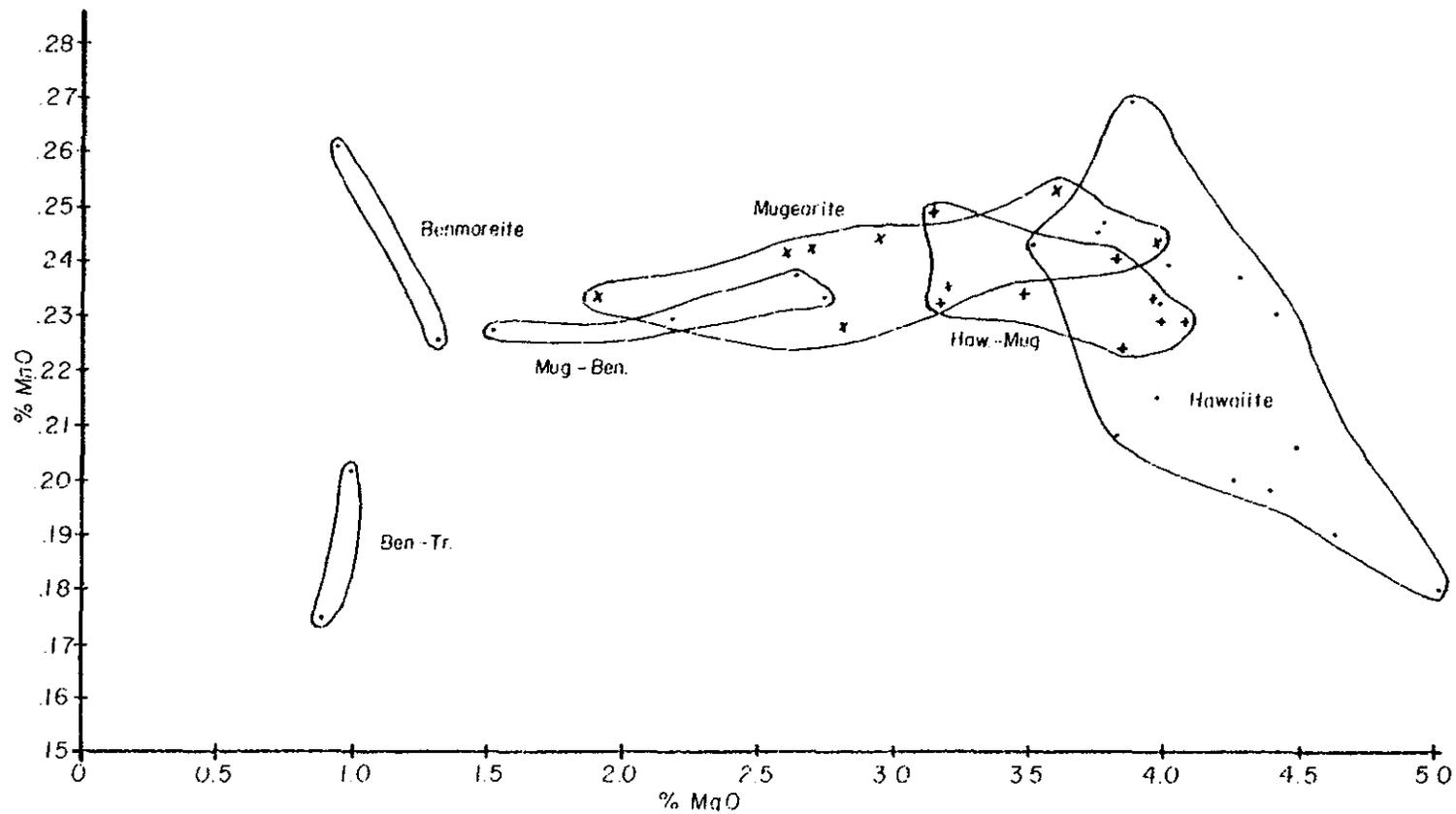


Fig. 8e. Magnesia - manganese diagram for Hawi V.S.

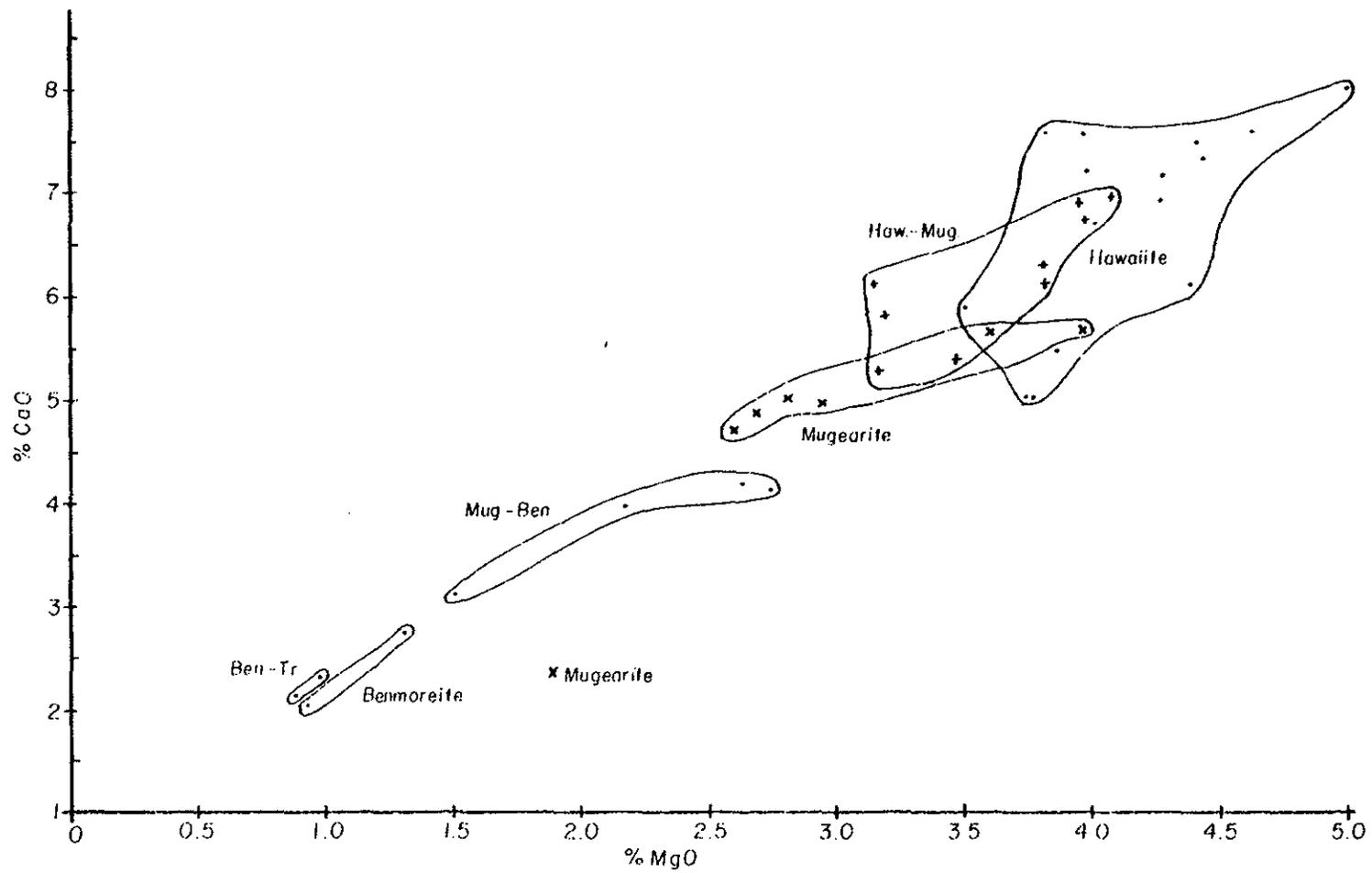


Fig. 8f. Magnesia - lime diagram for Hawi V.S.

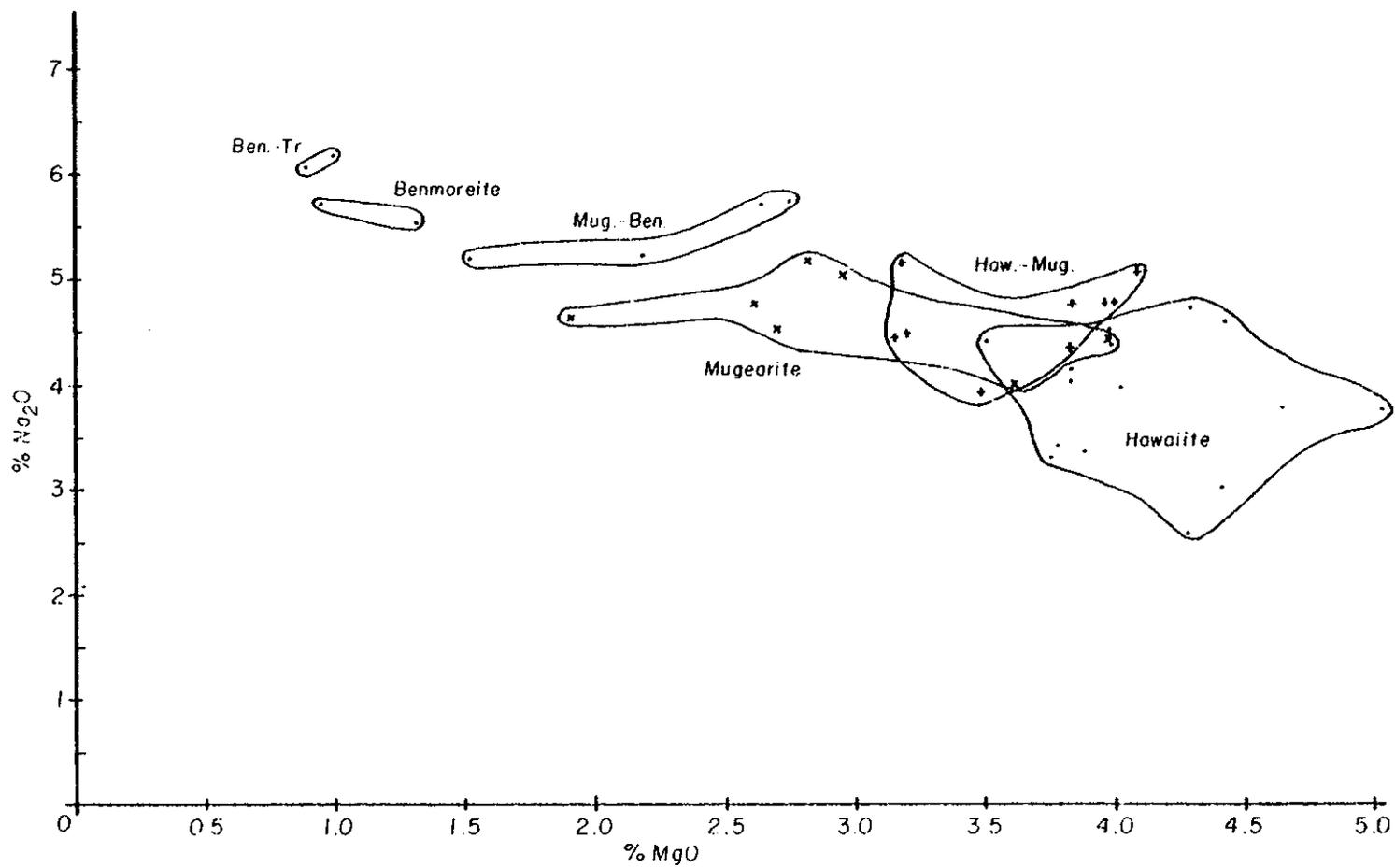


Fig. 8g. Magnesia - soda diagram for Hawi V.S.

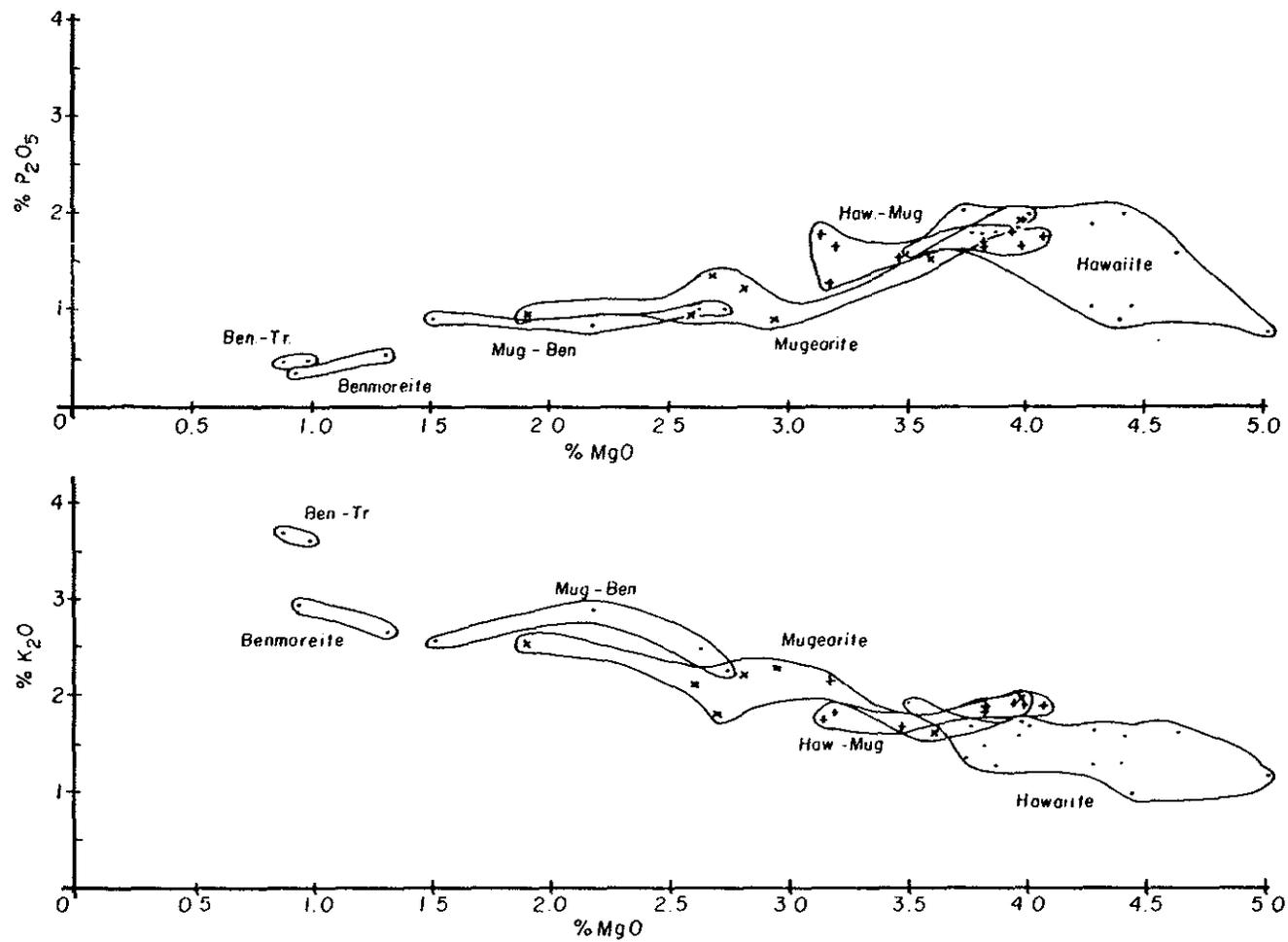


Fig. 8h. (top) Magnesia-phosphorous diagram for Hawi V.S. 8i. (bottom) Magnesia-potash.

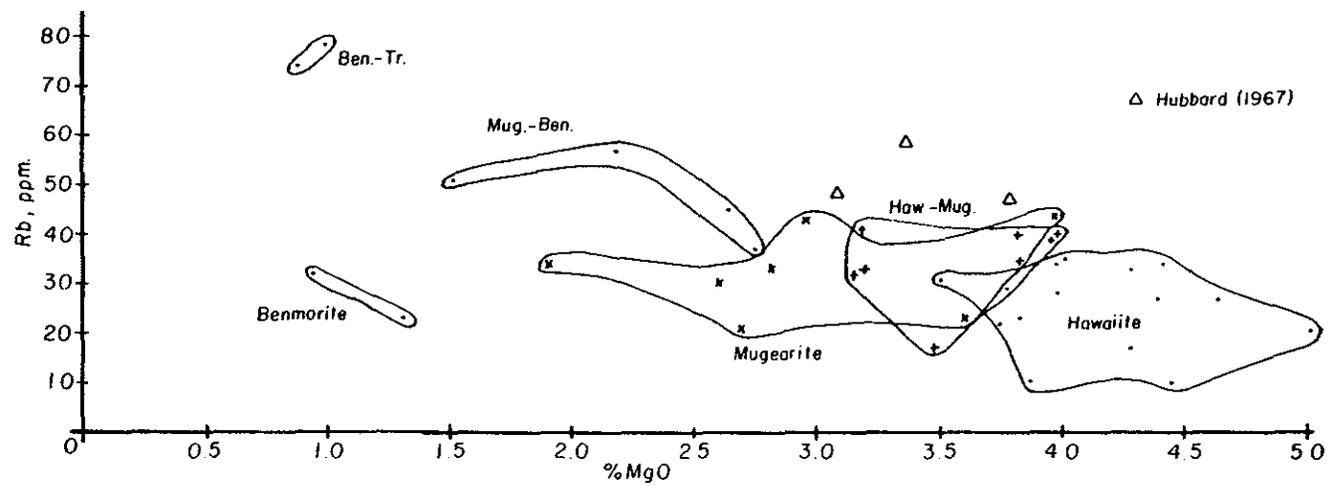
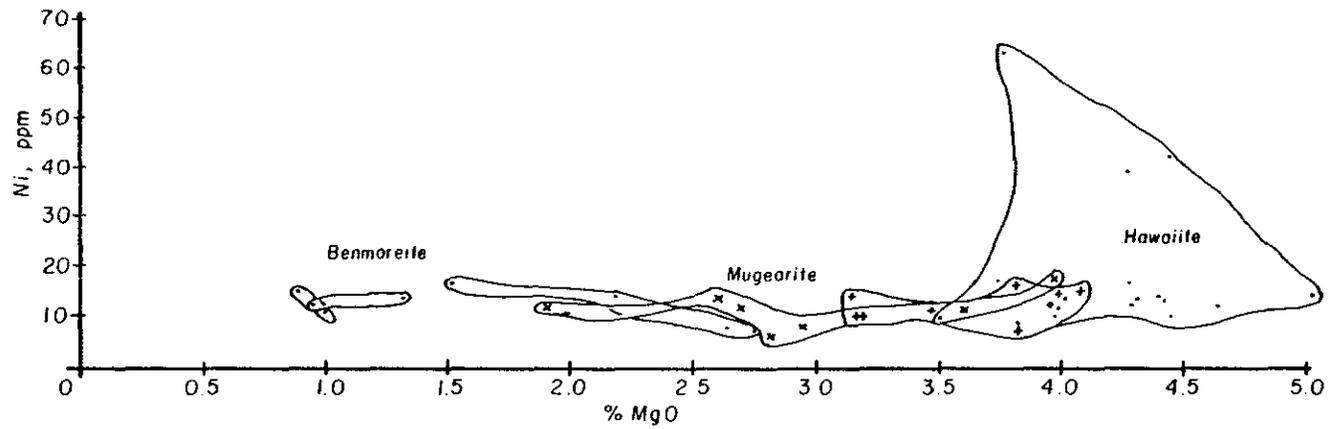


Fig. 8j. (top) Magnesia-nickel diagram for Hawi V.S. 8k. (bottom) Magnesia-rubidium.

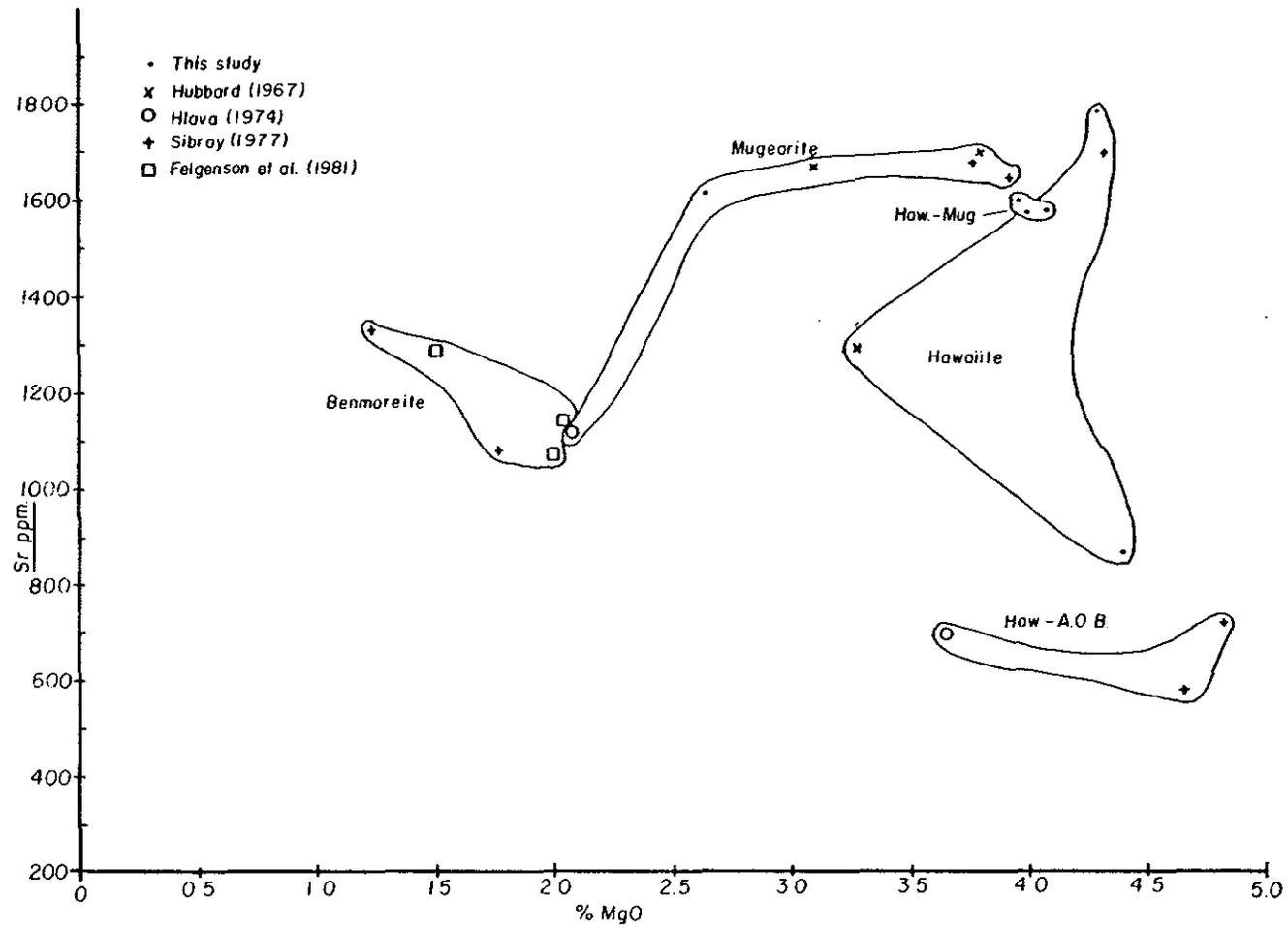


Fig. 81. Magnesia - strontium diagram for Hawi V.S.

The most obvious feature of these rocks is that most samples are quartz-normative, not nepheline-normative as expected by definition of alkalic suite rocks (Macdonald and Katsura, 1964). In fact, no rocks from this study are nepheline normative; those that are not quartz-normative have olivine in the norm. In contrast, no Kohala hawaiites and mugearites from Macdonald (1968) and Macdonald and Katsura (1964) are quartz-normative except for one trachyte. In a few instances, similar alkalic suite rocks from other Hawaiian volcanoes in these same papers are quartz-normative, and nepheline-normative when not quartz-normative. Sibray (1977) and Malinowski (1977) show that some Hawi mugearites and benmoreites analyzed by them are quartz-normative. Quartz-normative rocks tend to have slightly higher contents of CaO and FeO_T , and lower SiO_2 and alkalis for the hawaiites and mugearites; in benmoreites they are lower in silica, alkalis and magnesia than are nepheline-normative rocks.

Rocks from this study are also all hypersthene normative as were many from Sibray (1977) and Malinowski (1977). According to Yoder and Tilley (1962), normative hypersthene is indicative of tholeiitic basalt. Hawi hawaiite and mugearites from Macdonald (1968) and Macdonald and Katsura (1964) are lacking in hypersthene, whereas trachyte is hypersthene-normative.

A possible reason for quartz and hypersthene in the norm for these alkalic rocks lies in the rather high oxidation state of iron. The oxidation state of iron tends to influence the silica saturation of the norm calculation. A more oxidized rock (higher Fe^{+3}) will contain more magnetite, resulting in less iron available for normative olivine,

hypersthene and diopside. These silicate minerals also require less silica for their formation and therefore some SiO_2 may be left over for normative quartz. Cox et al. (1979) suggest that in order to avoid the problem of oxidation state in basalts, adoption of some standard $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio should be used in norm calculation. They cite the work of Brooks (1976), who used an $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio of 0.15 for basalt. $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios of rocks from this study range from 0.66 (hawaiite) to 1.67 (benmoreite trachytic rocks). This range is similar to that of the average analyses of Hawaiian alkalic suite rocks in Macdonald (1968). The closest basalt type to the value of 0.15 (Brooks, 1976) is a tholeiitic oceanite, 0.26, so the use of $\text{Fe}_2\text{O}_3/\text{FeO} = 0.15$ is of no real value in Hawaiian rocks.

Intracone Comparison - Several samples were obtained from a few selected cinder cones to see if there was more than one rock type being erupted from individual cones. Cones 1 (mugearite to benmoreite) and 21 (hawaiite-mugearite to benmoreite) showed wide ranges in composition, whereas Cones 8 and 12 showed limited compositional diversity. Cone 11 was basically isochemical. Rocks from Cone 11 were sampled horizontally (11-2 series), as well as vertically (11-1 and 11-2 series) possibly because of a gravel excavation. Again, no real change in composition was noted along the 40-meter horizontal distance or vertically.

Geographic Variation - Plots of composition versus geographic position along a line $\text{N}56^\circ\text{W}$ running through Puu Kehena (Cone 8) in the northwest through Kohala Summit and intersecting Highway 19, 3.73 km (2.30 mi) northeast of the Kamuela Post Office. On the plots, the Post

Office was set equal to the zero point with positive numbers to the northwest and negative to the southeast in units. Results (Figures 9a to 9i) suggest two distinct groupings. Cones along the NW-SE trend are generally high in FeO_T , TiO_2 and CaO , and lower in SiO_2 , K_2O , Na_2O and Rb than those of the E-W trend, while values of MgO , Al_2O_3 , P_2O_5 and Ni (except higher in a few instances) show no obvious differences. Comparison of these same trends by statistical analysis of rock types (see Table 5) confirms the difference. For instance, hawaiites from the NW-SE trend are distinctly lower in SiO_2 and alkalis and have higher TiO_2 , FeO_2 , MgO and CaO .

In summary, the E-W trend shows a more enrichment in SiO_2 and alkalis. The exact meaning of this trend is uncertain. Due to their limited geographic extent and their different composition, the E-W trend rocks may indicate a separate magma batch.

Temporal Variation - In general, the determination of cinder cone stratigraphy is very difficult due to extreme grass cover and distance between cones. Despite this, several cones sampled for this study are located in the Kawaihae quadrangle studied by Malinowski (1977). She placed these cones in the relative age sequence, from oldest to youngest, 21, 20, 11, 10 and 14. In addition, Cones 24 and 25 are older than Cone 21, as determined by inspection of aerial photographs in this study. As shown in Figure 10, there is a very slight chemical variation with time. There is an overall slight increase in Ti , Fe , Ca , Mg , Na and Ni , with a slight decrease in Si and Al . There was no change observed for K . P and Rb were erratic.

These irregular trends are similar to what Beeson (1976) found,

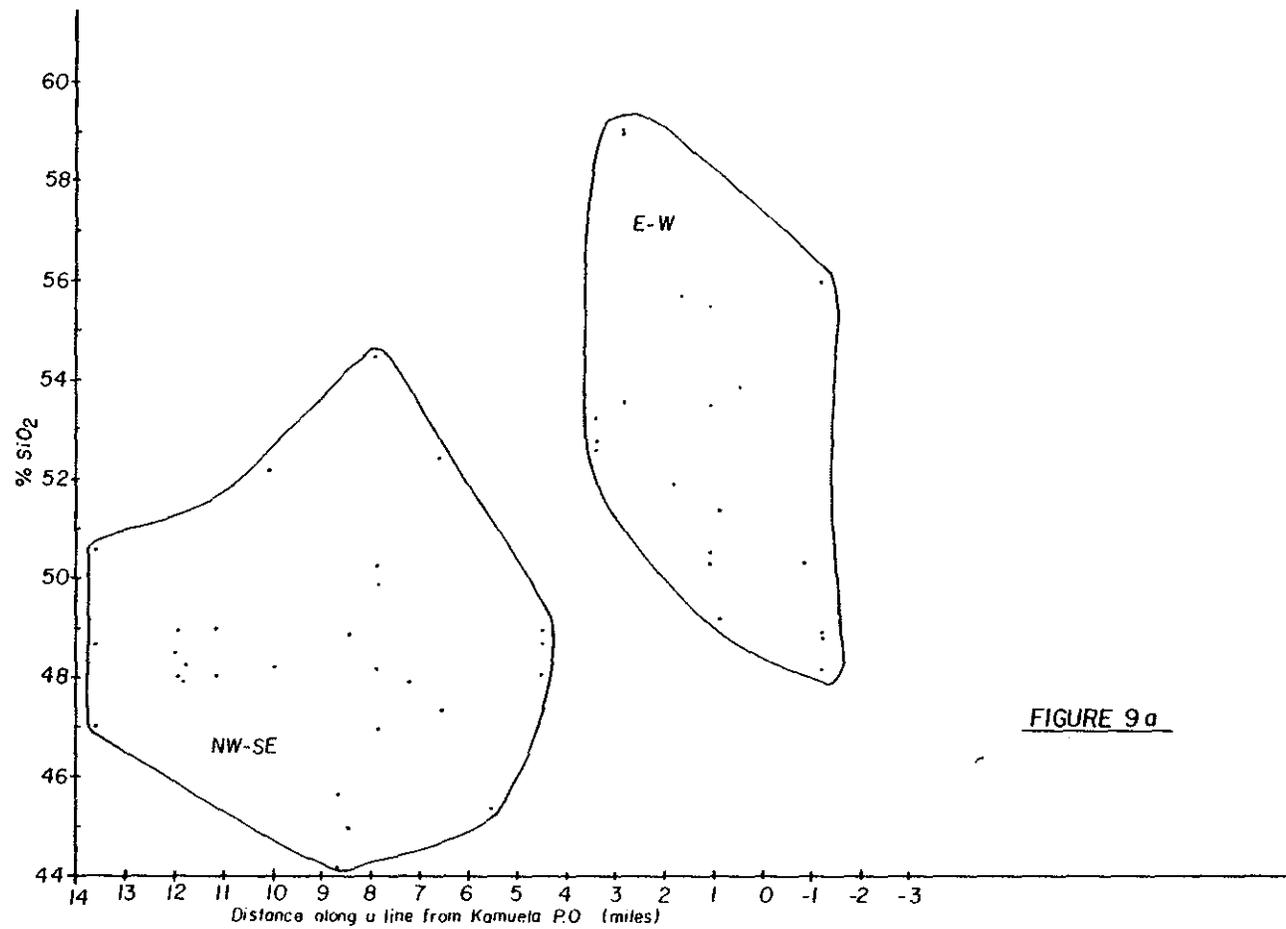


FIGURE 9a

Fig. 9. Plots of composition versus geographic position along a line N56⁰W over Kohala Summit (see text). a. Silica vs. geographic position

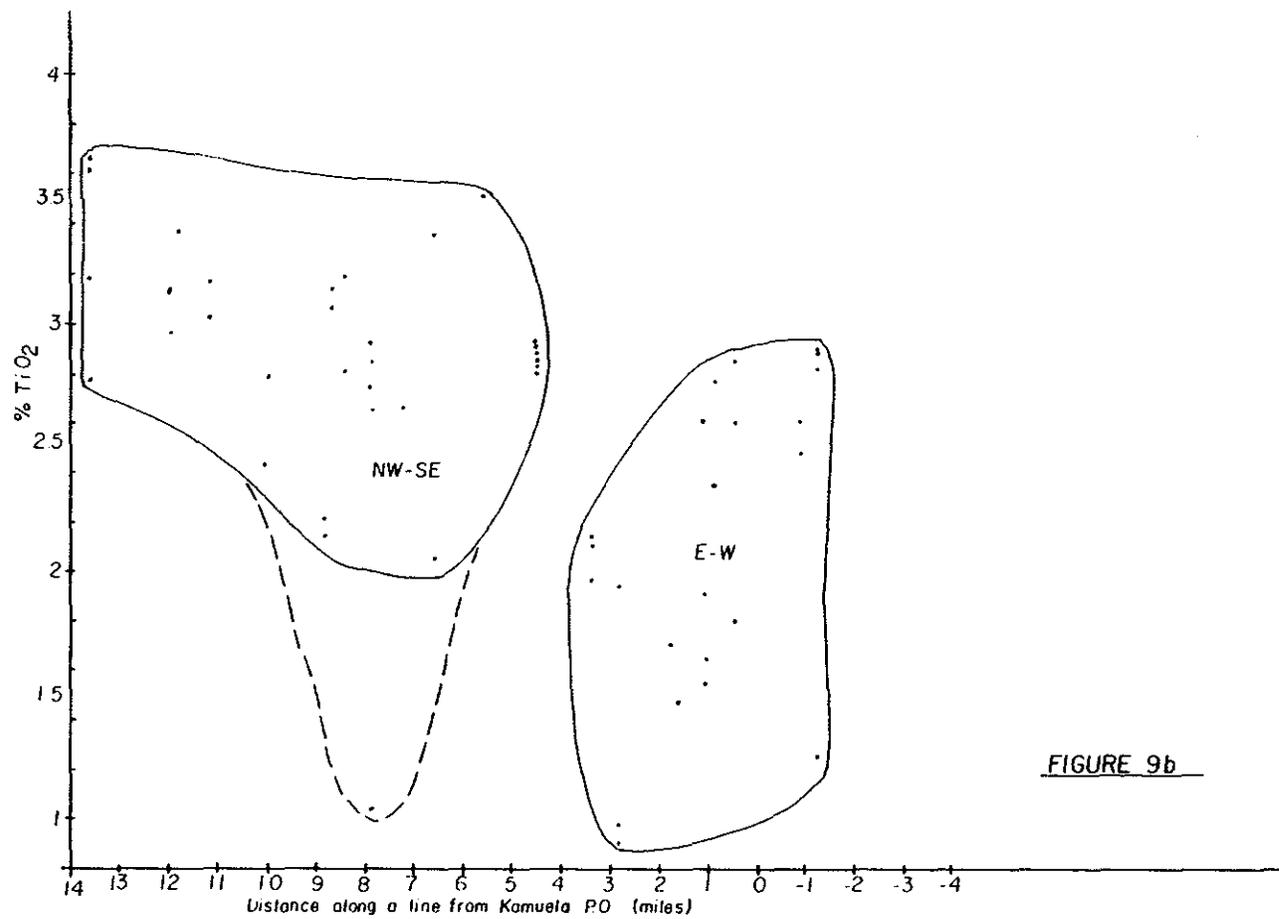


FIGURE 9b

Fig. 9b. Titania vs. geographic position

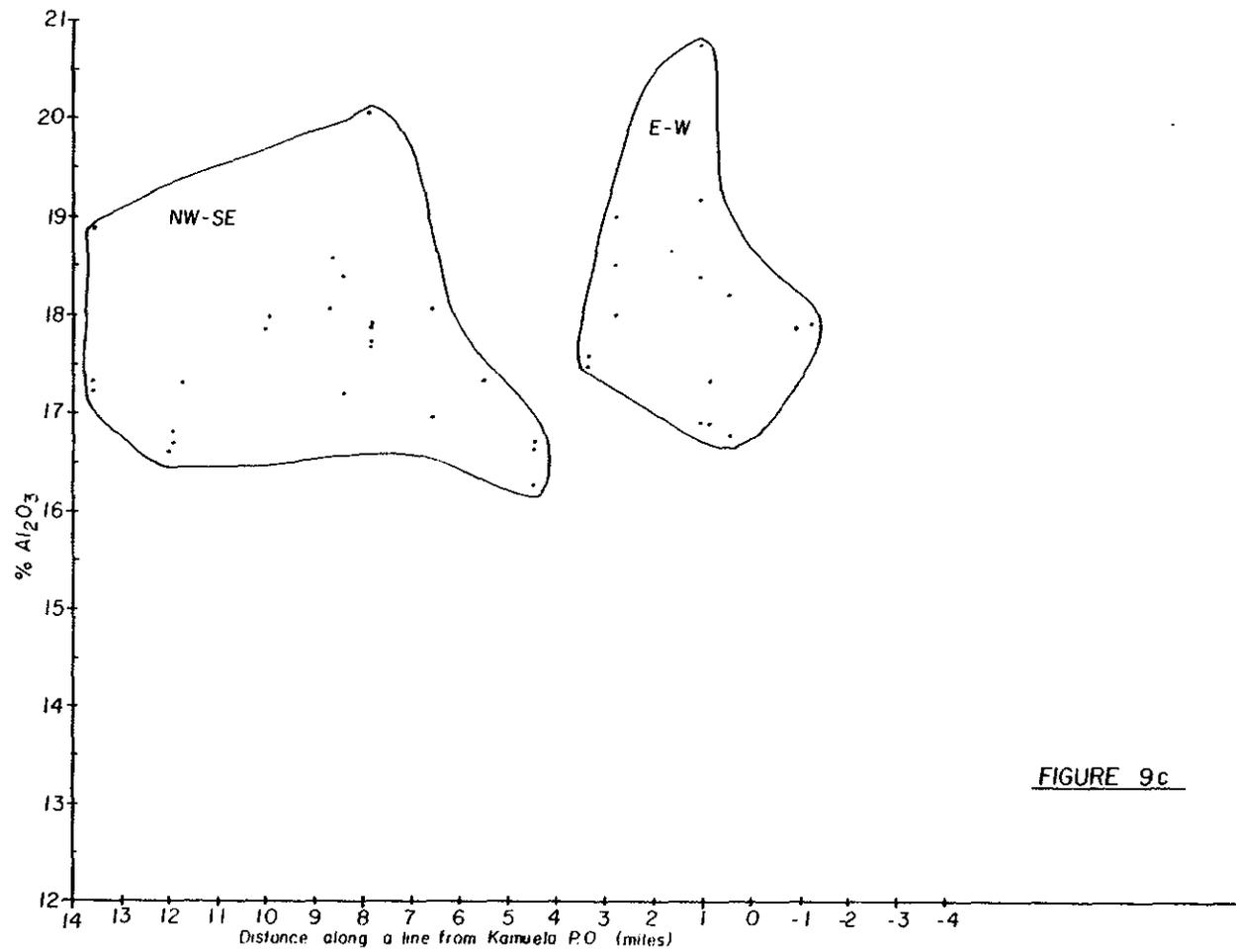


FIGURE 9c

Fig. 9c. Alumina vs. geographic position

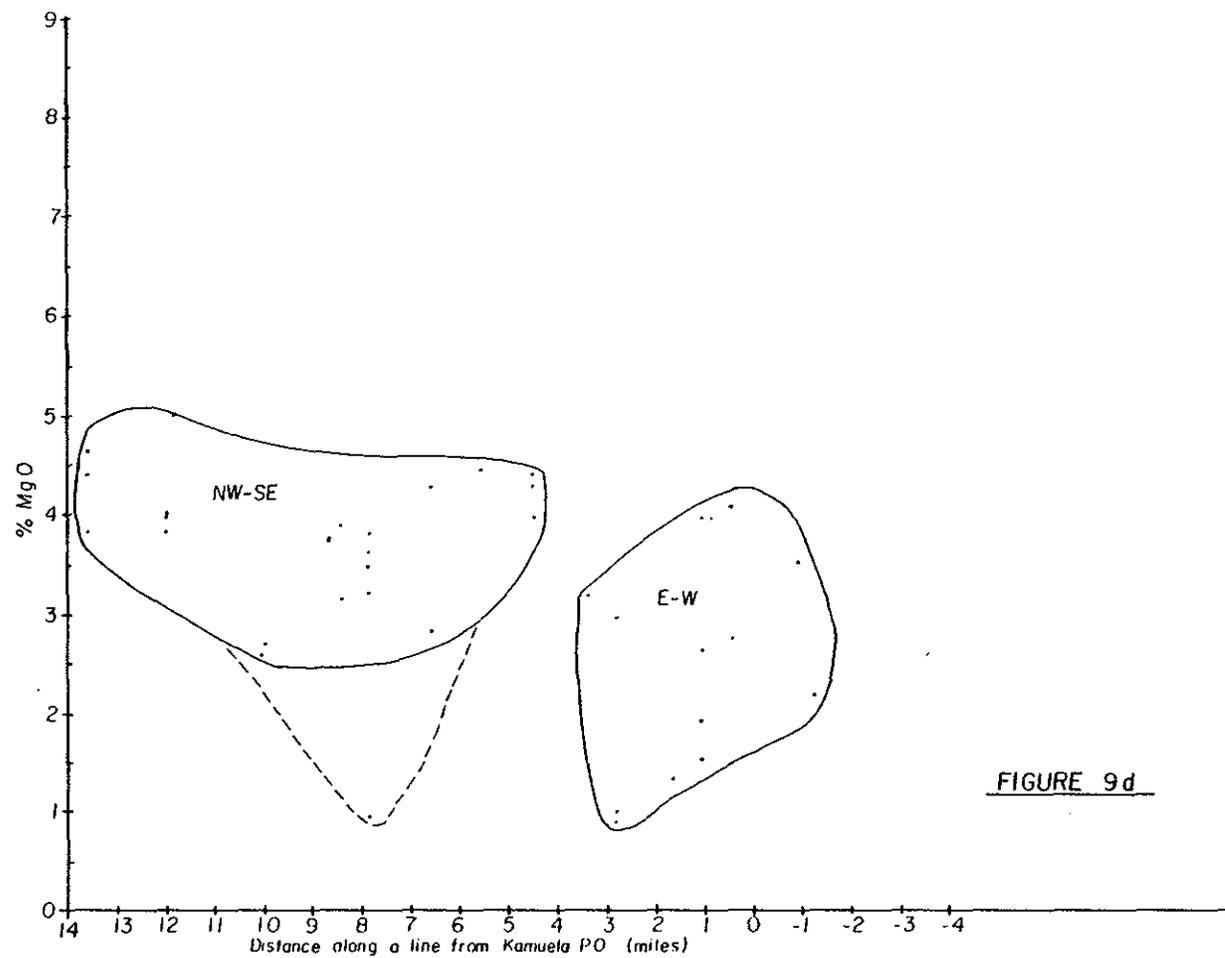


FIGURE 9d

Fig. 9d. Magnesia vs. geographic position

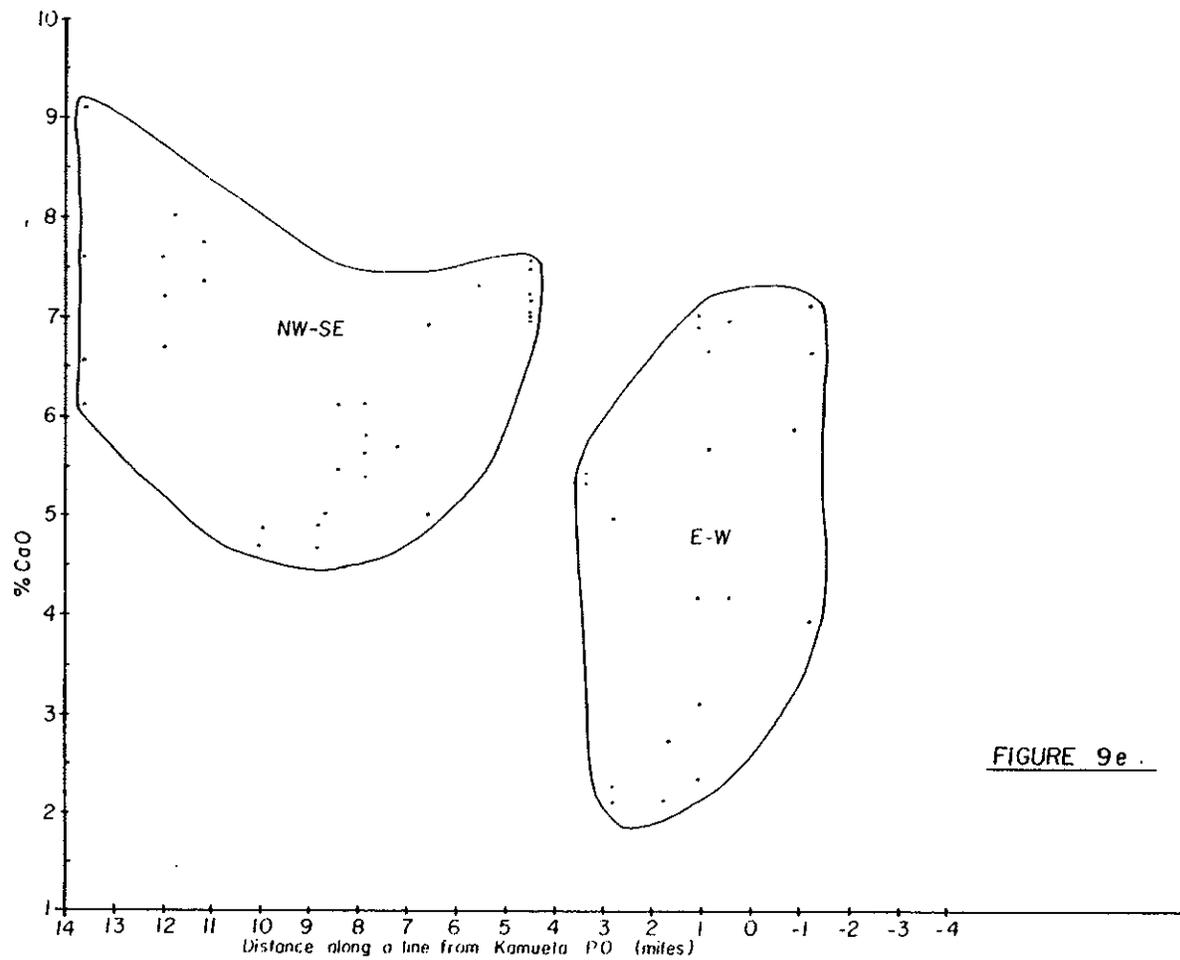


FIGURE 9e .

Fig. 9e. Lime vs. geographic position

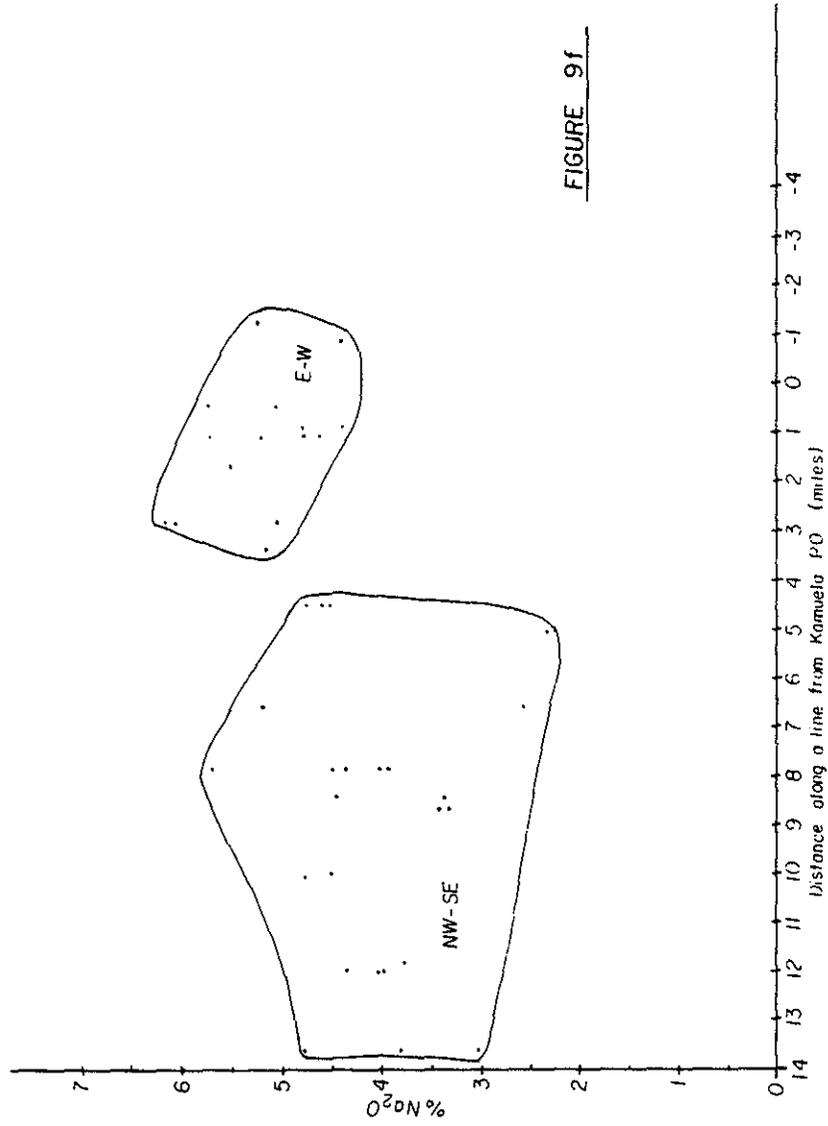


FIGURE 9f

Fig. 9f. Soda vs. geographic position

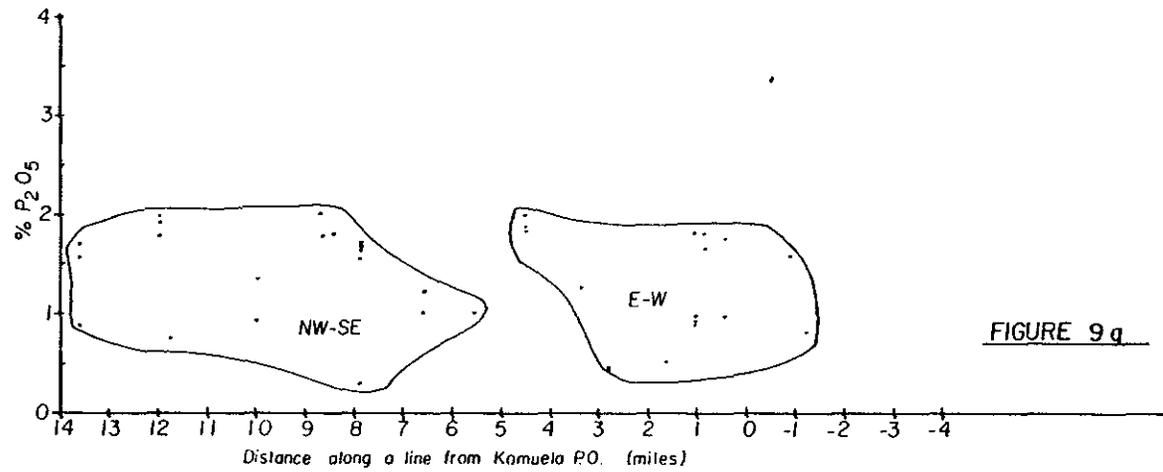


FIGURE 9g

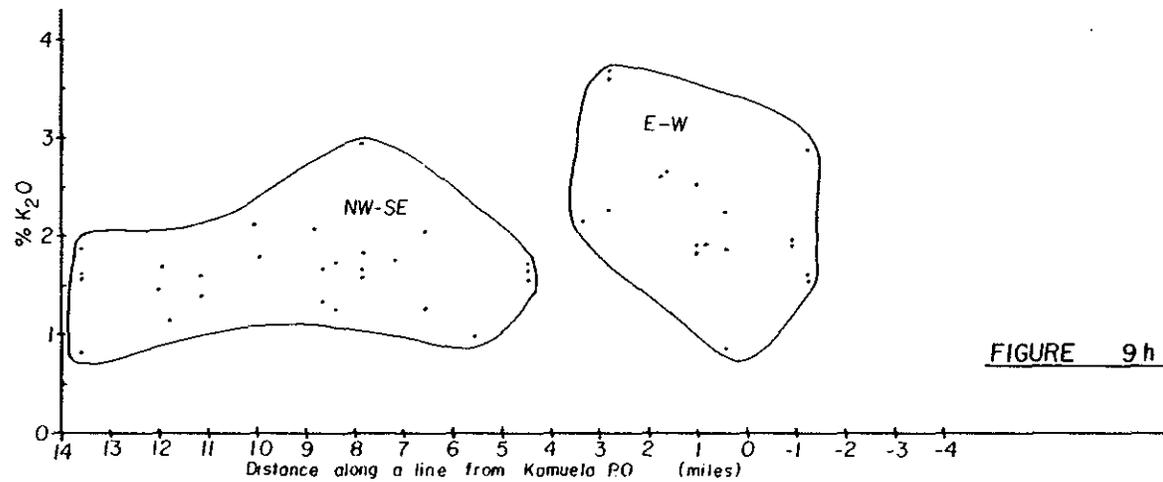


FIGURE 9h

Fig. 9g. (top) Phosphorous vs. geographic position. 9h. (bottom) Potash vs. geographic position.

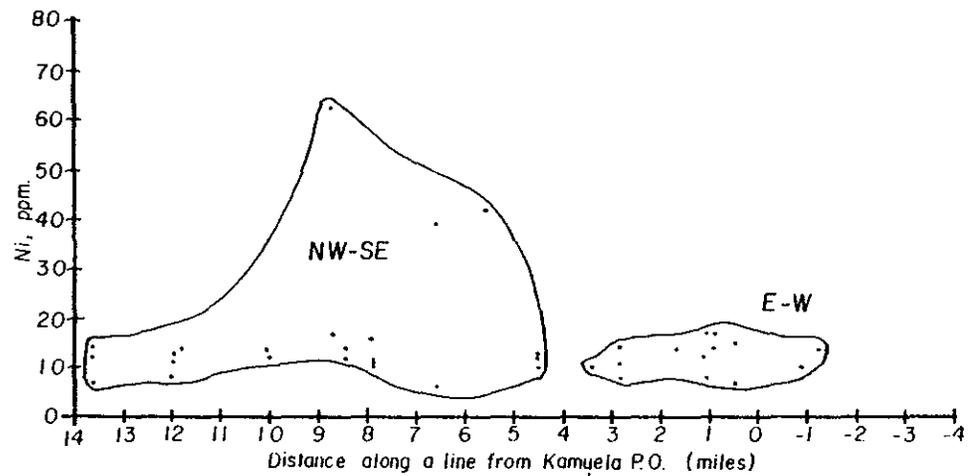
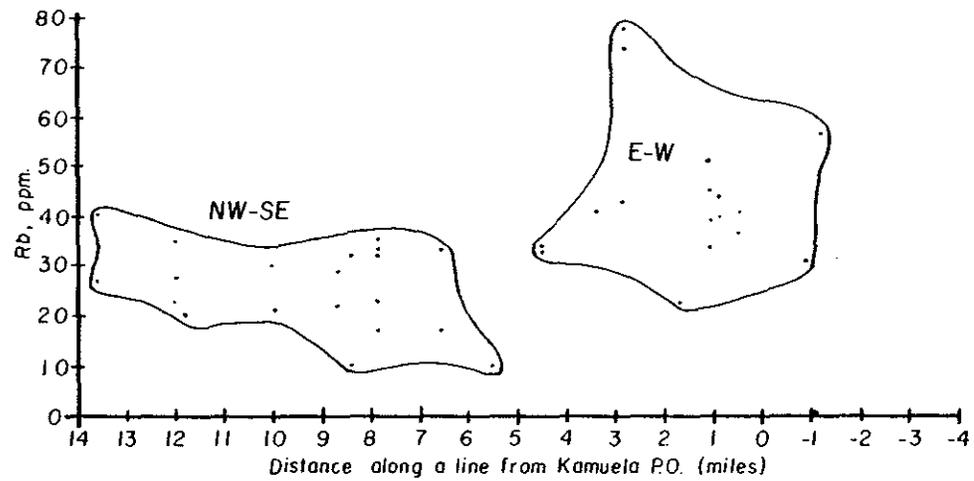


Fig. 9i. (top) Rubidium vs. geographic position. 9j. (bottom) Nickel vs. geographic position.

TABLE 5

Comparison of Compositional Variation Between Rock Types Relative to Position of Rift Zone

	Hawaiite		Hawaiite-Mugearite		Mugearite		Mugearite-Benmoreite		Benmoreite	
	Average	1 σ	Average	1 σ	Average	1 σ	Average	1 σ	Average	1 σ
<u>E-W Rift</u>										
SiO ₂	48.95	0.68	50.79	0.41	51.79	1.72	54.14	1.64	55.70	
TiO ₂	2.82	0.12	2.52	0.15	2.19	0.32	1.59	0.21	1.48	
Al ₂ O ₃	17.88	- ^a	16.86	0.08	18.67	1.56	18.56	0.78	18.65	
FeO _T	11.46	0.60	10.47	0.53	9.50	1.18	7.70	0.74	6.37	
MgO	3.51	-	4.01	0.06	3.01	0.85	2.28	0.56	1.32	
CaO	6.52	0.62	6.90	0.13	5.01	1.21	3.51	0.89	2.73	
H ₂ O	4.41	-	4.87	0.16	4.80	0.36	5.47	0.29	5.52	
K ₂ O	1.51	0.39	1.88	0.04	2.16	0.20	2.25	0.22	2.65	
P ₂ O ₅	1.58	-	1.74	0.08	1.23	0.42	0.93	0.08	0.53	
Ni	10	-	14	2	12	4	12	5	11	
Kb	31	-	40	1	41	5	48	9	23	
Number of Samples	5 ^b		4		7		5		1	
<u>NE-SL Rift</u>										
SiO ₂	47.81	1.52	49.07	1.43	50.80	1.82			54.44	
TiO ₂	3.14	0.27	2.69	0.15	2.40	0.31			1.04	
Al ₂ O ₃	17.32	0.83	17.60	0.24	17.92	0.12			20.05	
FeO _T	12.27	0.76	11.35	0.63	10.29	1.05			6.33	
MgO	4.20	0.37	3.50	0.33	2.94	0.46			0.95	
CaO	7.03	0.97	5.94	0.41	4.96	0.35			2.01	
H ₂ O	3.70	0.74	4.39	0.30	4.61	0.49			5.70	
K ₂ O	1.46	0.25	1.73	0.08	1.96	0.19			2.93	
P ₂ O ₅	1.59	0.45	1.67	0.03	1.29	0.28			0.33	
Ni	20	16	12	4	11	3			12	
Kb	25	8	31	9	27	6			32	
Number of Samples	21		6		7				1	

^a"Bar" indicates only one available analysis for this oxide.^bE-W rift Hawaiites include one complete (KV-5-2) and four partial analyses; therefore, a 1 σ value is not included. In all other cases there were more than two analyses including any partial analyses.

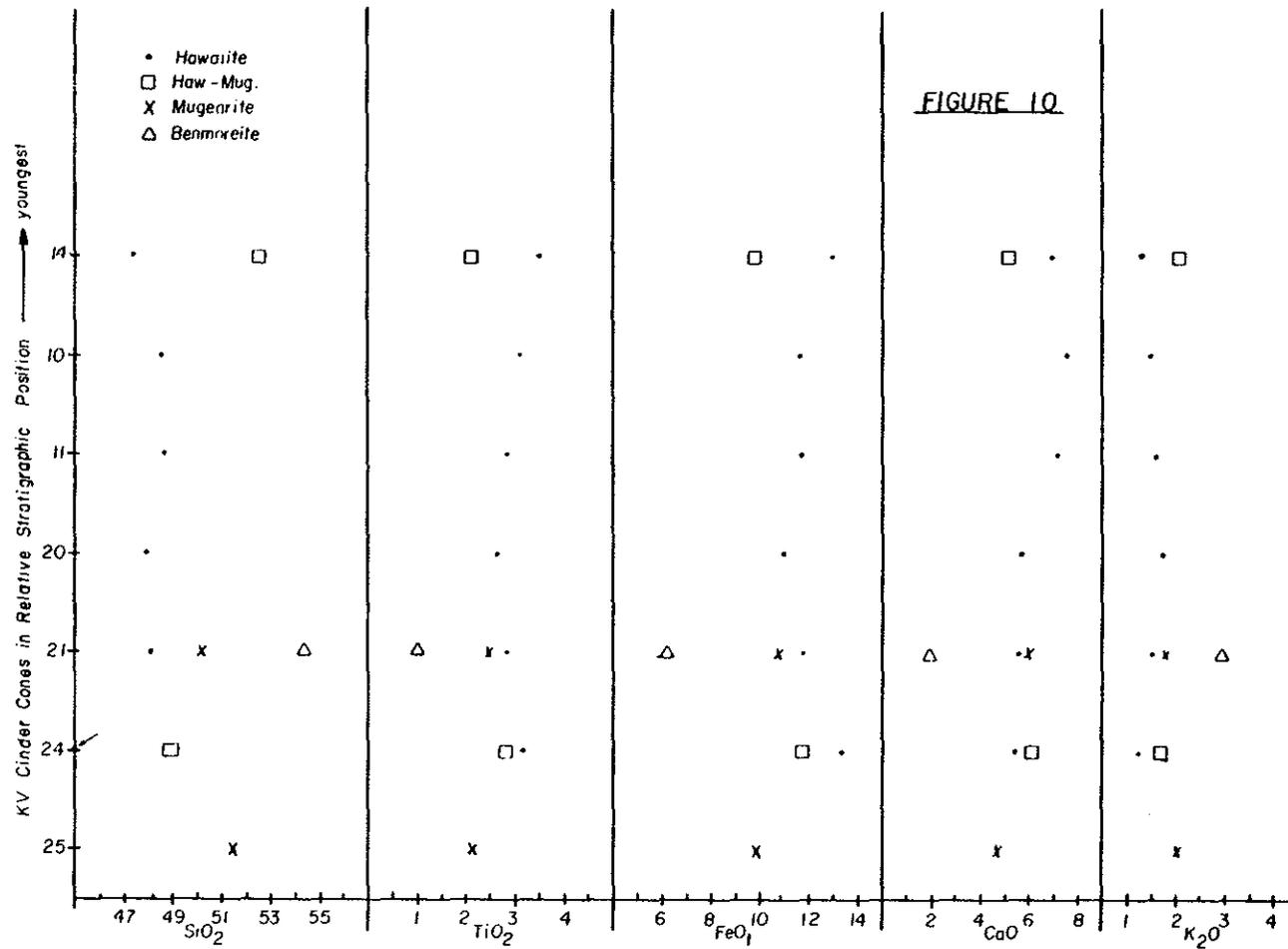


Fig. 10. Rock composition and relative stratigraphic position for a section of Hawi rocks.

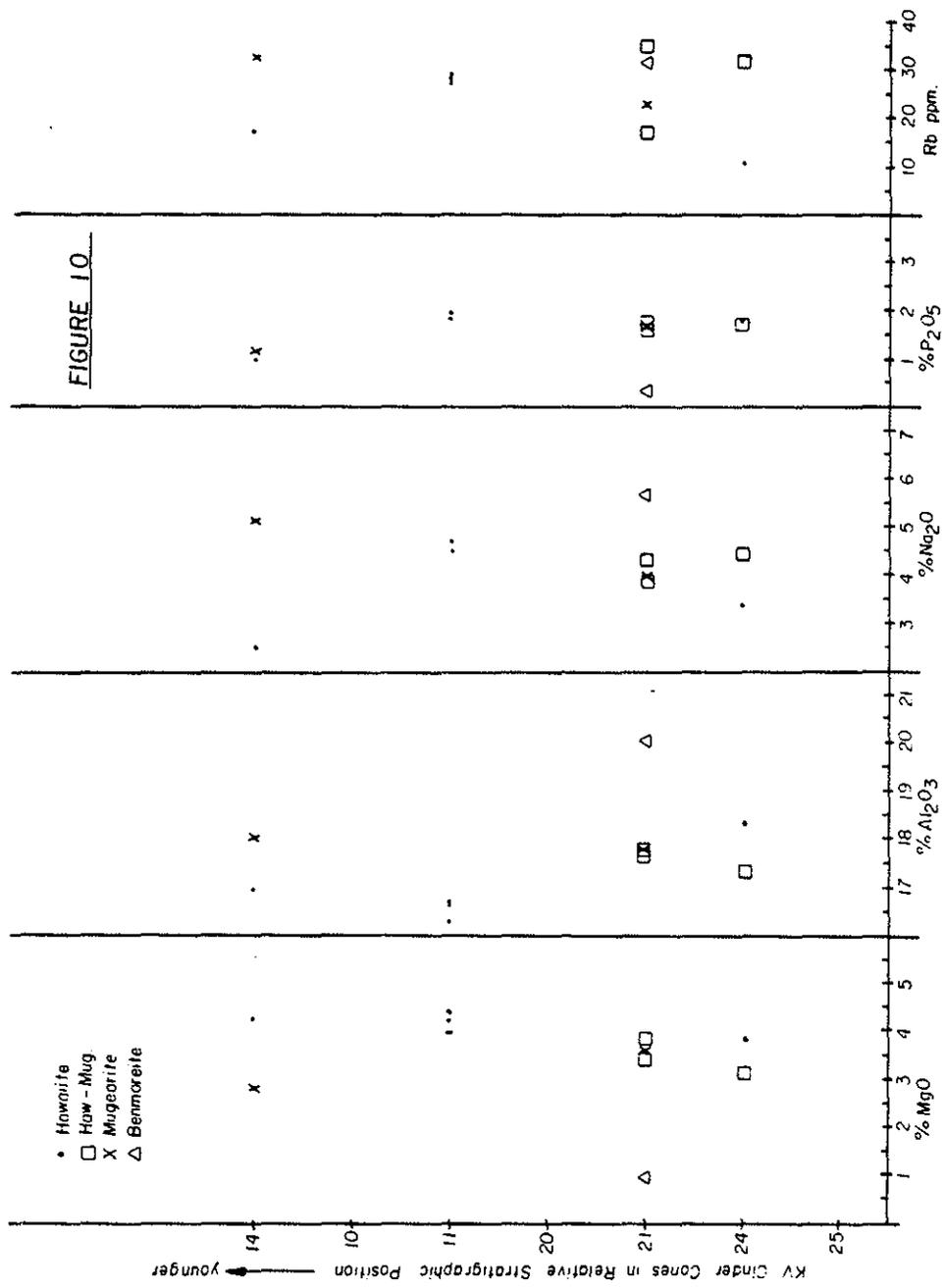


Fig. 10. continued.

i.e., stratigraphically-controlled sampling and detailed compositional analyses of the alkalic East Molokai Volcanic Series showed that the fractionation trend was discontinuous with stratigraphy.

Intra-Island Volcano Comparison - Of the five major centers on the island of Hawaii, only Mauna Kea and Hualalai have erupted alkalic lavas besides Kohala. Hualalai has erupted mostly alkalic basalt and a little trachyte (Macdonald, 1968; Macdonald and Katsura, 1964). This leaves only Mauna Kea for direct comparison to Kohala for the Hawaiian Isle. Comparison is made with caution because there are only thirteen modern-day analysis published for the alkalic suite. It appears that Kohala contains more CaO and P_2O_5 and less SiO_2 , FeO_T , and MgO comparatively for hawaiite and mugearite (Figures 11a-11h). Alumina is higher in Hawi mugearites and approximately the same for hawaiites. Titania is about the same. The Hawi series has about the same to slightly more alkalis than Mauna Kea.

Inter-Island Volcano Comparison - The following is a comparison of the composition of the Hawi Volcanic Series with other volcanoes of the Hawaiian Islands (Figures 11a-11h).

Comparison of 15 hawaiites from Waianae, Oahu (Macdonald, 1968), show that the Hawi Series contains more Al_2O_3 , CaO and P_2O_5 , and lower TiO_2 and MgO.

Comparison of hawaiite samples from Molokai (Hlava, 1974; Macdonald and Katsura, 1964) indicate that Molokai has higher MgO and K_2O , the same to slightly higher TiO_2 , Na_2O , the same SiO_2 , FeO_T and K_2O , and lower CaO and P_2O_5 than Hawi rocks. Mugearite from Molokai (Hlava, 1974; Macdonald, 1968) had the same SiO_2 , TiO_2 , FeO_T , MgO, K_2O

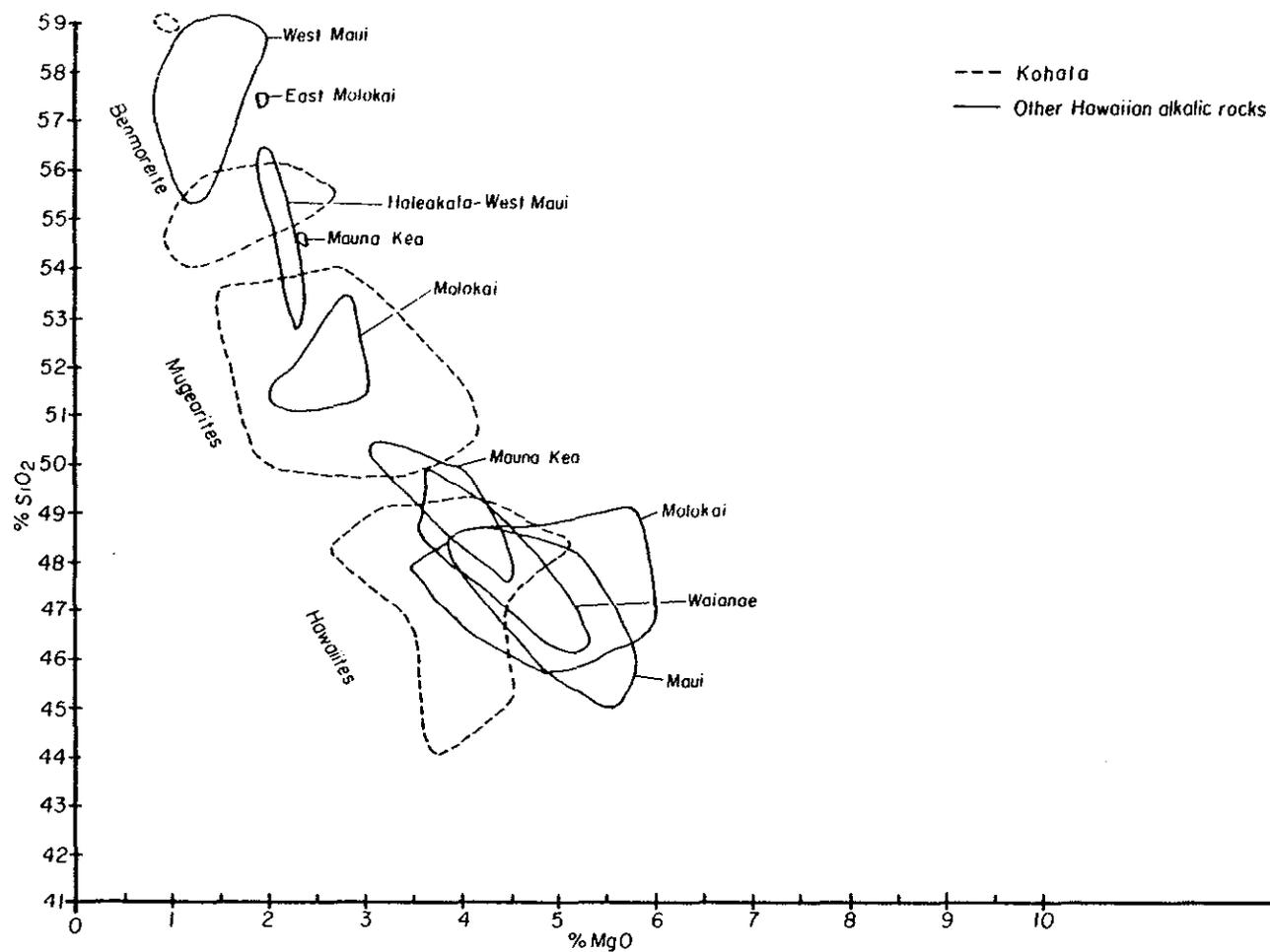


Fig. 11. Chemical composition of Kohala compared with other Hawaiian volcanoes. Other sources of data include Hlava (1974), Macdonald (1968), Hubbard (1967), Macdonald and Katsura (1964).
 11a. SiO₂ - MgO.

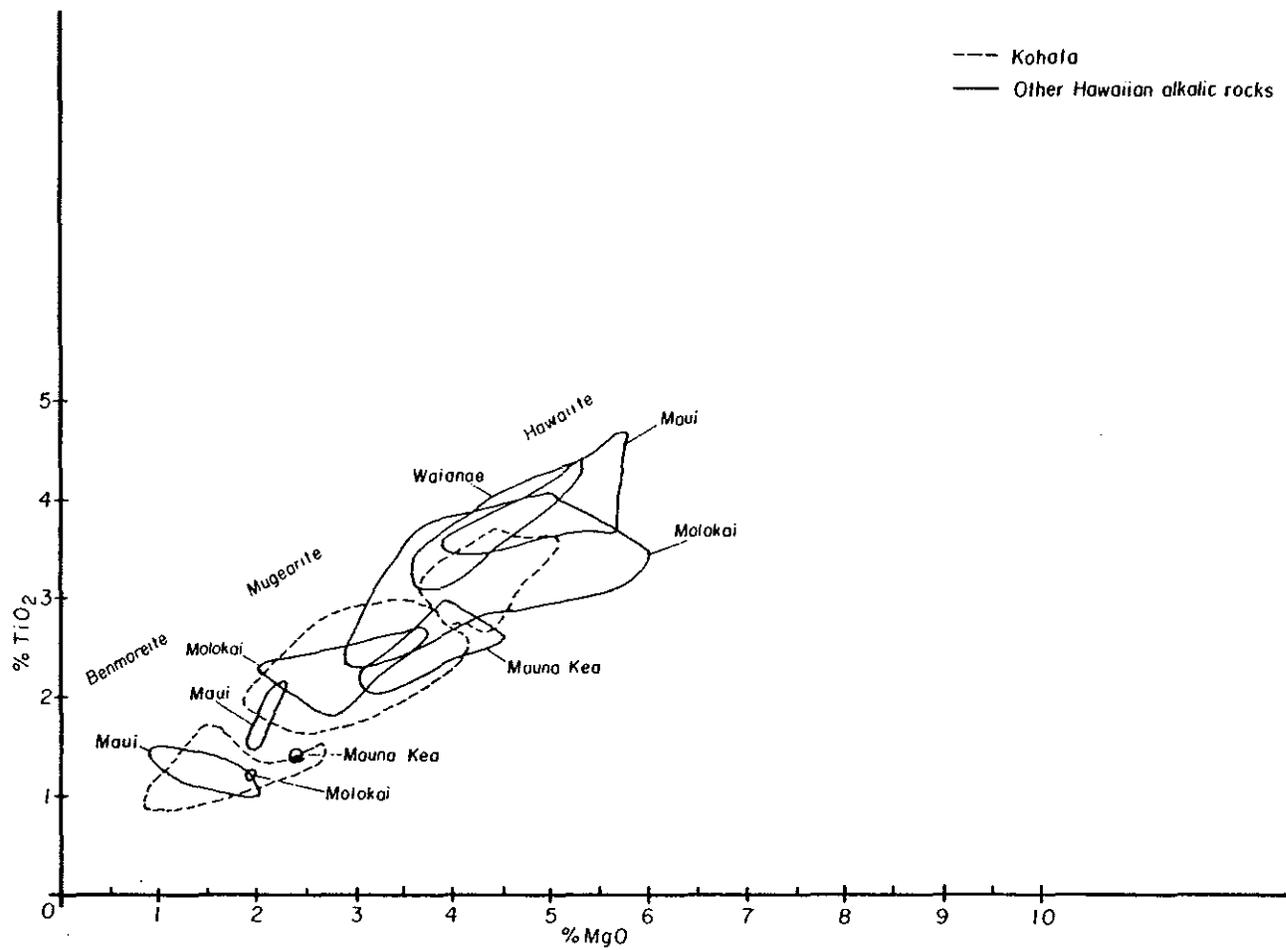


Fig. 11b. TiO₂ - MgO.

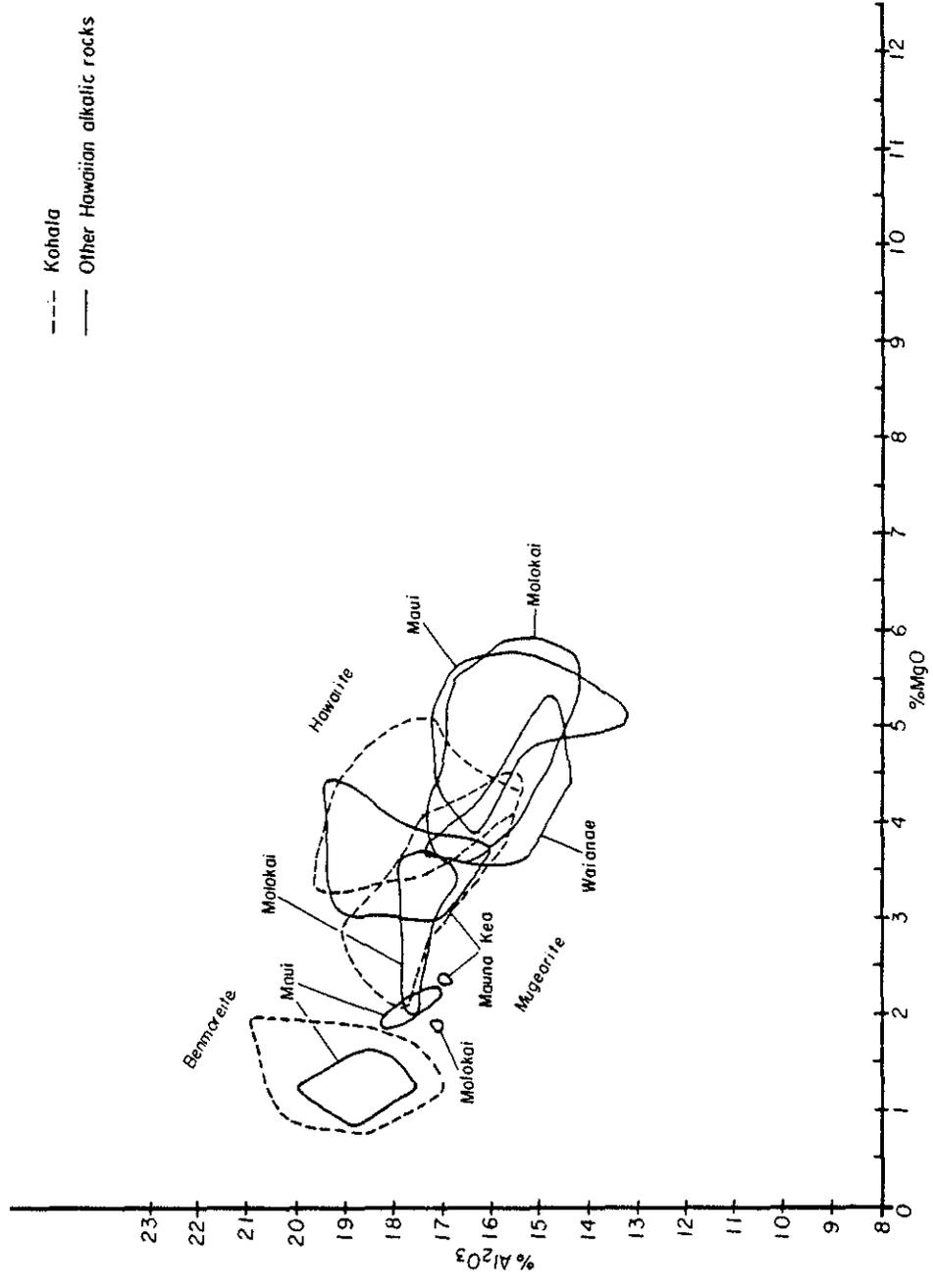


Fig. 11c. Al₂O₃ - MgO.

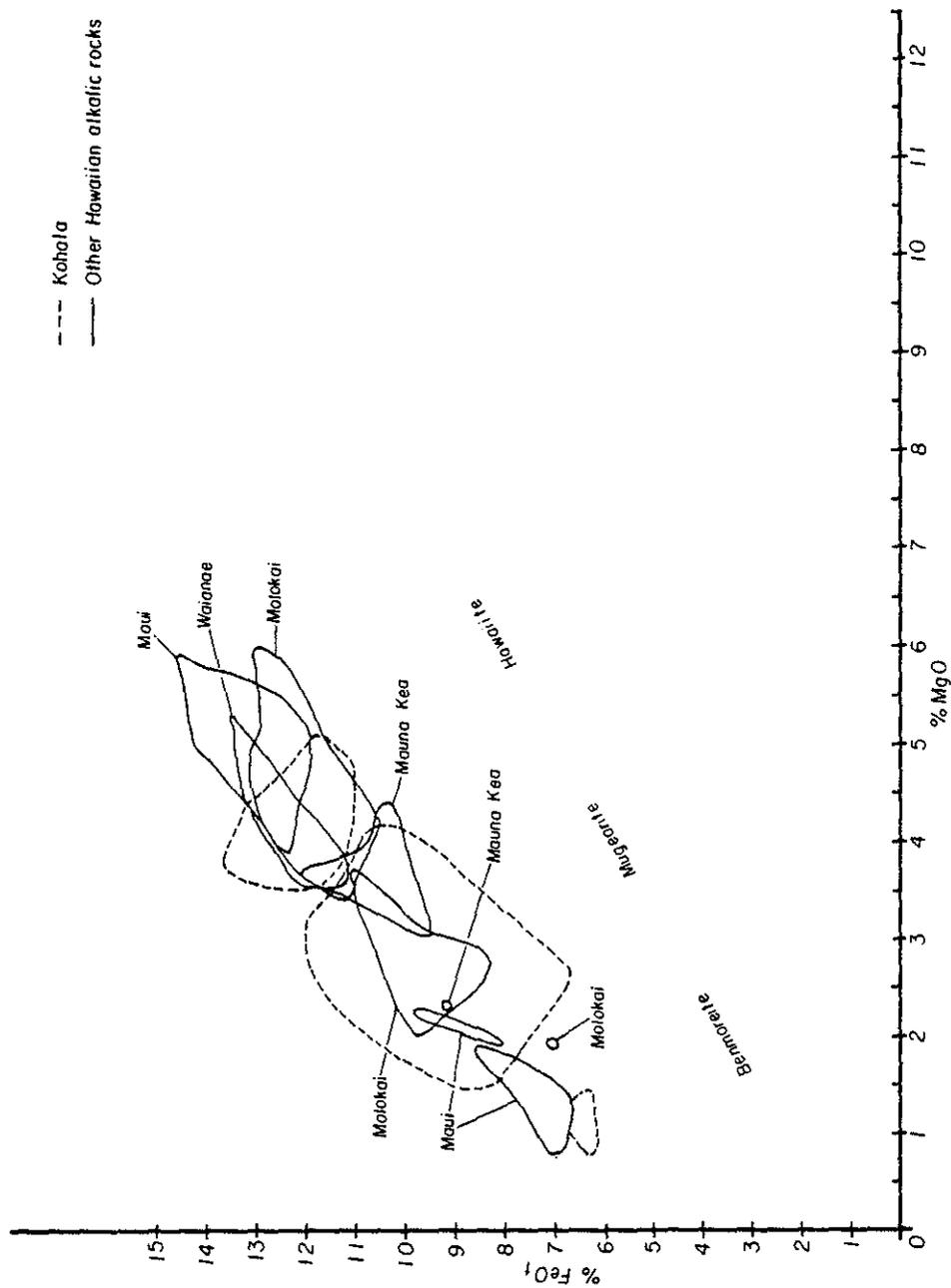


Fig. 11d. FeO_T - MgO.

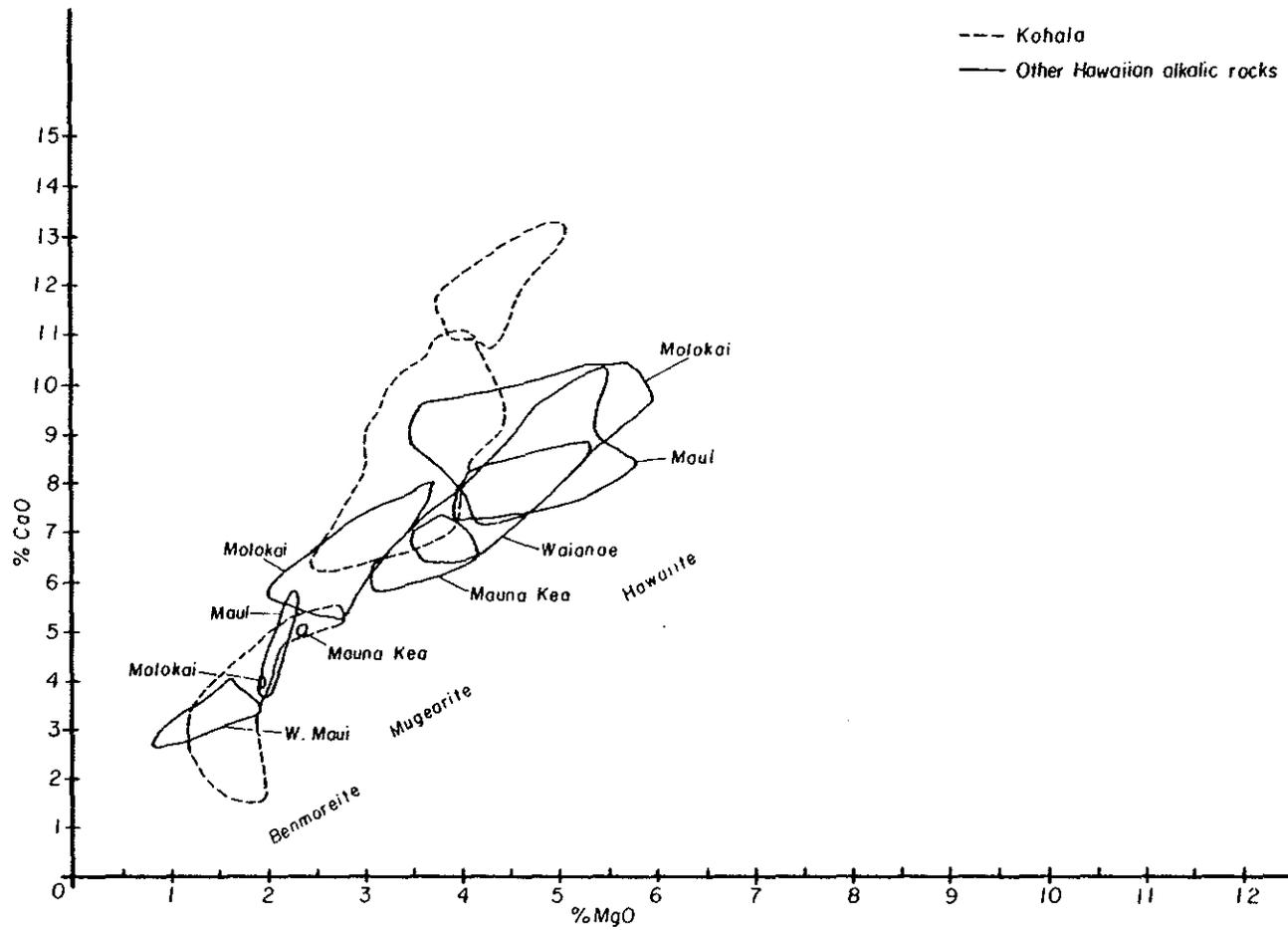


Fig. 11e. CaO - MgO.

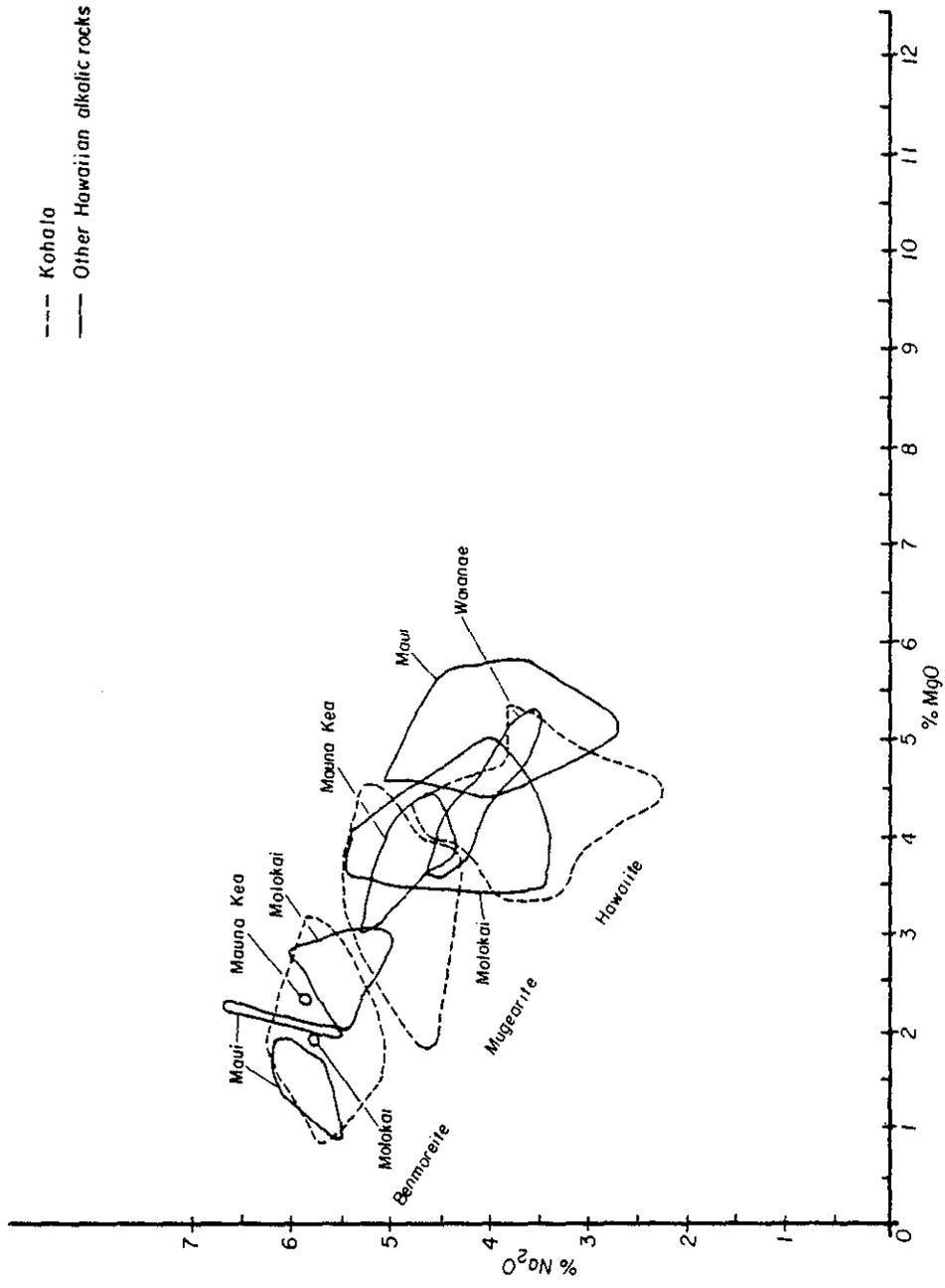


Fig. 11f. Na₂O - MgO.

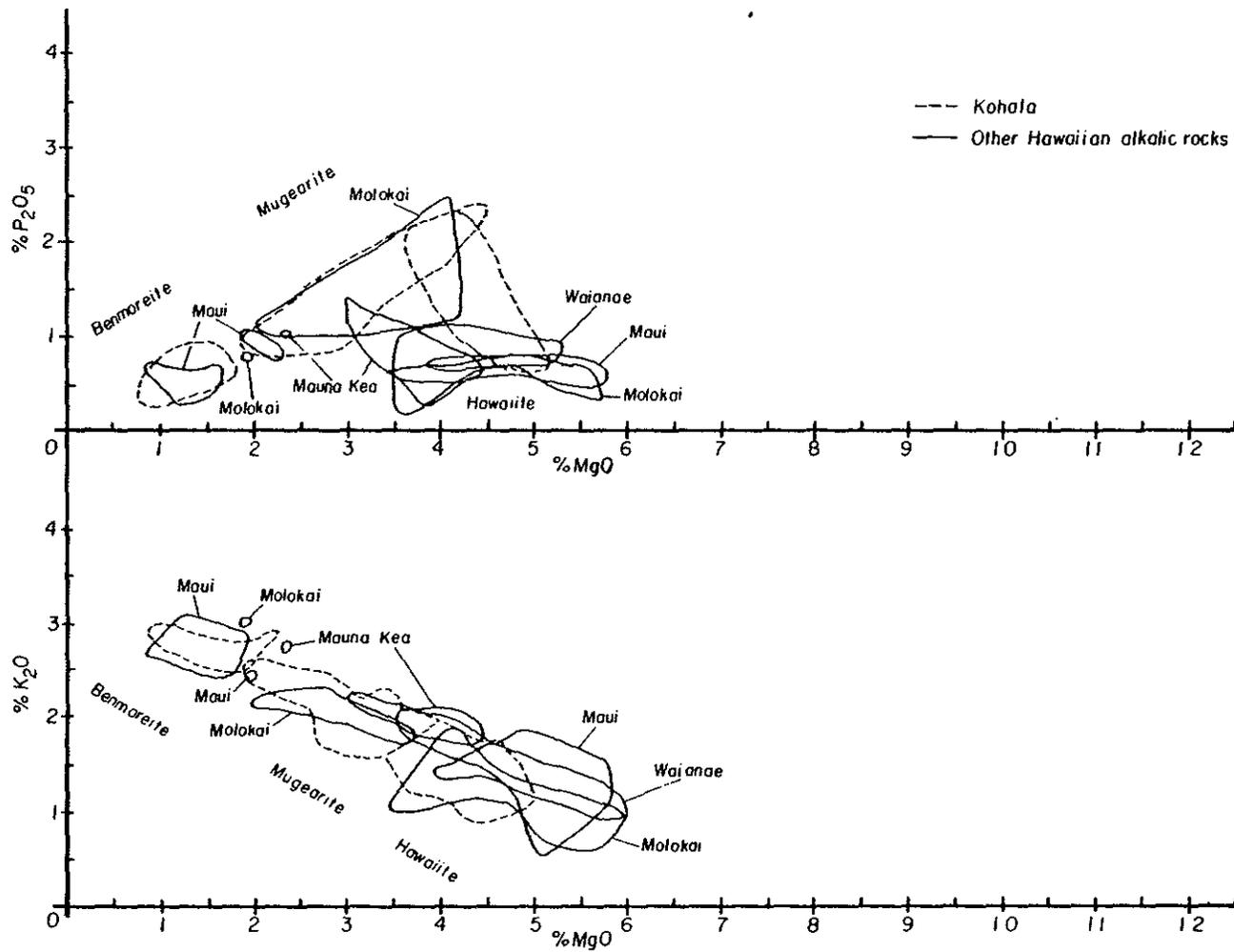


Fig. 11g. (top) P_2O_5 - MgO . 11h. (bottom) K_2O - MgO .

and P_2O_5 , the same to higher Na_2O , and less Al_2O_3 and CaO than Hawi mugearites. Comparison of benmoreites show Molokai (Macdonald, 1968) as having more SiO_2 , FeO_T , the same to slightly more K_2O , about equal amounts of TiO_2 , MgO and Na_2O , the same to slightly less CaO and P_2O_5 , and less Al_2O_3 .

Comparison of hawaiites from west Maui and Haleakala (Macdonald, 1968; Macdonald and Katsura, 1964) show that the East Maui volcano contains more TiO_2 , FeO_T and MgO , the same amounts of alkalis, the same to slightly less SiO_2 , and lower Al_2O_3 , CaO and P_2O_5 . Maui mugearites (Macdonald, 1968) have more SiO_2 and Na_2O , slightly more K_2O , about the same amount of MgO , slightly less FeO_T and TiO_2 , and less to much lower Al_2O_3 , CaO and P_2O_5 . Benmoreites from Maui (Macdonald, 1968; Macdonald and Katsura, 1964) have greater content of SiO_2 and FeO_T , the same to slightly more K_2O , the same MgO , Na_2O and TiO_2 , the same to slightly less CaO , P_2O_5 , and Al_2O_3 than Hawi benmoreites.

Regarding trace element comparisons, the only data available are largely from Hubbard (1967) and Feigenson (1981, communication), along with some Rb data from Lessing et al. (1963). Hawi rocks have the lowest Rb (and K_2O) of any Hawaiian alkalic rocks. There are no other Ni analyses available to compare Hawi series rocks to except three hawaiites from Waianae Volcano (Hubbard, 1967), where values of 339, 355 and 723 ppm are reported. These are obviously much higher values than Hawi hawaiites.

In summary, there appears to be a difference between Hawi alkalic rocks and those from other Hawaiian islands. In fact, there are differences in major-element composition for each volcano and each rock type.

The most significant differences between Hawi rocks and other volcanoes lie in contents of P_2O_5 , MgO, CaO, Al_2O_3 , K_2O and Rb, with lower MgO and K_2O , and significantly lower Rb. The low K_2O and Rb seem consistent with the low K_2O of Pololu tholeiites. Kohala has higher amounts of P_2O_5 , CaO and Al_2O_3 , with lower MgO.

SR-ISOTOPE TRACER STUDY

Introduction and Previous Work

Isotope tracer studies involve the use of radiogenic daughter product abundances as "fingerprints" to investigate the petrogenesis of igneous rocks (Hart, 1969). We are concerned here with the initial $^{87}Sr/^{86}Sr$ ratio. Since the time interval between the eruption of Kohala cones and the present is so short with respect to the half-life of ^{87}Rb , the amount of ^{87}Sr produced by in situ decay of parent ^{87}Rb is insignificant. It is assumed that Sr isotopes do not undergo appreciable fractionation in nature, and that uncontaminated rocks with different lithology that are derived from the same parent have identical initial $^{87}Sr/^{86}Sr$ ratios at their time of crystallization. Rocks with significant differences in this initial Sr ratio are considered not to be comagmatic or perhaps comagmatic and contaminated.

Basalts from oceanic islands are considered to represent material derived directly from the earth's mantle (Faure and Powell, 1972; Carmichael et al., 1974; Hoffman and Hart, 1975). In general, $^{87}Sr/^{86}Sr$ ratios of oceanic islands range from 0.702 to 0.706 and average about 0.7037 (Faure and Powell, 1972; Hedge and Peterman, 1970). These oceanic island basalts are quite distinctive from ocean-rise or ocean-ridge basalts, which generally have a $^{87}Sr/^{86}Sr$ ratio of

less than 0.7030 (Peterman and Hedge, 1971).

Strontium isotope data for the Hawaiian Islands are limited; most work has been confined to the islands of Oahu and Hawaii (Hedge and Walthall, 1963; Lessing and Cantanzaro, 1964; Powell et al., 1965; Powell and DeLong, 1966; Hedge, 1967). G. Faure and J. Powell (personal communication, 1979) suggest that their 1960's work is obsolete and should be discounted. All published Sr isotopic ratios for Hawaiian rocks are compiled in Appendix VII.

Published $^{87}\text{Sr}/^{86}\text{Sr}$ values of Hawaiian basalts fall within the range of other oceanic island basalts, 0.702 to 0.706. There is little difference detected in Sr isotope ratios between tholeiites and alkalic basalts from Hawaii. In contrast, there is a distinct separation observed between the tholeiite-alkalic suites and the nephelinitic group; the latter group has distinctly lower $^{87}\text{Sr}/^{86}\text{Sr}$ values. Powell et al. (1965) found a relationship between Sr isotopic composition and SiO_2 content, in which strongly undersaturated basalts have lower Sr isotopic ratios (Table 6). Peterman and Hedge (1971) found a positive relationship between $\text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O})$, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Figure 12). Rocks with the highest Sr ratios tend to have the highest K concentrations.

Results

The Sr isotopic data are presented in Table 7, along with standard deviations (2 σ), which is the square root of the variance or spread in distribution. Internal precision of the results are fair for use as tracer analyses. A one standard deviation value in excess of 0.0001 is not considered to be precise enough for tracer work. Samples 1-1E,

TABLE 6
 $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios vs. SiO_2 for Hawaiian Rocks
(Powell et al., 1965)

<u>Rock Type</u>	<u>% SiO_2</u>	<u>$^{87}\text{Sr}/^{86}\text{Sr}$</u>
Melilite-nepheline basalt I	36.3	0.7030
Melilite-nepheline basalt II	37.2	0.7031
Nepheline basalt	38.6	0.7031
Basanitoid	43.1	0.7033
Alkali olivine basalt	46.5	0.7040
Hawaiite	48.0	0.7043
Tholeiite	51.9	0.7041
Trachyte	62.0	0.7043

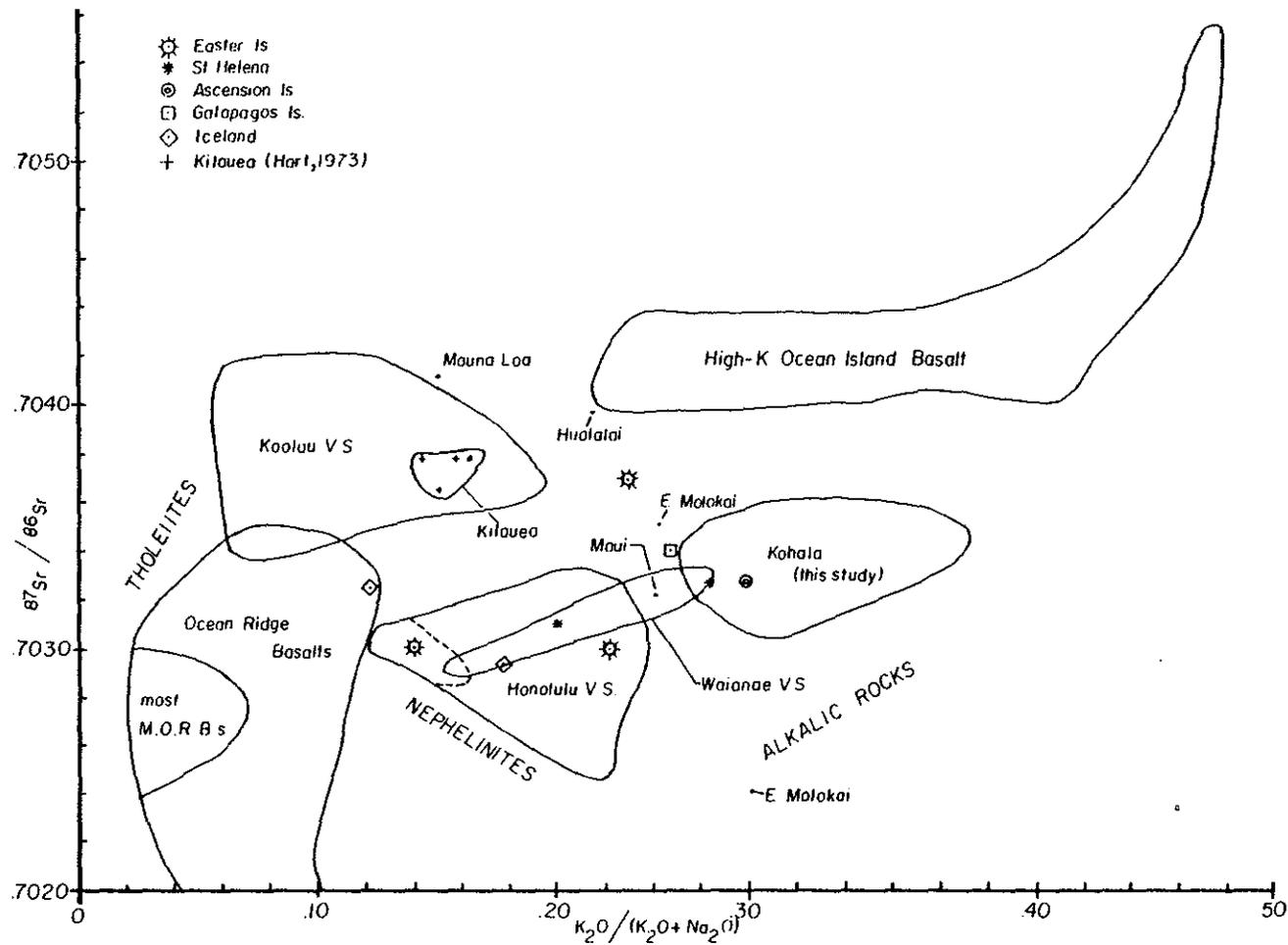


Fig. 12. $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\text{K}_2\text{O} + \text{Na}_2\text{O}$ diagram after Peterman and Hedge (1971). Field lines drawn by this author. Analyses of Kilauea from Hart (1973), East Molokai from Hlava (1974).

TABLE 7
 $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios of Hawi Volcanic Series

<u>Sample</u>	<u>Rock Type</u>	<u>$^{87}\text{Sr}/^{86}\text{Sr}$</u>	<u>2σ Error</u>	<u>Number of Ratios</u>	<u>Sr Conc., ppm</u>
1-1D	Mug.-Ben.	0.7036	± 0.0007	65	1616 \pm 8
1-1E	Mug.-Haw.	0.7034	± 0.0005	25	1601 \pm 2
		0.7034	± 0.0002	75	
2-1B	Mug.-Haw.	0.7031	± 0.0003	60	1577 \pm 2
3-2B	Mug.-Haw.	0.7031	± 0.0005	60	1582 \pm 3
6-3	Ben.-Tr.	0.7035	± 0.0006	60	
		0.7035	± 0.0008	70	
8-1 #2B	Hawaiite	0.7036	± 0.0006	80	870 \pm 1
11-2E	Hawaiite	0.7034	± 0.0003	70	1789 \pm 4
21-2B	Haw.-Mug.	0.7034	± 0.0003	70	
Pol. 16	Tholeiite	0.7038	± 0.0007	25	289 \pm 1
		0.7034	± 0.0008	45	
NBS Std.		0.7101	± 0.0013	45	
		0.7103	± 0.0015	50	
		0.7106	± 0.0003	40	
		0.7098	± 0.0010	35	
Average		0.7102	0.0010		

2-1B, 11-2E and 21-2B approach this value and can be considered to be of good quality. Replicate analyses of three samples, 1-1C, 6-3, Pol. 16, demonstrate significantly better precision; 0.00001, 0.000007, and 0.0003, respectively. As expected, the external precision was better than internal. Blank samples run toward the end of analyses showed no contributing Sr from external sources below 3.7 amps applied to the sample filament. All samples were run at under 3.7 amps.

The samples of the alkalic suite rocks studied show a limited range of 0.7031 to 0.7036. The average of two runs of the Pololu tholeiite is 0.7036. Sr isotope work by Feigenson et al. (1980) showed that alkalic and tholeiitic rocks from Kohala are similar, within error, and average 0.70359. Therefore, there is no apparent distinction between the tholeiite and alkalic suite samples in Sr isotope ratios. All values fall within the range of oceanic island basalts. As expected, the values are slightly higher than those reported for the nephelinitic suite of Oahu. The values are also much lower than those of earlier workers of the 1960's (Powell et al., 1965; Lessing and Catanzaro, 1963), but similar to more contemporary studies (Feigenson et al., 1980; Hlava, 1974; Hart, 1973). There is no correlation between Sr isotopes and geographic position (Figure 13) for Kohala.

Variation diagram plots for Kohala (Figures 14a-14c) show a lack of correlation for $^{87}\text{Sr}/^{86}\text{Sr}$ and MgO , SiO_2 and K_2O . Comparison of tholeiitic and alkalic rocks with isotope values on these same variation diagrams shows distinct separation between these rock fields due to differences in MgO and K_2O . Also, the nephelinitic suite rocks display a real separation from tholeiites and alkalic rocks by Sr isotopes,

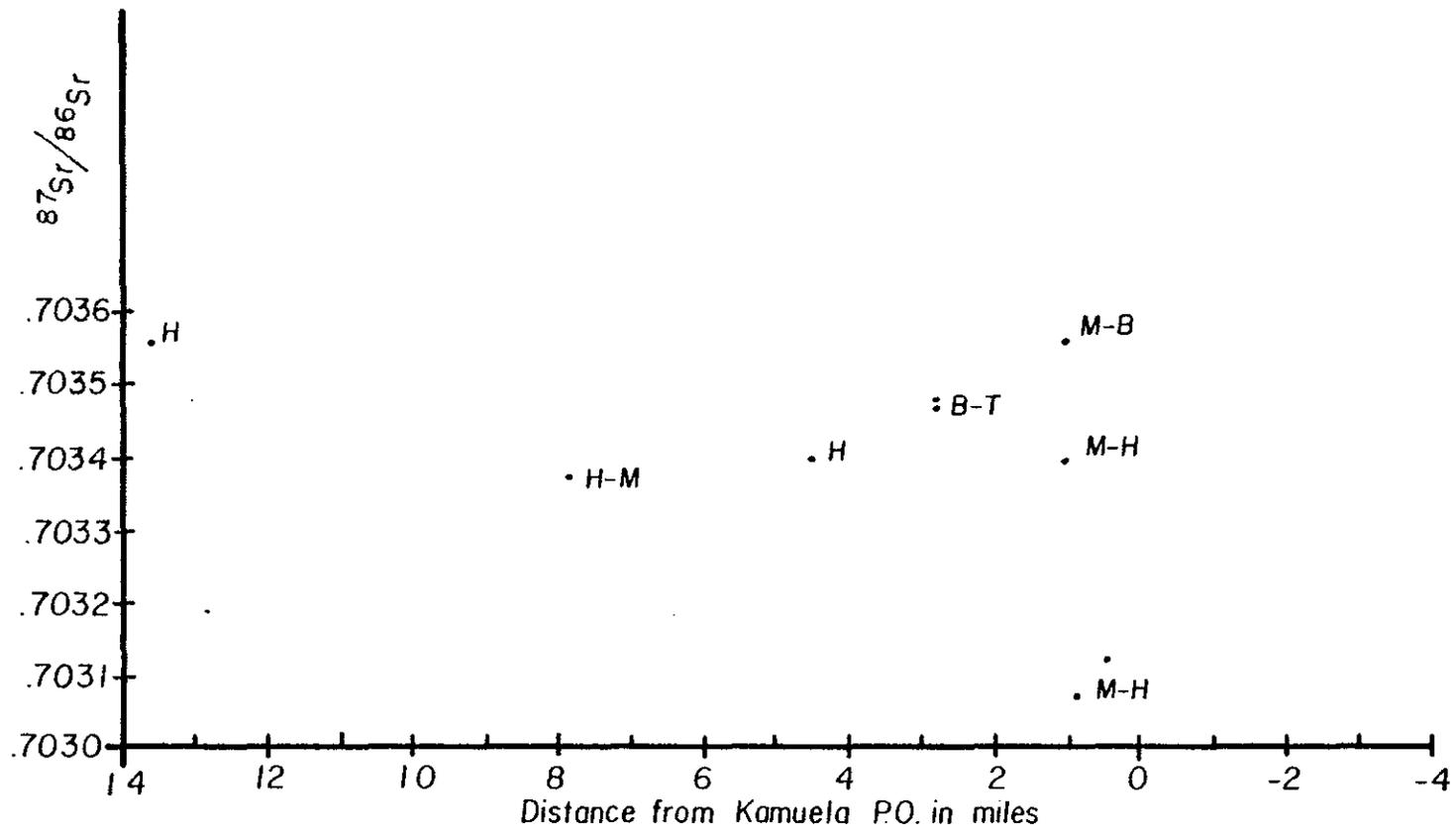


Fig. 13. Sr isotopes vs. geographic position on Kohala.

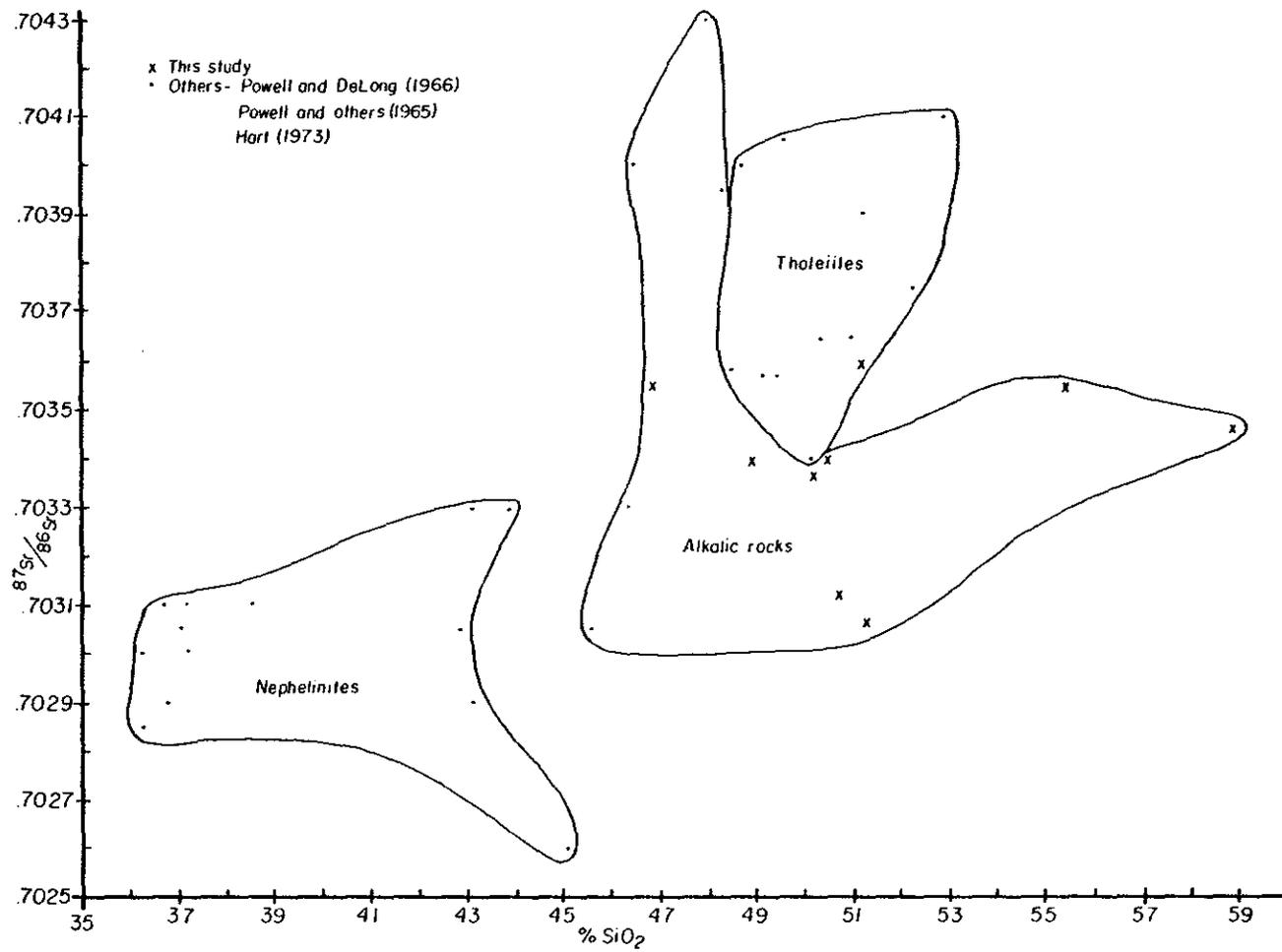


Fig. 14. Sr isotope variation diagrams. 14a. $^{87}\text{Sr}/^{86}\text{Sr}$ and SiO_2 .

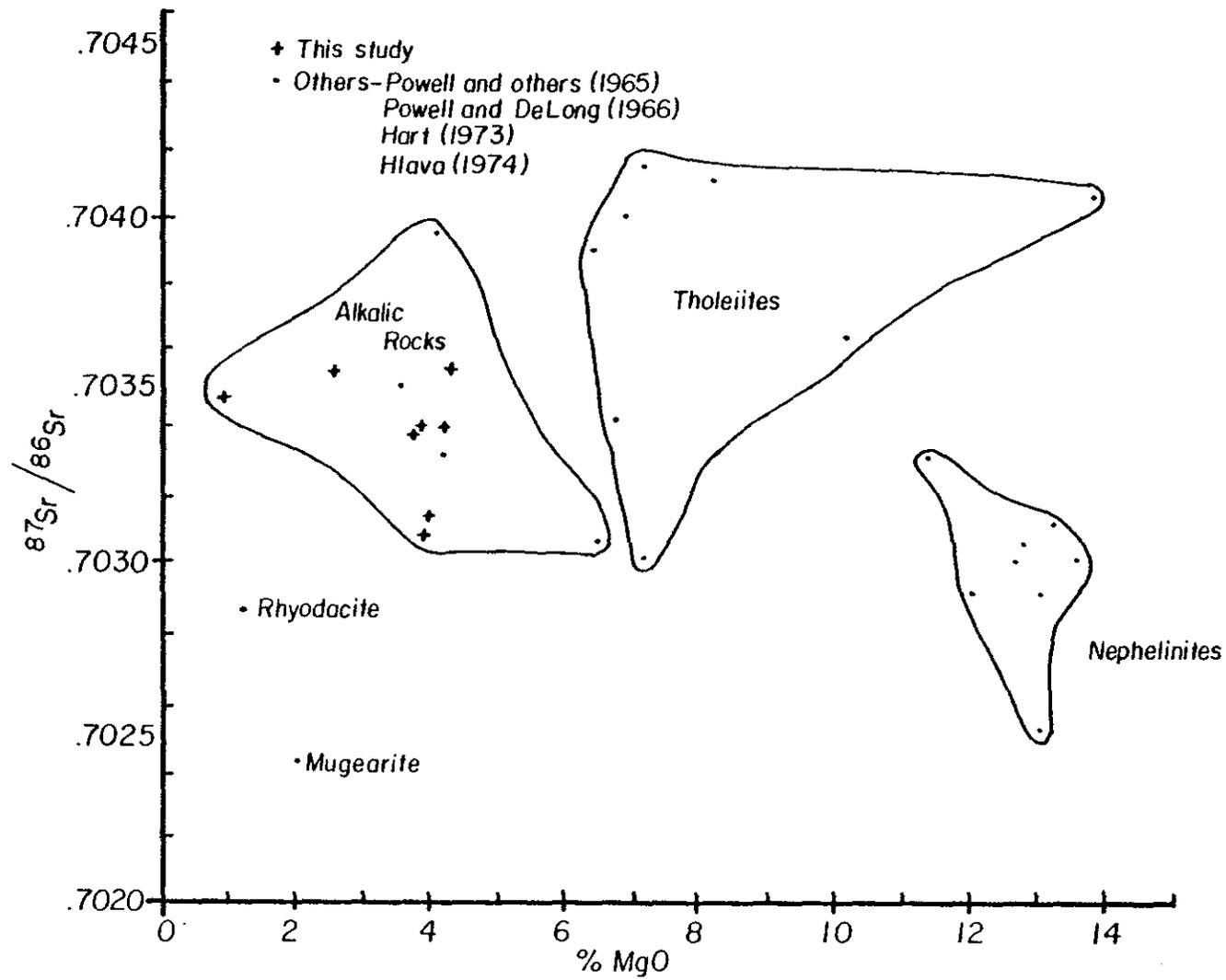


Fig. 14 b. $^{87}\text{Sr}/^{86}\text{Sr}$ and MgO.

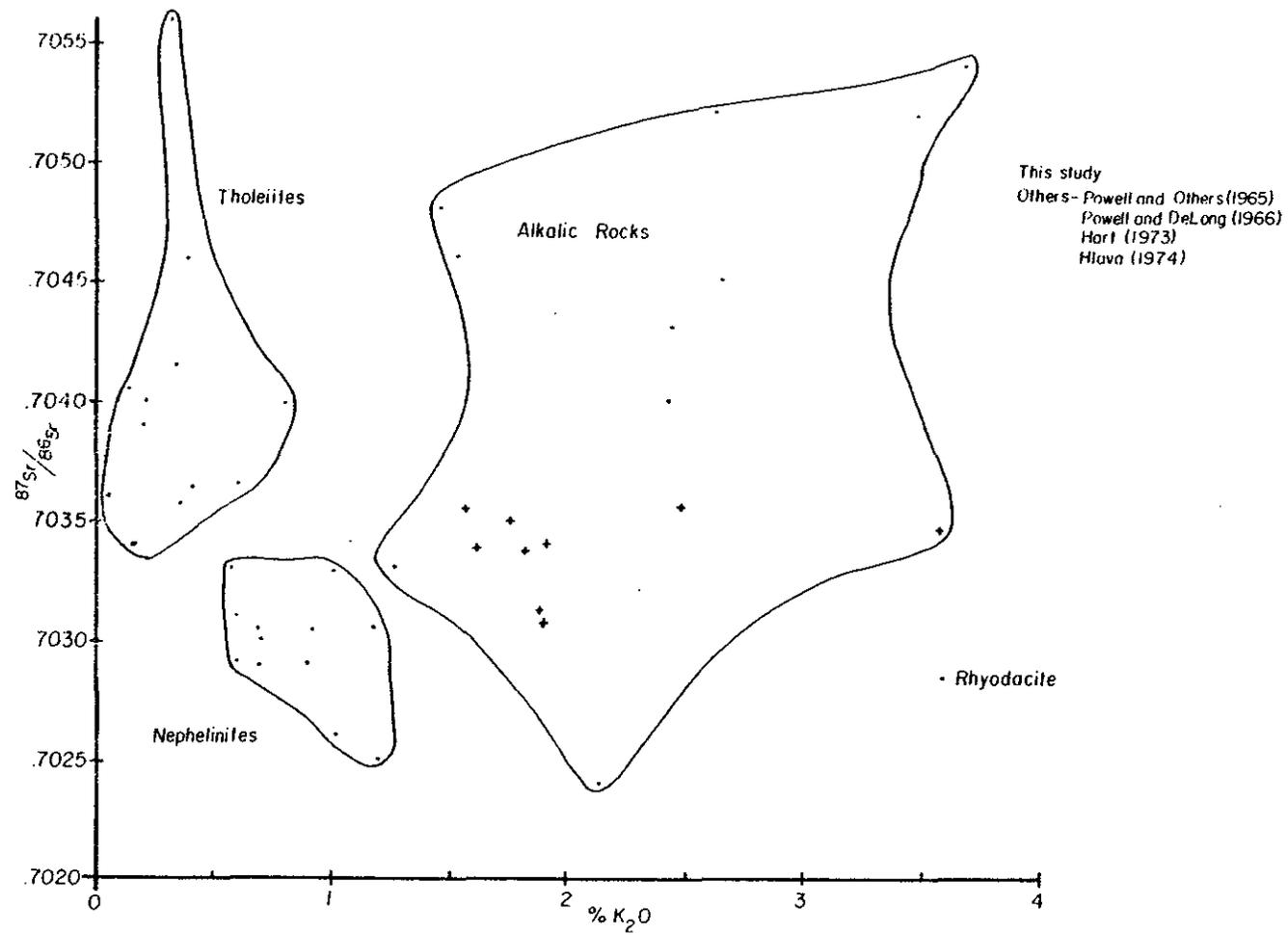


Fig. 14c. $^{87}\text{Sr}/^{86}\text{Sr}$ and K_2O .

MgO and K_2O . A plot of Sr isotopes and $K_2O/(K_2O + Na_2O)$ (Peterman and Hedge, 1971) (Figure 12) reveals there is good separation between ocean ridge basalts, high potassium island basalts and ocean island basalts. More pertinent to Hawaiian basalts is that there is a generally good separation between ocean island nephelinites and alkalic rocks from the ocean island tholeiites, as the tholeiites contain less alkalis and slightly higher $^{87}Sr/^{86}Sr$. There also appears to be a field separation between nephelinites and alkali (olivine) basalts and the evolved alkalic suite rocks. The more evolved alkalic rocks have greater $K_2O/(K_2O + Na_2O)$ and higher $^{87}Sr/^{86}Sr$.

Intra-Island Patterns - There appears to be little to no distinction for Sr isotopes between Kohala, Mauna Kea, Mauna Loa (Steve Josephs, 1978, personal communication) and Kilauea. Tholeiite and alkalic basalt (Kohala and Mauna Kea) range from low to mid 0.703X. The trachytes of Hualalai are much more radiogenic than any other lavas on Hawaii, and are not included in this discussion.

Powell and DeLong's (1966) study of Oahu volcanics showed that there are no $^{87}Sr/^{86}Sr$ variations within a volcanic series, despite compositional differences. The Waianae (tholeiite, alkalic basalt, hawaiite and rhyodacite) and Honolulu (only nephelinitic rocks) Volcanic Series have the same 0.703 ratios.

Inter-Island Patterns - A discussion of inter-island Sr isotope variance can only be tentative and subject to revision as more data become available. There is a general lack of consistency in the $^{87}Sr/^{86}Sr$ values for volcanic series within a given volcano studied by previous workers. Personal communications with J. Powell and G. Faure

suggest that their Sr values are obsolete. Values from Lessing and Catanzaro (1964) vary significantly and are higher than most. Exclusion of their data allows for slightly more consistency.

Figure 15 is a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ for each island of the Hawaiian chain where data are available. Comparison of Oahu, Molokai and Hawaii appears to indicate that there is a definite difference between Oahu and Molokai-Hawaii. It therefore appears that there is an inter-island, with little to no intra-island variation in $^{87}\text{Sr}/^{86}\text{Sr}$ for the Hawaiian Islands. This implies a regional variation in the Rb/Sr for the upper mantle beneath the Hawaiian Islands.

DISCUSSION

Variation Within the Hawaiian Volcanic Series

MgO-Variation Diagrams - In general, there is a rather coherent trend (except for Si, Al and, to a lesser extent, Fe) observable on the MgO-variation diagrams (Figures 8a-81). These trends suggest that rocks in this study are related by a "liquid line-of-descent" via the process of fractional crystallization. Similar trends are noticeable in other Hawaiian alkalic rocks. Therefore, the process producing these variations may be applicable to all Hawaiian alkalic rocks.

"Liquid line-of-descent" describes a parent-daughter chemical evolution of magmatic liquids. It is best defined from chemical analyses of non-porphyritic or phenocryst-poor lavas (Bowen, 1928). Besides geochemical coherence, one must take into account the time sequence of the erupted lavas as eruptions take place at random. Therefore, lavas from a certain volcanic series can represent either a specific event or a "series of overlapping lines-of-descent" (Cox et al., 1980).

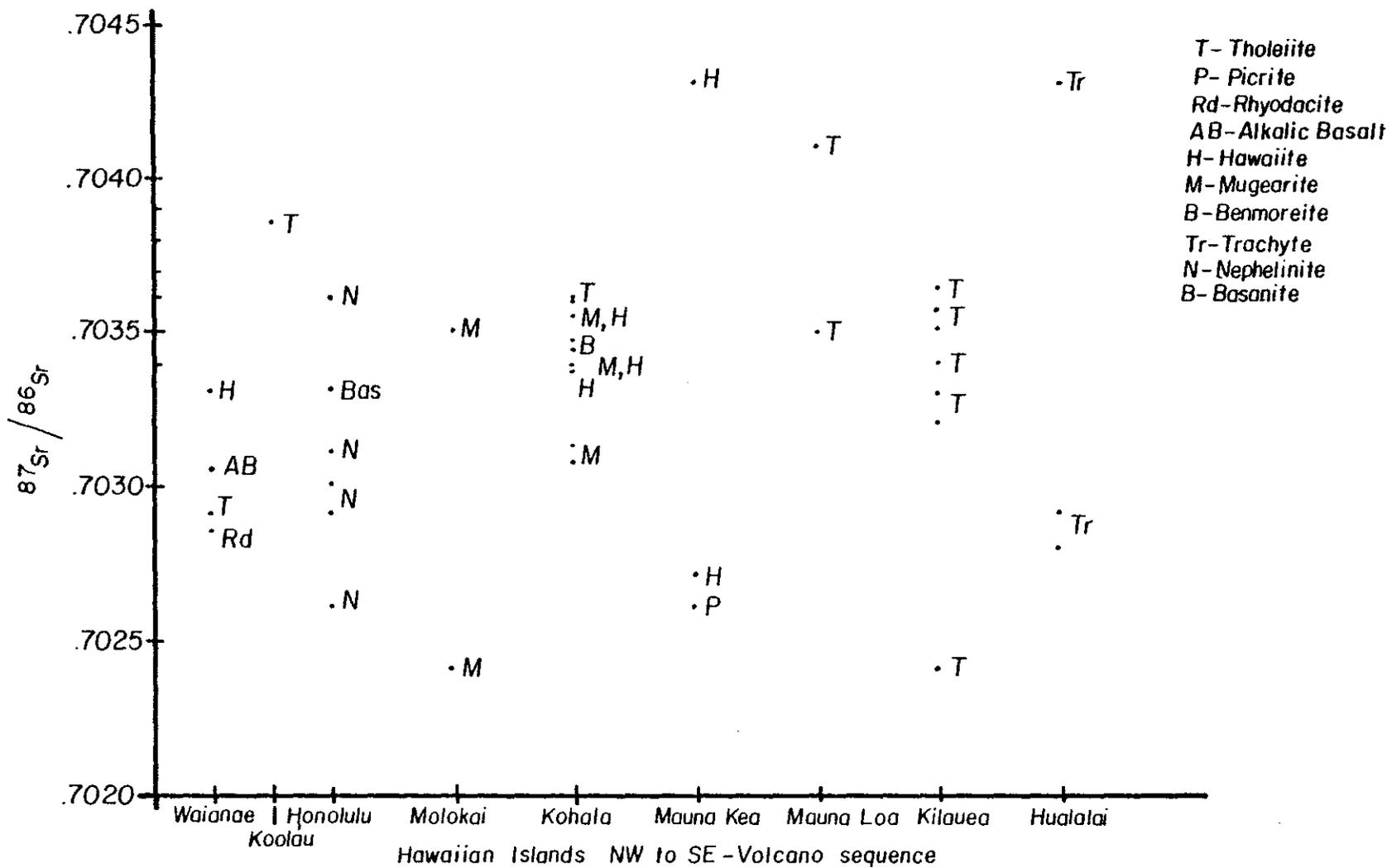


Fig. 15. Comparison of Sr isotope ratios for the various Hawaiian Islands. Data from Appendix VII and this study.

Lavas of this study were generally porphyritic, but microphenocrystic. Stratigraphic position was either very difficult to determine or obscured. Interpretation of these variation diagrams is therefore difficult. Of primary importance is the generally good coherence observable. The scatter seen in the Al, Si and Fe diagrams may be due to several processes: (1) differentiation is not consistently reproduced, (2) there could be incorporation of xenoliths or xenocrysts, possibly plagioclase (the high plagioclase content of Kohala alkalic rocks), or (3) selective tapping of a plagioclase-rich layer in a differentiated magma chamber. Second, the variations exhibited are typical of magmatic differentiation; i.e., increase in Si, Na, K, and decrease in Ti, Fe, Mg and Ca proceeding from hawaiiite to mugearite to benmoreite.

The result of this process is that batches of magma can be supplied to a high-level magma chamber where they can undergo crystal fractionation, the products of which can then be tapped from time to time. So, Hawi lavas can be related by overlapping lines-of-descent and magmatic differentiation.

Chemical Variation Based on Relative Stratigraphy - Comparison of cinder cone composition with relative stratigraphic position reveals some interesting trends. Referring to Figure 10, (a) there is a change in chemical composition with time, (b) mugearite composition appears to be a "mirror image" to that of hawaiiite for each period of time. The first trend can be generally described as becoming more silica and alkali deficient, with calcium, iron and magnesian enrichment of the lavas as the cones get younger. At both ends of the stratigraphic section here there are sharp inflection points where there is a change in

composition of the erupting magma. These inflection points may represent a time of injection of new magma into the rift system which supplies the cinder cones. The time in between the inflection points might represent the tapping of a zoned magma chamber, where more siliceous alkali-rich magmas are tapped off first, followed by increasingly more calcium, iron and magnesian-rich lavas (i.e., less siliceous and alkali-rich). The process might be analogous to that observed in resurgent silicic cauldrons of Long Valley, California (Hildreth, 1979) and the Jemez Mountain, New Mexico (Smith, 1979). The "mirror image" chemical trend observed for mugearite and hawaiite may be explained in a manner analogous to that of the "liquid line-of-descent" magma theory, where fractional removal of a hawaiite will cause a change in the bulk composition of the residual magma. Removal of, say, a silica and alkali depleted magma (hawaiite) from a differentiating magma chamber (or magma in a rift) will cause the residual magma to become slightly more enriched in these components (i.e., a mugearite).

Mineralogical Variation - There were several variations and trends observed in the mineralogy of the Hawi series. Most noticeable is the increase in plagioclase and its Ab content, with decreasing olivine, clinopyroxene and opaques from hawaiite to mugearite to benmoreite. There was also an increase in the corrosion, alteration and relict mineral structures with the more evolved members of the alkalic suite. The appearance of hydrous minerals (kaersutite and biotite) in the benmoreites indicates hydrous conditions usually associated with late-stage differentiation.

The result of this is that there appears to be a gradational

nature in the rocks of the alkalic suite that is suggestive of differentiation, but the evidence is not conclusive.

Origin and Source Area of Alkalic Rocks

A fundamental question concerns the relationship between alkalic and tholeiitic magmas and their origins. Two genetic models for the origin of alkalic basalt have received wide support. The first (and generally older hypothesis) is that alkalic rocks are derived from tholeiitic basalt by differentiation (Bowen, 1928; Macdonald, 1949; Tilley, 1950; Powers, 1955; Macdonald and Katsura, 1961, 1962, 1964; Lessing and Catanzaro, 1964; O'Hara, 1965; Engel et al., 1965; Green and Ringwood, 1967; Macdonald, 1968). The second theory is that alkalic rocks have their own line of descent due to very low(er) percentage of partial melting and derivation from greater depths within the earth than tholeiites; therefore they are also primary magmas (Kennedy, 1933; Kuno et al., 1957; Yoder and Tilley, 1962; Kushiro and Kuno, 1963; Powell et al., 1965; Hedge, 1966; Webber, 1966; Schilling and Winchester, 1966, 1967; Green, 1968, 1970; Hubbard, 1969; Kushiro, 1973; Kay and Gast, 1973; Sun and Hanson, 1975).

Differentiation from Tholeiite - Arguments in favor of the production of alkalic magma by differentiation from tholeiitic magma include: (1) intergradation of the two rock series in the field, (2) a slow increase in alkalies toward the end of the tholeiite eruptive cycle, (3) no difference in the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio between tholeiitic and alkalic rocks, (4) higher iron oxide ratio for alkalic rocks indicating a low-pressure environment of crystallization, (5) time-stratigraphic relationships where alkalic rocks are the cap rock on top of voluminous

tholeiite shields, (6) the relative smaller volume of alkalic rocks (~1-2%) relative to tholeiite (98%).

Macdonald (1968) makes a convincing case for derivation of alkalic rocks from tholeiite by crystal fractionation of large amounts of hypersthene. According to Macdonald, the Sr and Pb isotope data indicate a similar source for these rocks. He further argues that the original primitive olivine basalt at depth in the mantle is not the same as the tholeiite at the surface. With this in mind, the process is as follows: a magma chamber under a volcanic summit may be filled with fluid magma due to high eruptive rates. With cooling (from top down) due to a decrease in eruptive rate, an increase in pressure on the cooling magma will cause pyroxene precipitation instead of olivine, producing alkalic basalt.

Eaton and Murata (1960) suggest that with vigorous ascent of lavas, only slight cooling occurs, allowing olivine to crystallize. With a decline in volcanic activity, the magma may cool much slower, allowing pyroxene and olivine crystallization, thus desilicating the tholeiitic parent to produce alkalic basalt.

O'Hara (1965) says that all magmas change with ascent and do not reflect the original composition, thereby inferring that fractional crystallization at various depth (pressures) can yield magmas of wide compositional ranges.

Arguments against the differentiation hypothesis are numerous. First, these magma types produce completely different terminal differentiates, suggesting that parental composition and not cooling is the major control on the composition of the end products (Kennedy, 1933).

The differences in pyroxene composition also tends to argue against differentiation schemes. Fodor et al. (1975) found that pyroxenes from the alkalic suite from Maui tend to have generally higher Wo contents as well as their own unique and limited fractionation trend. In addition, alkalic basalts have only high Ca pyroxenes (augite), while tholeiites contain high and low Ca clinopyroxene plus orthopyroxene as phenocryst phases. These differences in pyroxene composition can cause changes in the resultant magma; i.e., a more Ca-rich augite in alkalic magmas causes alumina to bond with alkalies, producing alkali plagioclase with cooling, whereas, in a more Ca-poor augite of tholeiite, magma allows for calcium to bond with alumina in calcic plagioclase.

Arguments against differentiation based on chemical composition are that the desilication process of Eaton and Murata (1960) is contrary to the usual silica increase with differentiation. Gast (1968) says that the high amount of large ion elements in alkali basalt precludes its derivation from tholeiite. A good example of this is K_2O content—13 Kohala tholeiites average 0.13% K_2O , while alkalic basalt from Kohala average about 1% K_2O (Macdonald and Katsura, 1964), increasing up to greater than 3.5% K_2O in the benmoreite-trachytes. One would normally expect the "low-K signature" of the Pololu rocks to show up in the Hawi rocks if these are related by differentiation; it does not. Macdonald (1968) admits that incompatible trace-element chemistry presents a problem in his theory as alkalic basalts have much higher amounts. He calls upon wall-rock reaction of alkalic basalts to pick up excess trace elements.

The argument of the interfingering field relationships can be

explained two ways. Alkalic basalts could invade a tholeiitic magma chamber forcing the tholeiite out of the volcano to be followed by an alkalic eruption. Or, there could be a momentary up and down migration of a zone of fusion in the mantle, tapping alkalic and tholeiitic source areas, as suggested by McBirney (1967).

Finally, high- and low-pressure experimental studies preclude the production of alkalic basalt from tholeiite by differentiation at low pressure. Yoder and Tilley (1962) first demonstrated that a low-pressure thermal barrier prevents production of alkalic basalt (ne-normative) from tholeiite (hyp-normative). Fractionation of tholeiite at low pressure, instead, produces quartz-normative residual liquids. At high pressure, the thermal barrier becomes unstable, thus allowing tholeiite to produce nepheline-normative magmas. So, a similar source area at high pressure may be the explanation for tholeiite and alkali basalt origins. Another high-pressure experiment that had profound effects on ideas concerning basalt genesis was that of Green and Ringwood (1967). In it they propose the production of alkali basalts from the fractionation of clino- and ortho-pyroxene from an olivine basalt. Thus, olivine is not a liquidous phase at intermediate pressure because they say it is already saturated in the liquid. The problem here is that the original material used in the experiment was an olivine-rich picrite.

Plots of tholeiite and alkali olivine basalt on a $MgO-SiO_2$ diagram (Figure 16) show no simple relationship to single mineral fractionation. Olivine fractionation plus clinopyroxene and plagioclase in combination may produce alkali olivine basalt from tholeiite (or other common

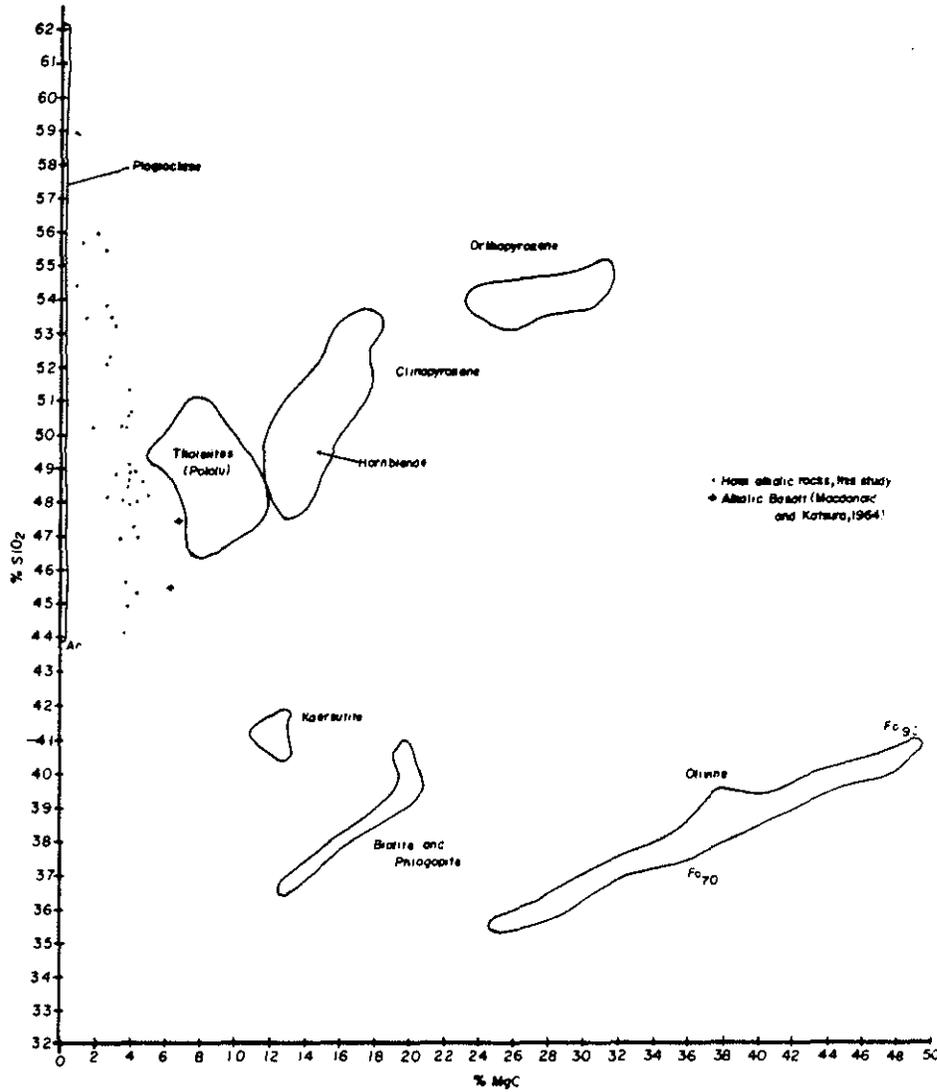


Fig. 16. MgO-SiO₂ diagram for tholeiite and alkalic rocks with mineral compositions. Mineral analyses from Fodor et al. (1977, olivine), Sibray (1977, olivine, clinopyroxene, plagioclase and kaersutite), Beeson (1976, olivine, clinopyroxene, plagioclase), Fodor et al. (1975, pyroxene), Hlava (1974, olivine, clinopyroxene and plagioclase), Green et al. (1974, kaersutite), Keil and Fodor (1972, plagioclase), Wright (1971, olivine).

parental material) at low pressure. It should also be kept in mind that the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope data suggests either that tholeiite is parental to alkalic basalt or that they have a similar source area.

Primary Alkalic Basalt Magma and its Relationship to Tholeiite -

Various degrees of partial melting of the upper mantle is the alternative theory to differentiation of a tholeiitic magma to produce alkalic magma. Partial melting is the melting of some portion of solid material with equilibration between the interstitial melt and the entire residual solid (Schilling and Winchester, 1967). Two other processes are at work when melting occurs; fractional and zone melting. Fractional melting is successive partial meltings with subsequent removal of the melt each time. Zone melting is the vertical movement upward of a small zone of molten material by progressive melting above and freezing below. These processes at work in a vertically and horizontally heterogeneous mantle can produce the chemical differences between tholeiite and alkalic basalts, as well as lithologic interfingering, Sr isotopes and stratigraphic relationships. More importantly, they can provide for a separate origin for alkalic magmas distinct from tholeiite.

Kennedy (1933) provided some criteria for definition of "primary magmas". These are a worldwide distribution, uniform composition and great aggregate bulk. Kennedy (1933) and the more recent work of Schwarzer and Rogers (1974) confirm that alkalic basalts fit all of the criteria.

The early high-pressure experimental petrology works of Yoder and Tilley (1962), Kushiro and Kuno (1963), Green and Ringwood (1964, 1967), and Green (1968, 1970) set the precedence for the theory of the

production of alkalic magmas by different degrees of partial melting and different depths of melting within the earth's mantle. They found that greater pressure and lower partial melts produced magmas that were silica undersaturated. These early studies and more recent studies of trace- and rare-earth-element partition coefficients (Schilling and Winchester, 1966, 1969; Gast, 1968; Hubbard, 1969; Green, 1970; Kay and Gast, 1973; Sun and Hanson, 1975), place the range of degree of partial melts for basalt production as:

tholeiitic	20-30%
alkalic	3-15%
nephelinitic	1-7%

The switch from tholeiite to alkalic basalt has been discussed by several authors. Kay and Gast (1973) suggest that the thickening of the lithosphere due to depletion of mantle material from below allows for only lower percentages of melting to occur in the next batch of rising magma (i.e., greater overpressure). McBirney (1967) says that basalt type is dependent on the heat flow in the region of melting, where the more siliceous magmas are produced in areas of greater heat flow (the result is more partial melting) as in the tholeiites. The changeover to alkalic basalt reflects a downward migration of the zone of fusion. This migration is a natural consequence of the process of progressive heating and partial melting of the mantle. Initial melting will occur when the thermal gradient intersects the liquidus of mantle rocks at a depth determined by local thermal regimes. Since the rate of conductivity of rocks decreases with increasing temperature (until magmatic temperatures), heat transfer to a melted upper zone will be

impeded by the lower conductivity of partially melted rocks. The result is a transient instability and self-acceleration of magma generation (McBirney, 1967). Prolonged magmatic activity normally results in tapping of progressively deeper levels.

A question then arises, just what is it that controls the chemistry of a basaltic magma? Is it the degree of partial melt, or is it the depth or pressure of the source area, and what part does the composition of the source area play? Gast (1968) suggests that the extent of partial melting influences the composition and amounts of trace elements. To get alkalic basalts with greater Sr and a more extensive light-rare-earth fractionation than tholeiite, the degree of partial melting must be less than that of tholeiite. Hubbard (1969, 1967) says that concentrations of Al_2O_3 , TiO_2 and Zr appear dependent on the depth of magma segregation, thus higher amounts of TiO_2 , Al_2O_3 and Zr indicate magma generation at greater pressure (depth). MacGregor (1965) found that TiO_2 content may reflect the depth to partial melting. The higher the TiO_2 content, the greater the depth to melt. Green and Ringwood (1967) say that Al_2O_3 concentration is indicative of the depth where equilibration and partial melting takes place. The positive correlation between TiO_2 and Al_2O_3 (Hubbard, 1969) is applied to Kohala basalts in Figure 17 and shows a good separation of alkalic from tholeiite lavas, with greater concentrations of Al_2O_3 in the alkalic suite, thereby indicating a deeper source for the alkalic suite parent.

So, alkalic basalt can be produced from greater depths in the upper mantle and at smaller degrees of partial melting than for tholeiite. The next problem is that of the source area composition.

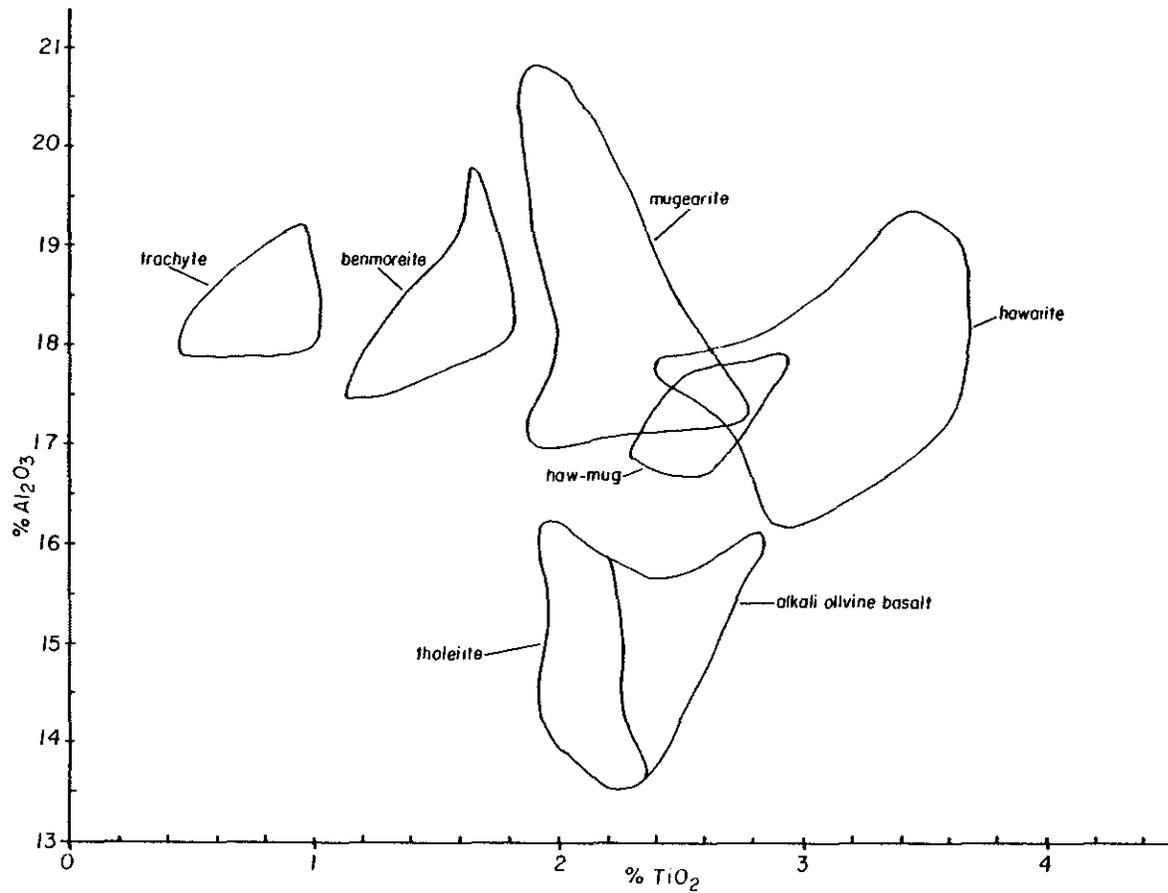


Fig. 17. TiO_2 vs. Al_2O_3 diagram as an indicator of depth of origin of basaltic rock types for Kohalan basalts. Data from this study, Sibray (1977), Malinowski (1977), Macdonald (1968), and Macdonald and Katsura (1964).

Yoder and Tilley (1962) agree that alkalic basalts are generated at greater depths than tholeiite, but both come from the same source rock. Thus, varying degrees of partial melting due to physicochemical conditions produce the differences in composition. Peterman and Hedge (1971) suggest that it is the chemical heterogeneity in the upper mantle that exerts influence on the composition of magmas derived therefrom. They point to a positive correlation of $K_2O/(K_2O + Na_2O)$ with $^{87}Sr/^{86}Sr$ for all ocean basalts. In this case then, there is a vertically zoned upper mantle and, due to the depth of generation, only certain amounts of partial melting can occur, thus limiting the composition of the magma.

The chemical and mineralogical differences displayed by various ultramafic inclusions and their host basalt would tend to agree with the preceding. In Hawaii, tholeiites principally contain dunite xenoliths, alkalic basalts have predominantly dunites and wehrlites, while nephelinites carry wehrlite and lherzolite (White, 1966; Jackson, 1968). This suggests that the mantle beneath the Islands is heterogeneous with depth. Due to the different pressure and temperature requirements for the production of each of these types of inclusions, one can infer that the xenoliths carried by host basalts place a limit on the depth of generation of each magma type (Jackson, 1968). The alkalic and nephelinitic magmas then appear to be derived from greater depths than tholeiite.

Relation of Hawaiite-Benmoreitic Suite Rocks to Alkalic Basalt -
Previous studies (Kennedy, 1933; Powers, 1935; Kuno et al. 1957; Macdonald and Katsura, 1964; Macdonald, 1968) suggest that Hawaiian

alkalic basalt is the parent basalt for the differentiated alkalic suite. Unfortunately, thus far, sampling of Kohala Volcano has not yielded a true alkalic basalt, although transitional calcic hawaiites or alkalic basalt-hawaiites and tholeiite-alkalic basalt samples are found. The tholeiite-alkalic basalt samples of Macdonald and Katsura (1964) were located from the upper sections of the Pololu V.S. beneath the erosional unconformity separating Pololu from Hawi rocks, and could represent a possible parent. Therefore, until a true alkalic basalt is found on Kohala, discussion of the relation between the evolved Hawi volcanic series with alkalic basalt is tentative. In any event, since the Hawi hawaiites appear to have lower SiO_2 (44-46%) than "normal" alkalic basalt (46.5%-Hualalai), it is difficult to envision their being derived by fractionation of an alkali olivine basalt. MgO-variation diagrams further suggest that the alkali basalt to hawaiite fractionation trend is controlled mainly by clinopyroxene removal. Unfortunately, this mineral is not on the liquidus at low pressure (Tilley et al., 1965). So some other parent with less SiO_2 than Hualalai, or a separate magma batch seems necessary. Also, most hawaiites have olivine plus plagioclase phenocryst assemblages (Appendix III), whereas alkali basalts tend to have a lot of olivine.

Therefore, the lack of a true alkali basalt on Kohala, lower SiO_2 content of hawaiite compared to alkali basalt, phenocryst mineralogy and MgO-variation diagram trends could suggest a different origin for the Kohala hawaiite-benmoreite suite, not related to alkali basalt.

Crystal Fractionation Models - The trends observable in the MgO-variation diagrams can represent the crystallization and subsequent

removal of mineral phases by the process known as "fractional crystallization". This process causes profound changes on the composition of the resultant magma (i.e., "parent" to "daughter" magma). It is possible to graphically portray such a relationship on variation diagrams, "mixing relationships".

In principle, as fractional crystallization proceeds, variation trends become distinguishable. The variation trend of the daughter magma can extrapolate through the parent magma to the mineral phase(s) being crystallized. This extrapolation line is called a "mineral control line" (Wright and Fiske, 1971; Wright, 1971). Difficulties can be encountered where there is solid solution in the crystallizing phase(s), as well as in multiple phase crystallization. Therefore, graphical analysis is limited, semi-qualitative at most. Computer programs (Wright and Doherty, 1970) can be used to calculate various percentages of mineral phase(s), accumulation, and daughter magma composition with more accuracy and speed.

For purposes of this study, it is sufficient to identify possible minerals that are controlling the chemical variation of hawaiiite to mugearite to benmoreite and trachyte. Figures 18a to 18e show some of the more positive relationships, Appendix VIII, the nonconclusive. Conclusions based on these graphs are qualitative. It appears that olivine precipitation controls the elements Si, Fe and Mg; clinopyroxene—Al, Ca and Na; plagioclase—K and Na; kaersutite—Si, Al, Ca, K and Na. Other minerals that control chemistry of daughter magmas, but are not graphically represented here are magnetite—Fe and Ti; apatite—P. Unfortunately, no analyses are available for potassium feldspar,

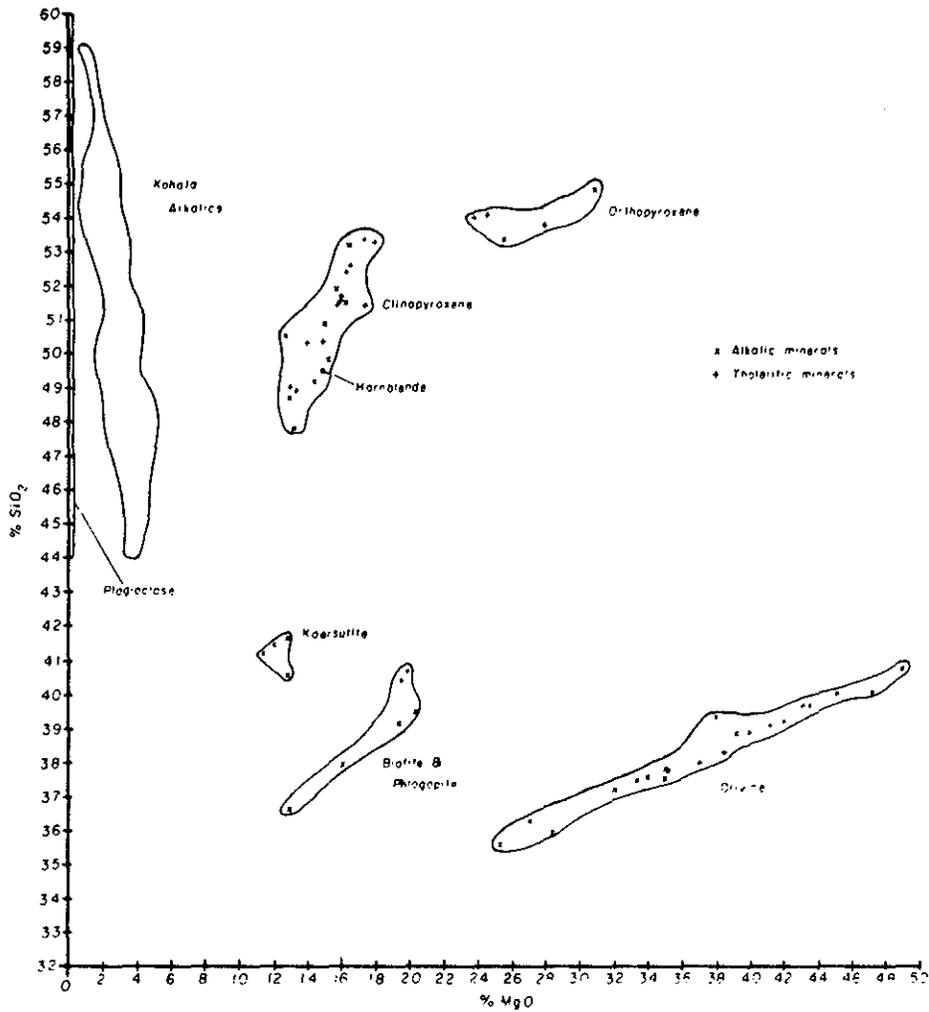


Fig. 18. Crystal fractionation diagrams for Hawi rocks of this study. Mineral analyses from Fodor et al. (1975, 1977), Sibray (1977) and Keil and Fodor (1972). 18a. Silica-magnesia.

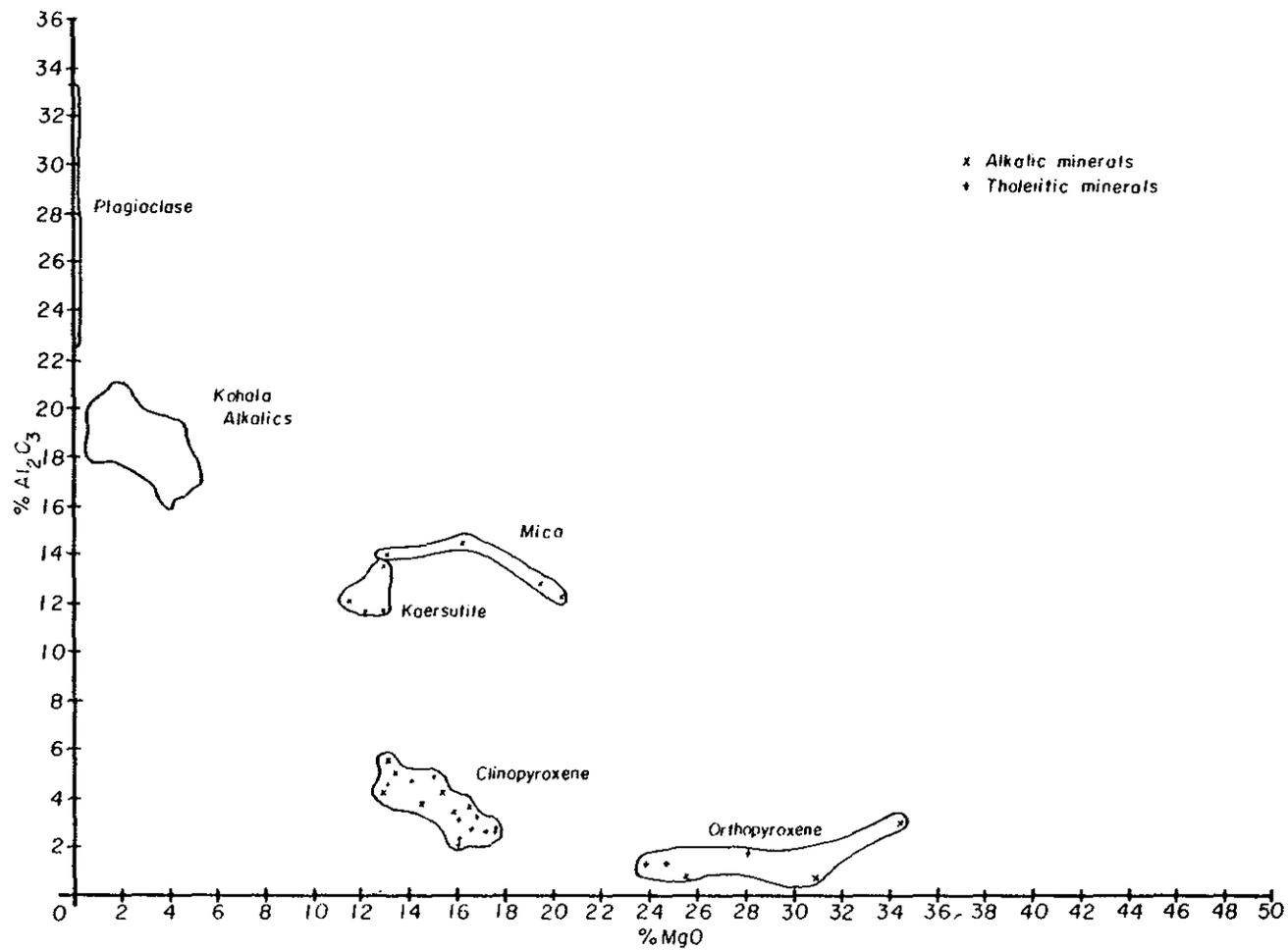


Fig. 18b. Alumina vs. magnesia.

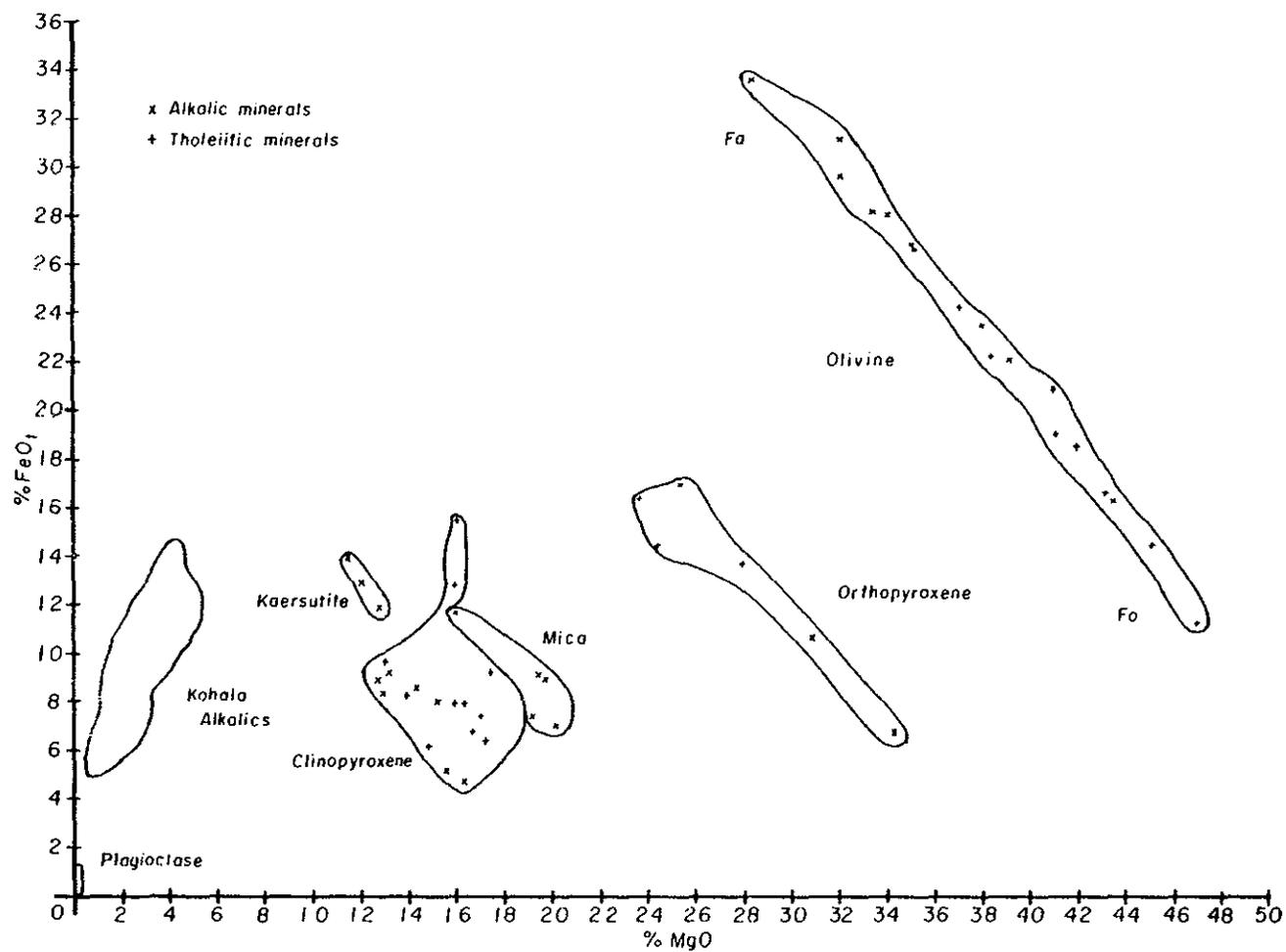


Fig. 18c. Iron vs. magnesia.

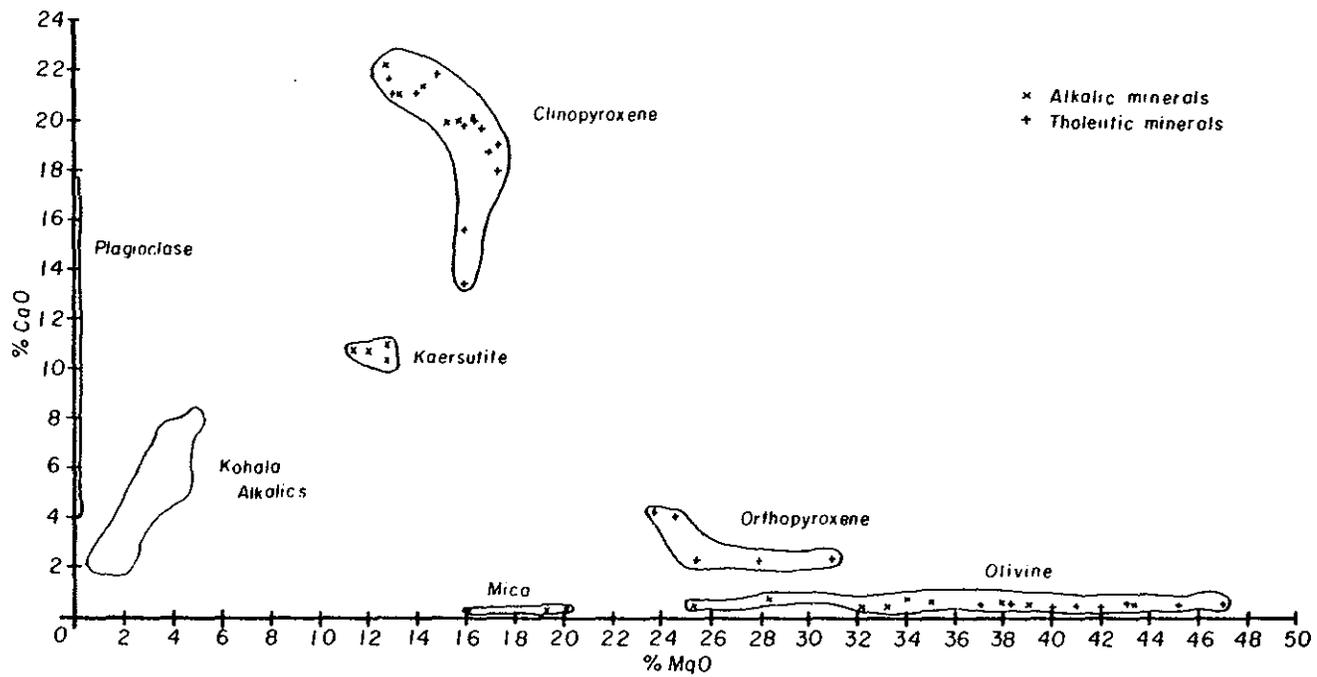


Fig. 18d. Lime vs. magnesia.

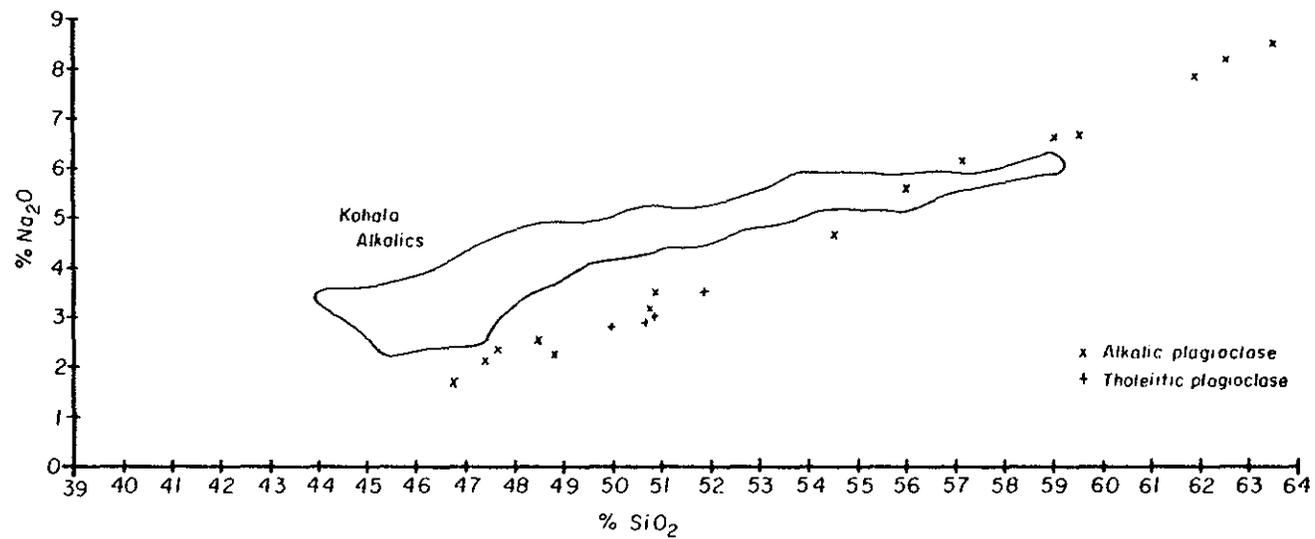


Fig. 18e. Soda vs. silica.

which should play a role in alumina and potash.

In summary, it appears that clinopyroxene precipitation is a major phase controlling alkali basalt suite chemical variation. Clinopyroxene alone does not explain all variation, but in combination with other minerals, such as olivine, plagioclase, kaersutite, magnetite and apatite, most variation is covered.

There appears to be some conflict between the crystal fractionation model and petrography. The fractionation model suggests that clinopyroxene (cpx) should be a liquidus phase. Petrography indicates that clinopyroxene is not a phenocryst phase (except in Sample KV 21-2A, a benmoreite), but is confined to the groundmass. Olivine, plagioclase and some magnetite are the major phenocryst phases. Experimental petrology studies by Tilley et al. (1965) show that cpx is not a liquidus phase. Their work on the feldspar-phyric Kohala sample, "X" (a hawaiite?) shows that plagioclase is the first liquidus phase at 1187°C, followed by cpx at 1170°C, and olivine at 1135°C. This, too, tends to still conflict with observed petrography and textural evidence. An explanation is offered by Tilley et al. (1965); it is that plagioclase may be xenocrystic and that it was incorporated into a magma that already contained olivine phenocrysts. Microprobe studies by Malinowski (1977) and Sibray (1977) indicate that there are two distinct plagioclase phenocryst phases in Kohala alkalis. The rounding, core reabsorption, wide range in plagioclase phenocryst composition and rather high content of plagioclase in Kohala rocks observed in this study appears to confirm this idea of xenocrystic plagioclase. This obviously complicates any simple fractionation modeling. The

multi-stage modeling necessary to solve this problem is beyond the scope of this study.

Contamination - The possibility of contamination of Hawaiian volcanics was first suggested by Daly (1944). He proposed that alkalic and nephelinitic lavas were formed by assimilation of carbonates in a primary basaltic magma. Later, Lessing and Catanzaro (1963, 1964), believed that trachytes were formed by assimilation of marine sediments, resulting in rather high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Lessing and Catanzaro further suggested that trachytes with their low K/Rb (due to rather high K_2O , greater than 2%) would be more likely affected by Rb-rich marine sediments, thereby causing a decrease in K/Rb with increasing $^{87}\text{Sr}/^{86}\text{Sr}$.

Samples analyzed as part of this study do not support the contamination theory. First, Sr isotope values are rather low (less than 0.7035) and are rather tightly grouped, thus precluding the possibility of Rb-rich sediment contamination. Second, major-element trends do not show scatter, especially in the more differentiated lavas, as would be expected if contamination were present. Lessing and Catanzaro (1964) suggest that inverse relationships for K_2O and K/Rb and also for K/Rb with $^{87}\text{Sr}/^{86}\text{Sr}$ can indicate contamination. Figure 19 shows that high-K lavas do not necessarily have lower K/Rb ratios. Figure 20 does, though, confirm an inverse relation for K/Rb with Sr isotope ratios. This, though, does not have to indicate contamination by marine sediments, as marine sediments in the vicinity of Hawaii are basaltic (mostly tholeiite) in composition and would have low Rb. Assimilation of these sediments would result by increasing K/Rb and lowering

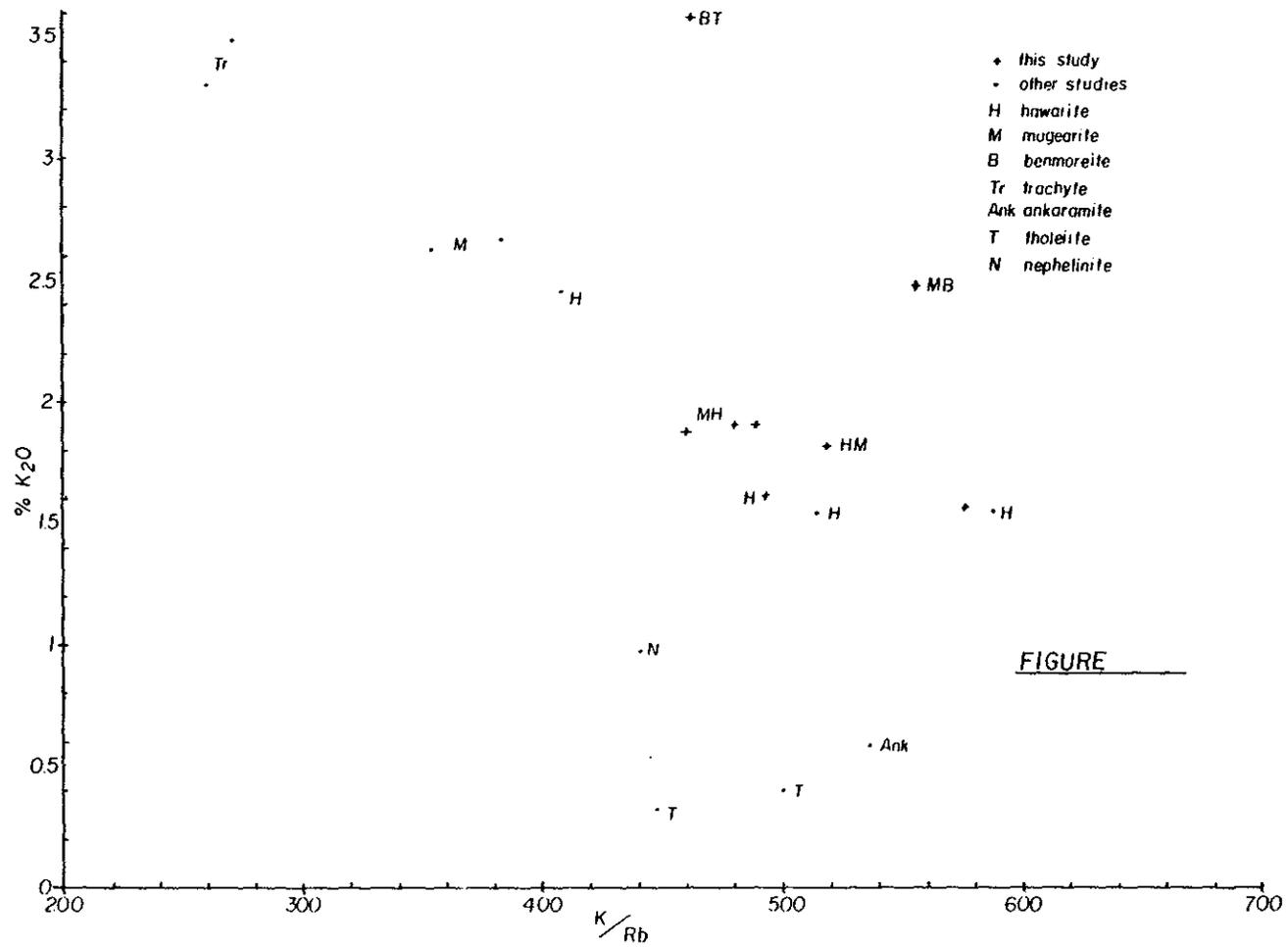


Fig. 19. K₂O vs. K/Rb diagram.

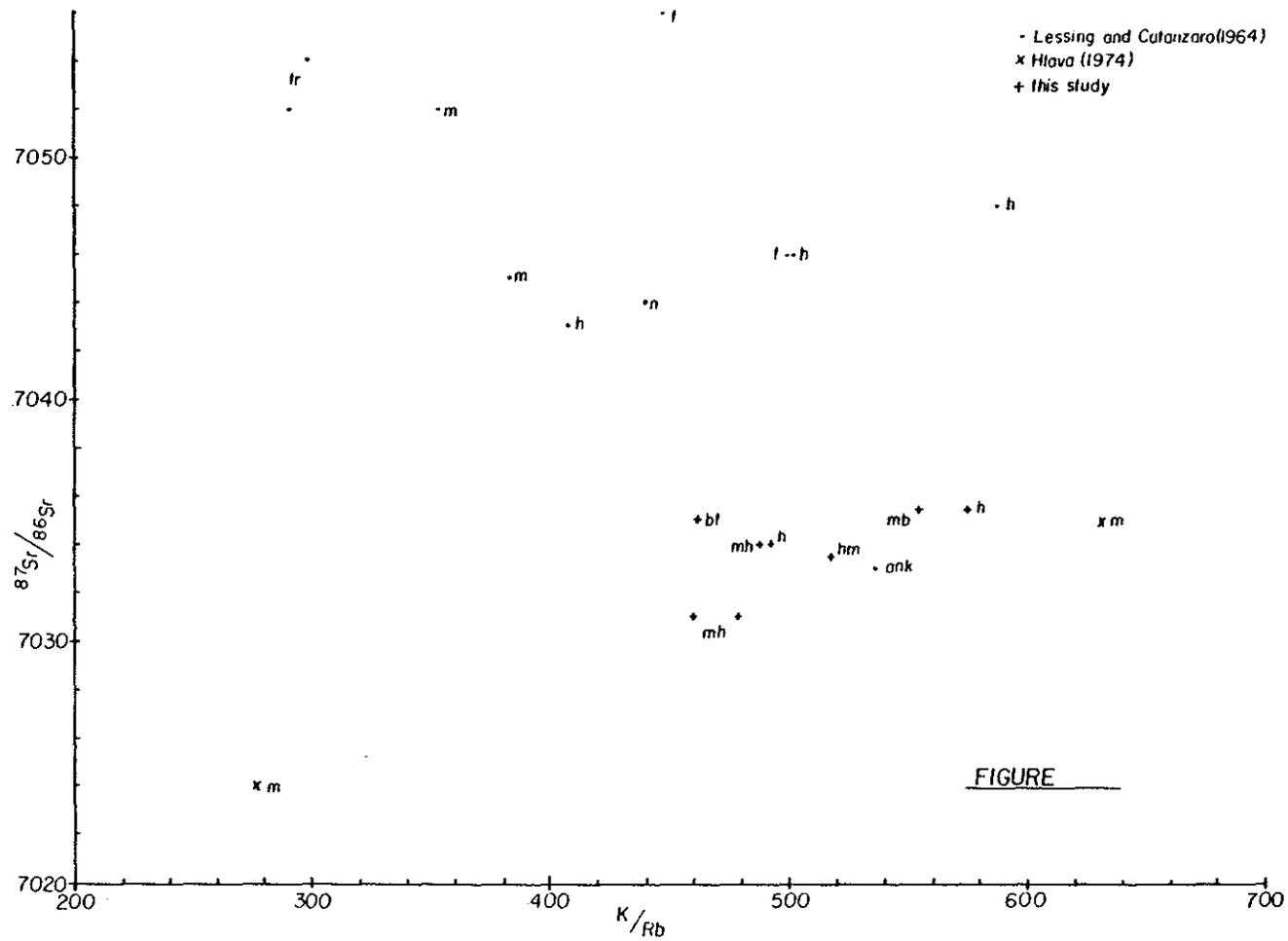


Fig. 20. K/Rb vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagram.

$^{87}\text{Sr}/^{86}\text{Sr}$ (Hamilton, 1965). Gast et al. (1964) also found unusually high $^{87}\text{Sr}/^{86}\text{Sr}$ in trachytes from Ascension Island, and suggest that trachytes could be the result of early melt fractions of a mantle that contains mineral phases high in Rb-Sr.

Other arguments against contamination are that there is no known source of highly radiogenic Sr in the ocean basins to cause high $^{87}\text{Sr}/^{86}\text{Sr}$ values (Hedge, 1966; Gast et al., 1964). Assimilation of sea water ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7081$, Hedge and Walthall, 1963), carbonates (0.7088, Powell and DeLong, 1966), or low-silica sediments on the order of 10-20% (quite substantial) would raise the $^{87}\text{Sr}/^{86}\text{Sr}$ of basalt by only 0.002 (Hedge, 1966; Gast et al., 1964). This does not appear to fit the rather uniform composition of Hawaiian basalts. Finally, Powell and DeLong (1966) believe a better measure of contamination is a correlation between silica content and $^{87}\text{Sr}/^{86}\text{Sr}$. Figure 14a shows that there is no such correlation, but in fact scatter, thus further eliminating any possibility of contamination.

Therefore, it appears that the Sr isotope study, variation diagrams and previous work precludes the possibility of contamination of Kohalan alkalic lavas. One must keep in mind, though, the preceding section's discussion of xenocrystic plagioclase, which could have an affect on these lavas.

Origins and Sources-Conclusions - The experimental petrology studies on partial melts and fractionation of the resultant magmas, migration and depth of the zone of melting theory, differences in ultramafic inclusion composition, significant differences in major element (trace and rare earth elements) data as well as the arguments

against the "differentiation model" leads this author to favor a model of decreasing partial melts of chemically heterogeneous upper mantle material at increasing depth to produce respectively tholeiite, alkalic, and nephelinitic parental magmas. Parental magmas in this case meaning magma that has produced other magma compositions by fractional crystallization (Presnall, 1979).

Cooling of the parental magma causes precipitation of olivine, clinopyroxene, plagioclase, etc.. For the alkalic suite, this fractionation appears to have occurred in a low-pressure environment as water reaction and high iron oxidation are evident in the more evolved members. Tapping of the magma chamber(s) at various times gives rise to lavas of varying composition.

The source region for alkalic basalts is probably the "low velocity zone" of the upper mantle. The low degree of partial melting needed for magma would fit the physical conditions of a "plastic layer" where water would be available for easy melting. This water would appear to come from hydrous minerals such as amphibole (and possibly phlogopite).

Lastly, whether or not the parental magma for the alkalic suite is an alkali olivine basalt, alkali basalt or ankaramite in nature remains to be seen, as there has yet to be found any of these rocks on Kohala. The closest has been some rather calcic hawaiites (or AOB-hawaiite transition rocks).

CONCLUSIONS

1. The major conclusion to be made as a result of this study is that the Hawi Volcanic Series rocks represent a series of overlapping

liquid lines of descent via the process of fractional crystallization. Positive trends in the presence of certain mineral phases, associated corrosion and alteration features, plagioclase composition, major-element chemistry, as well as the narrow range of the Sr isotopes, strongly support a differentiation model. There is, though, the problem of the identification of the "true" parental magma for the daughter Hawi rocks. Until a "true" alkalic basalt is found, it is possible that the hawaiite-mugearite-benmoreite trend is a rather unique series of rocks.

2. Chemical composition of individual cinder cones has revealed that there are compositional differences observable along Kohalan rift zones (analogous to that of Kilauea). One group of cones lies along a NW-SE lineament and is generally more enriched in CaO and TiO_2 and poorer in silica and alkalis (than the second group). A second group lies along an E-W trend and is enriched in SiO_2 and alkalis, and TiO_2 ; CaO-poor. Overlap in chemical fields for MgO, Al_2O_3 , FeO_T and P_2O_5 limit any real statement about this condition, but this might indicate separate magma chambers. Cinder cones are the sites of multiple or singular chemistry (or lava composition), possibly reflecting eruption of certain "magma batches". Lastly, the general decrease in the silica and alkalis with generally increasing FeO_T , CaO and MgO (with minor fluctuations) as the cinder cones get younger, may reflect the eruption of a vast differentiated magma chamber beneath Kohala. Inflections of chemical trends may represent re-injection of new magma into the volcanic plumbing system, which later differentiates and is then tapped from time to time.

3. Comparison of the Hawi Series with other alkalic Hawaiian volcanics reveals substantial similarities, though certain differences exist. Hawi rocks are basically more enriched in phosphorus, calcium and alumina, while being generally poorer in MgO, K₂O and Rb. These differences can be seen in the mineralogy where Kohala has very high amounts of plagioclase and apatite, while having low clinopyroxene and olivine.

4. Results of the Sr isotope tracer study indicate that each island has a relatively uniform ratio, and that differences appear to exist on an inter-island scale (more data needed for other islands). This reflects a variation in the mantle source along the Hawaiian Archipelago, thus further confirming the model of mantle heterogeneity.

The isotope study also indicated that the Hawi rocks (and possibly the Pololu rocks) were not affected by contamination of the basalts with limestones, or siliceous sediments.

5. The similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and unique low-K and Rb, as well as similarly high Al, chemistry exhibited by both Kohala tholeiites and alkalic rocks indicates either a similar source area and/or common "primary" parental magma to both rock series. This author opts for a similar source area that is lower in K and Rb than other Hawaiian volcanoes (implying a heterogeneous mantle). Production of tholeiite and alkalic rocks from this source area is by differences in partial melting and depth of generation.

6. Crystal fractionation diagram analysis (qualitative) indicates that clinopyroxene, along with combinations of olivine, plagioclase, kaersutite and opaques, control the chemical evolution of the

hawaiite-mugearite-benmoreite trend. A problem with this is that clinopyroxene is not a liquidus phase at the low pressures probably encountered at low-level differentiation.

ACKNOWLEDGMENTS

I wish to acknowledge the great deal of help and inspiration from Dr. Peter Weigand. His faith and forbearance helped significantly in the completion of this thesis. I also want to thank the Parker Ranch Company of Waimea, Hawaii, and Monte Richards of Kahua Ranch, Limited, for allowing me access to their land holdings to sample cinder cones. Lastly, I wish to thank my wife, Bonnie, for her patience while I completed the writing of this manuscript.

REFERENCES

- Anderson, A.T. and Greenland, L.P. (1969) Phosphorus fractionation diagrams as a quantitative indication of crystallization differentiation of basaltic liquids: *Geochim. Cosmochim. Acta* 33, 493-505.
- Beeson, M.H. (1976) Petrology, mineralogy and geochemistry of East Molokai Volcanic Series, Hawaii: U.S. Geol. Survey Prof. Paper 961, 53 p.
- Bingler, E.G., Trexler, D.T., Kemp, W.R. and Bonham, H.F. (1966) PETCAL: A basic language computer program for petrologic calculations: Nevada Bureau of Mines and Geology, Report 28, Univ. of Nevada, Reno Publications, 28 p.
- Bowen, N.L. (1928) Evolution of Igneous Rocks: Dover Publications, New York, 332 p.
- Carmichael, I.S.E., Turner, F.J. and Verhoogen, J. (1974) Igneous Petrology, McGraw-Hill Book Co., New York, 739 p.
- Cox, K.G., Bell, J.D. and Pankhurst, R.J. (1979) The Interpretation of Igneous Rocks: George Allen and Unwin Ltd., London, 450 p.
- Cross, W. (1915) Lavas of Hawaii and their relations: U.S. Geol. Survey Prof. Paper 88, 97 p.
- Dalrymple, G.B. (1971) K-Ar Ages from Pololu V.S., Kohala Volcano, Hawaii: *Geol. Soc. Amer. Bull.* 82, 1997-2000.
- Dalrymple, G.B., Silver, E.H. and Jackson, E.D. (1973) Origin of the Hawaiian Islands: *American Scientist*, 61, 294-308.
- Daly, R.A. (1944) Volcanism and petrogenesis as illustrated in the Hawaiian Islands: *Geol. Soc. Amer. Bull.* 55, 1363-1400.
- Dana, J.D. (1890) Characteristics of Volcanoes, Sampson, Marston, Serle, and Rivington Pub., London, 339 p.
- Deer, W.A., Howie, R.A. and Zussman, J. (1966) Introduction to the Rock-Forming Minerals: Wiley and Sons Inc., 528 p.
- Dutton, C.E. (1884) Hawaiian Volcanoes: U.S. Geol. Survey, 4th Annual Report, p. 171.
- Eaton, J.P. and Murata, K.J. (1960) How volcanoes grow: *Science*, 132, 925-938.
- Engle, A.E.J., Engle, C.G. and Havens, R.G. (1965) Chemical characteristics of ocean basalts and the upper mantle: *Geol. Soc. Amer. Bull.* 76, 719-724.

Evernden, J.F., Savage, D.E., Curtis, G.H. and James, G.T. (1964) K-Ar ages and Cenozoic mammalian chronology of North America: *Am. Jour. Sci.* 262, 145-198.

Faure, G. (1977) Principles of Isotope Geology: Wiley and Sons Publ., New York, 464 p.

Faure, G. and Powell, J.L. (1972) Strontium Isotope Geology: Springer-Verlag, Berlin, 188 p.

Feigenson, M.D., Spera, F.J. and Hofmann, A.W. (1980) Trace element geochemistry of Kohala Volcano, Hawaii: *Geol. Soc. Amer. Abstr. Prog.* 12, 424.

Flanagan, F.J. (1976) Descriptions and analyses of eight new USGS rock standards: *U.S. Geol. Survey Prof. Paper* 840, 192 p.

_____ (1973) 1972 Values for international geochemical reference samples: *Geochim. Cosmochim. Acta* 37, 1189-1200.

Gast, P.W. (1968) Trace-element fractionation and origin of tholeiitic and alkaline magma types: *Geochim. Cosmochim. Acta* 32, 1057-1086.

_____ (1967) Isotope geochemistry of volcanic rocks. In: H.H. Hess and A. Poldervaart (eds.), Basalts - Poldervaart Treatise on Rocks of Basaltic Composition 1, Wiley and Sons Publ., New York, 325-358.

_____ (1960) Limitations on the composition of the upper mantle: *Jour. Geophys. Res.* 65, 1287-1297.

Gast, P.W., Tilton, G.R. and Hedge, C. (1964) Isotopic composition of lead and strontium from Ascension and Gough Islands: *Science* 145, 1181-1185.

Green, D.H. (1970) Origin of basaltic and nephelinitic magmas: *Leicester Lit. Phil. Soc.* 64, 28-54.

_____ (1967) Origin of basaltic magmas. In: H.H. Hess and A. Poldervaart (eds.), Basalts - Poldervaart Treatise on Rocks of Basaltic Composition 2, Wiley and Sons Publ., New York, 835-862.

Green, D.H., Edgar, A.E., Beasley, P., Kiss, E. and Ware, N.G. (1974) Upper mantle source for some hawaiites, mugearites and benmoreites: *Contr. Mineral. Petrol.* 48, 33-43.

Green, D.H. and Ringwood, A.E. (1967) The genesis of basaltic magmas: *Contr. Mineral. Petrol.* 15, 103-190.

_____ (1964) Fractionation of basaltic magma at high pressure: *Nature* 201, 1276-1279.

- Hamilton, E.I. (1965) Distribution of some trace elements and the isotopic composition of strontium in Hawaiian lavas: *Nature* 206, 251-253.
- Hart, S.R. (1973) Submarine basalts from Kilauea, Hawaii: Nondependence of trace-element composition on extrusion depth: *Earth Planet. Sci. Lett.* 20, 201-203.
- _____ (1969) Isotope geochemistry of crust-mantle processes: In the earth's crust and upper mantle: Hart, ed., *Geophysical Monograph #13*, Amer. Geophys. Un., 58-62.
- Hedge, C. (1966) Variations in radiogenic Sr found in volcanic rocks: *Jour. Geophys. Res.* 71, 6119-6126.
- _____ and Peterman, Z. (1970) The Sr-isotopic composition of basalts from the Gorda and Juan de Fuca Rises, NE Pacific Ocean: *Cont. Mineral. Petrol.* 27, 114-120.
- _____ and Walthall, F. (1963) Radiogenic strontium-87 as an index of geological processes: *Science* 140, 1214-1217.
- Hlava, P.F. (1974) Unusual lavas from Molokai, Hawaii: Alkalic olivine basalts transitional to hawaiites and Sr-rich mugearites: Unpublished M.S. thesis, Univ. of New Mexico, 170 p.
- Hoffman, A.W. and Hart, S.R. (1975) An assessment of local and regional isotopic equilibrium in a partially molten mantle: *Ann. Report Dir. Terr. Magnetism, Carnegie Inst.*, 1974-1975, 195-210.
- Hubbard, N. (1969) A chemical comparison of oceanic ridge tholeiites and Hawaiian alkalic basalts: *Earth Planet. Sci. Lett.* 5, 346-352.
- _____ (1967) Some trace elements in Hawaiian lavas: Univ. of Hawaii, Unpublished Ph.D. thesis, 123 p.
- Iddings, J.P. (1913) Composition, textures and classification of igneous rocks: *Igneous Rocks Vol. 2*, Wiley and Sons Publ., New York, 685 p.
- Irvine, T.N. and Baragar, W.R.A. (1971) A guide to the chemical classification of the common igneous rocks: *Can. Jour. of Earth Sci.* 2, 523-548.
- Jackson, E.D. (1968) Characteristics of the lower crust and upper mantle beneath the Hawaiian Islands: 23rd Internat. Geol. Congress 1, 135-150.
- Kay, R.W. and Gast, P.W. (1973) Rare-earth content and origin of alkali-rich basalts: *Jour. Geol.* 81, 653-682.

- Keil, K., Fodor, R.V., Bunch, T.E. (1972) Contribution to the mineral chemistry of Hawaiian rocks, Part II: Feldspars and interstitial materials in rocks from Haleakala and West Maui volcanoes, Maui, Hawaii: *Contrib. to Mineral. Petrol.* 37, 253-276.
- Kennedy, W.Q. (1933) Trends of differentiation in basaltic magmas: *Amer. Jour. Sci.* 25, 5th Series, 239-255.
- Kuno H., Yamasaki, K., Iida, C. and Nagashima, K. (1957) Differentiation of Hawaiian magmas: *Japanese Jour. Geol. Geogr.* 28, 179-218.
- Kushiro, I. (1973) Origin of some magmas in oceanic and circum-oceanic regions: *Tectonophysics* 17, 211-222.
- Kushiro, I. and Kuno, H. (1963) Origin of primary basalt magmas and classification of basaltic rocks: *Jour. Petrol.* 4, 75-89.
- Lessing, P. and Catanzaro, E.J. (1964) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in Hawaiian lavas: *Jour. Geophys. Res.* 69, 1599-1601.
- Lyons, P. (1896) Chemical composition of Hawaiian soils and their rocks from which they are derived: *Amer. Jour. Sci.* 2, 4th Series, 425.
- Macdonald, G.A. (1968) Composition and origin of Hawaiian lavas: *Geol. Soc. Amer. Memoir* 116, 447-522.
- _____ (1949b) Petrography of the island of Hawaii: U.S. Geol. Survey Prof. Paper 214D, 51-96.
- _____ (1949a) Hawaiian petrographic province: *Geol. Soc. Amer. Bull.* 60, 1541-1596.
- _____ (1942a) Potash-oligoclase in Hawaiian lavas: *Amer. Mineral.* 27, 793-800.
- Macdonald, G.A., Powers, H.A. and Katsura, T. (1973) Interlaboratory comparison of some chemical analyses of Hawaiian volcanic rocks: *Bull. Volcanologique* 36, 127-139.
- _____ and Abbot, A.T. (1970) Volcanoes in the Sea: Univ. of Hawaii Press, 441 p.
- _____ and Katsura, T. (1964) Chemical composition of Hawaiian lavas: *Jour. Petrol.* 5, 82-103.
- _____ (1962) Relation of petrographic suites in Hawaii: The crust of the Pacific Basin: *Amer. Geophys. Union Mon.* 6, 187-195.
- _____ (1961) Variation in lava of 1959 eruption in Kilauea Iki: *Pacific Science*, 15, 358-369.

- MacGregor, I.D. (1965) The effect of pressure on the minimum melting composition in the system $MgO-SiO_2-TiO_2$: Ann. Report to the Dir. Geophys. Lab., Carnegie Inst. Year Book (1964-1965), 135-139.
- Malinowski, M.J. (1977) Geology of the Kawaihae Quadrangle, Kohala Mountain, Island of Hawaii: Univ. of Hawaii, Unpublished Masters thesis, 155 p.
- McBirney, A.C. (1967) Genetic relationships of volcanic rocks of the Pacific Ocean: Geol. Rundschau, 57, 21-32.
- McDougall, I. (1969) K-Ar ages of Kohala Volcano, Hawaii: Geol. Soc. Amer. Bull. 80, 2597-2600.
- _____ (1964) K-Ar ages from lavas of Hawaiian Islands: Geol. Soc. Amer. Bull. 75, 107-128.
- McDougall, I. and Swanson, D.A. (1972) K-Ar ages of lavas from the Hawi and Pololu Volcanic Series, Kohala Volcano, Hawaii: Geol. Soc. Amer. Bull. 83, 3731-3738.
- Muir, I.D. and Tilley, C.E. (1961) Mugearites and their place in the alkaline igneous rock series: Jour. Geol. 69, 186-203.
- O'Hara, M.J. (1968b) The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks: Earth Sci. Rev. 4, 69-133.
- O'Hara, M.J. (1973) Non-primary magmas and dubious mantle plume beneath Iceland: Nature 243, 507-508.
- O'Neil, J.R., Hedge, C.E. and Jackson, E.D. (1970) Isotopic investigations of xenoliths and host basalts from the Honolulu Volcanic Series: Earth Planet. Sci. Lett. 8, 253-257.
- O'Nions, R.K. and Pankhurst, R.J. (1974) Petrogenetic significance of isotope and trace-element variations in volcanic rocks from the mid-Atlantic Ridge: Jour. Petrol. 15, 603-634.
- _____ (1973) Secular variation in the Sr-isotope composition of Icelandic volcanic rocks: Earth Planet. Sci. Lett. 21, 13-21.
- Peterman, Z. and Hedge, C. (1971) Related Sr isotopes and chemical variation in oceanic basalts: Geol. Soc. Amer. Bull. 82, 493-500.
- Poldervaart, A. (1968) Zircons in rocks: In Zircon, Murthy, M.V.N., ed., Geol. Survey Indian, Misc. Publ. 9, 2-52.
- _____ (1964) Chemical definition of alkalic basalt and tholeiite: Geol. Soc. Amer. Bull. 75, 229-232.

- _____ (1956) Zircon in rocks; part II, igneous rocks: *Amer. Jour. Sci.* 254, 521-554.
- Powell J.L. and DeLong, S.E. (1966) Isotopic composition of strontium in volcanic rocks from Oahu: *Science*, 153, 1239-1242.
- Powell, J.L., Faure, G. and Hurley, P.M. (1965) ^{87}Sr abundance in a suite of Hawaiian volcanic rocks: *Jour. Geophys. Res.* 70, 1509-1513.
- Powers, H.A. (1955) Composition and origin of basaltic magmas of the Hawaiian Islands: *Geochim. Cosmochim. Acta* 7, 77-107.
- _____ (1935) Differentiation of Hawaiian lavas: *Amer. Jour. Sci.* 30, 57-71.
- Presnall, D.C. (1979) Fractional crystallization and partial fusion: In *Evolution of the Igneous Rocks*, Yoder, ed., Princeton Univ. Press, New Jersey, 59-75.
- Schilling, J. (1973) Iceland mantle plume: Geochemical evidence along the Reykjanes Ridge: *Nature* 242, 565-571.
- Schilling, J. and Winchester, J.W. (1969) Rare-earth contribution to the origin of Hawaiian lavas: *Contr. Mineral. Petrol.* 23, 27-37.
- _____ (1967) Rare-earth fractionation and magmatic processes: In *Mantles of Earth and Terrestrial Planets*, Wiley and Sons, Publ., New York, 267-283.
- Schwarzer, R.R. and Rogers, J.W. (1974) A worldwide comparison of alkali olivine basalts and their differentiation trends: *Earth Planet. Sci. Lett.* 23, 286-296.
- Shapiro, L. (1975) Rapid analysis of silicates, carbonate and phosphate rocks-revised edition: *U.S. Geol. Survey Bull.* 1401, 76 p.
- Sibray, S. (1977) Mineralogy, petrology and geochemistry of some lavas from Kohala Volcano, Hawaii: Unpublished Masters thesis, Univ. of New Mexico, 113 p.
- Smith, R.L. (1979) Ash-flow magmatism: In *Geol. Soc. Amer. Spec. Paper* 180, Chapin and Elston, eds., 5-27.
- Stearns, H.T. (1946) Geology of the Hawaiian Islands: *Hawaii Division of Hydrography Bull.* 8, 106 p.
- _____ (1940) Four-phase volcanism in Hawaii: *Geol. Soc. Amer. Bull.* 51, 1947-1948.

- Stearns, H.T. and Macdonald, G.A. (1946) Geology and groundwater resources of the island of Hawaii: Hawaii Division of Hydrography Bull. 9, 363 p.
- Strong, D.F. (1969) Formation of hourglass structure in augite: Mineral. Mag. 37, 472-479.
- Sun, S.S. and Hanson, G.W. (1975) Evolution of the mantle: Geochemical evidence from alkali basalt: Geology 3, 297-302.
- Tilley, C.E. (1950) Some aspects of magmatic evolution: Geol. Soc. London Qtrly. Jour. 106, 37-61.
- Tilley, C.E., Yoder, H.S. and Schairer, J.F. (1965) Melting relationships of volcanic tholeiite and alkalic rock series: Geophys. Lab. Annual Report, 1964-1965, Carnegie Inst. Year Book 64, 69-82.
- Wager, L.R. (1956) A chemical definition of fractionation stages as a basis for comparison of Hawaiian, Hebridian and other basic lavas: Geochim. Cosmochim. Acta 9, 217-248.
- Wager, L.R. and Brown, G.M. (1967) Layered Igneous Rocks: Freeman and Co. Publ., San Francisco, 585 p.
- Washington, H.S. (1923) Petrology of the Hawaiian Islands: I. Kohala and Mauna Kea, Hawaii: Amer. Jour. Sci. Series 5, 465-502.
- Wright, T.L. (1971) Chemistry of Kilauea and Mauna Loa in space and time: U.S. Geol. Survey Prof. Paper 735, 40 p.
- Wright, T.L. and Doherty, P.C. (1970) A linear programming and least squares computer method for solving petrologic mixing problems: Geol. Soc. Amer. Bull. 81, 1995-2008.
- Yoder, H.S. and Tilley, C.E. (1962) Origin of basalt magmas: An experimental study of natural and synthetic rock systems: Jour. Petrol. 3, 342-532.



Photo 1.(a)-Fine-grained hawaiiite (KV 5-2),
polarized light (pol), 2.5X, 2.7 mm
(photo length).



Photo 1.(b)-Hawaiiite (KV 5-2), iddingsitized
olivine phenocryst, pol., 10X,
0.71 mm.

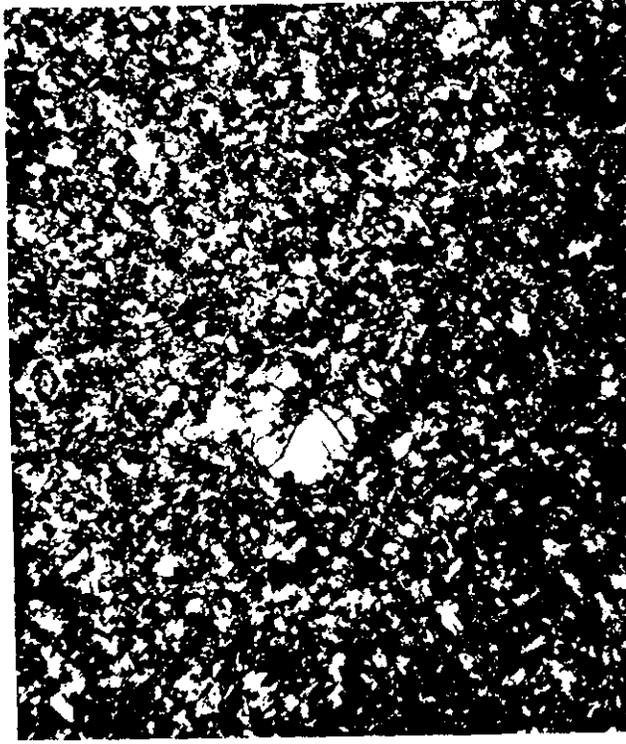


Photo 3. (a) - Fine-grained mugearite (KV 12-1A),
olivine phenocrysts, pol., 2.5X,
2.7 mm.



Photo 2. - Augite (KV 8-2), hourglass extinction,
pol., 10X, 0.71 mm.

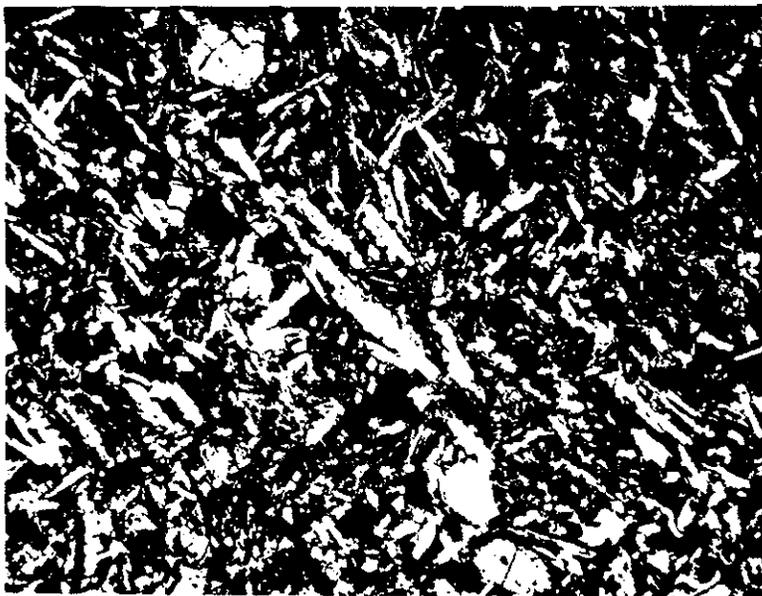


Photo 3.(b)-Coarse-grained mugearite (KV 1-1E0, olivine and plagioclase phenocrysts, pol., 2.5X, 0.71 mm.



Photo 4.(a)-Plagioclase with reabsorbed core (KV 21-2A), pol., 2.5X, 2.7 mm.

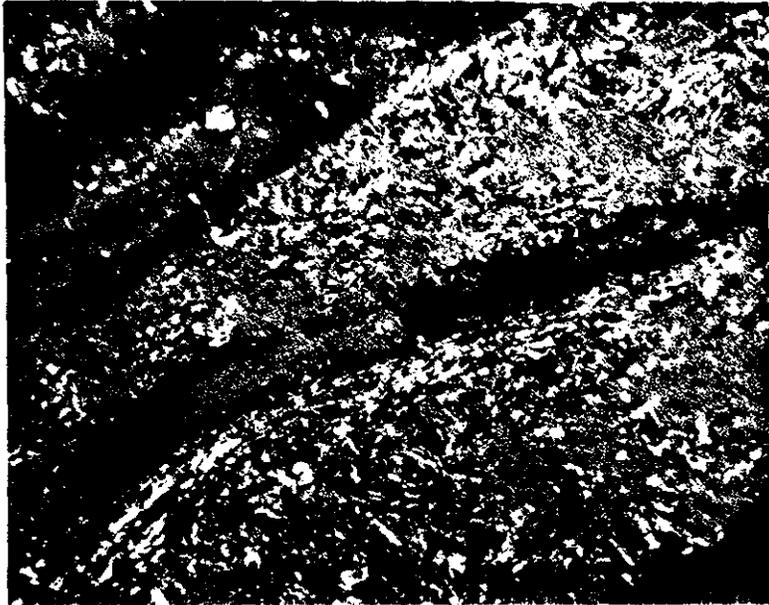


Photo 4.(b)-Relict kaersutite (KV 21-2A), pol.,
2.5X, 2.7 mm.

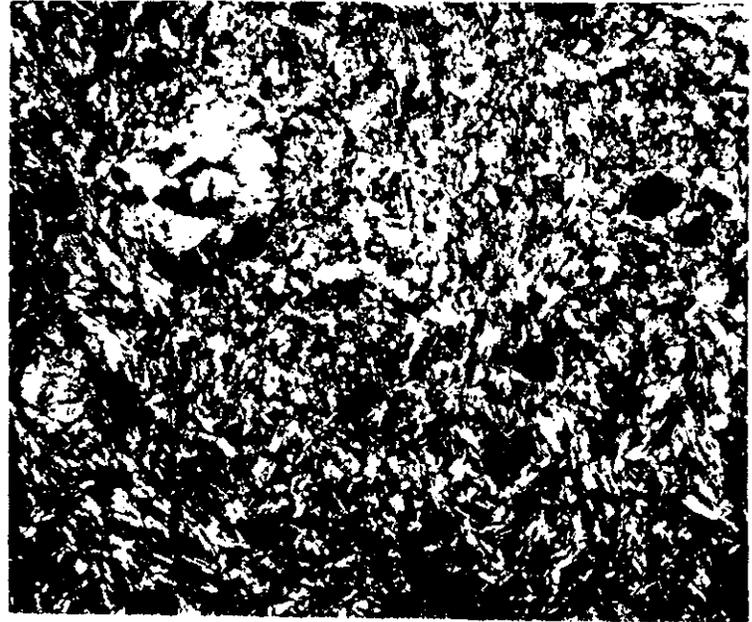


Photo 5.(a)-Benmoreite (KV 17-1), olivine and
plagioclase phenocrysts, vesicular,
pol., 10X, 0.71 mm.

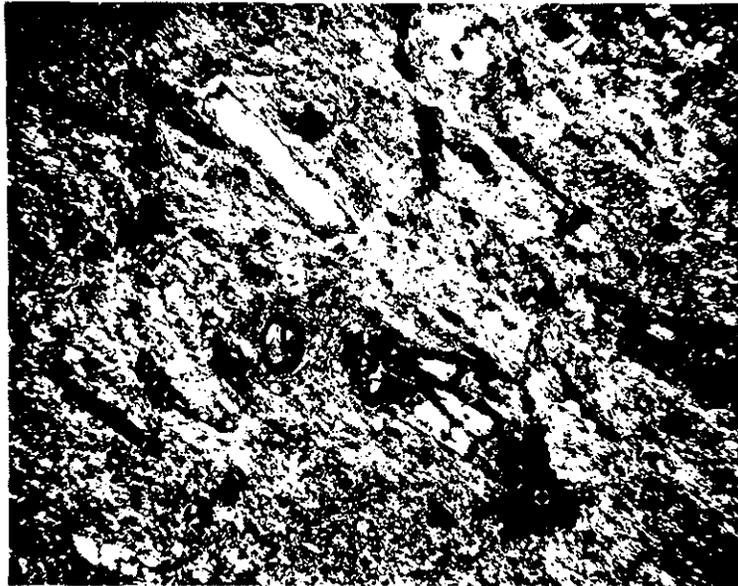


Photo 5.(b)-Benmoreite (KV 16-1), kaersutite and plagioclase phenocrysts, localized flow textures, pol., 2.5X, 2.7 mm.



Photo 6.-Kaersutite (KV 16-1) with opacite rims, pol., 2.5X, 2.7 mm.



Photo 7.(a)-Dunitite nodule (KV 15-1), pol., 2.5X,
2.7 mm.



Photo 7.(b)-Dunitite nodule (KV-11-2H), olivine,
kink bands, host basalt, pol.,
2.5X, 2.7 mm.



Photo 7.(c)-Dunite nodule (KV 23-1), sharp contact with host hawaiite, pol., 2.5X, 2.7 mm.

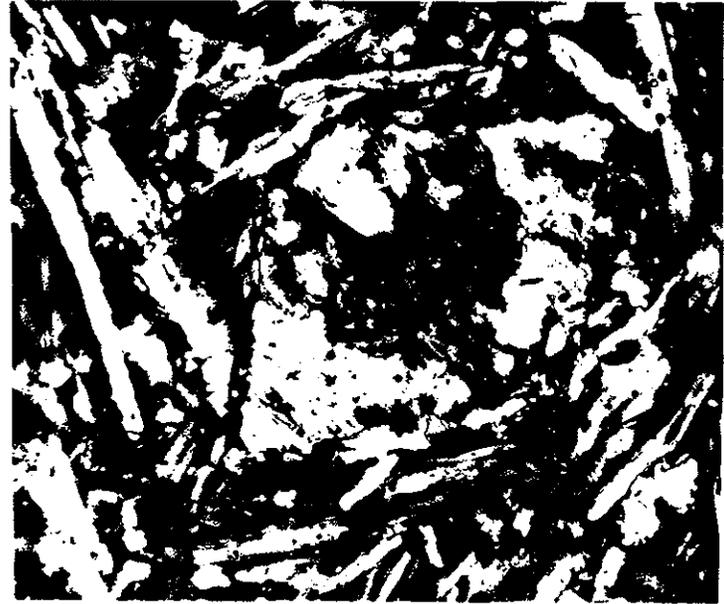


Photo 8.-Altered olivine (KV 14-1), opaque inclusions, pol., 25X, 0.30 mm.



Photo 9.-Corroded augite (KV 21-2A) oxide rim,
pol., 2.5X, 2.7mm.

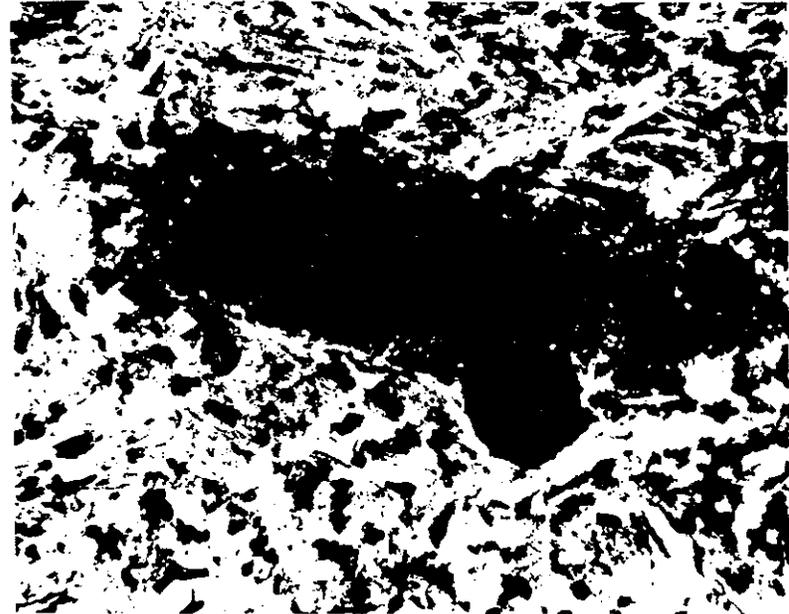


Photo 10.-Corroded opaques (KV 21-2A), pol.,
10X, 0.71mm.



Photo 11.(b)-Zircon(?)(KV 24-2), plane light,
25X, 0.30 mm.

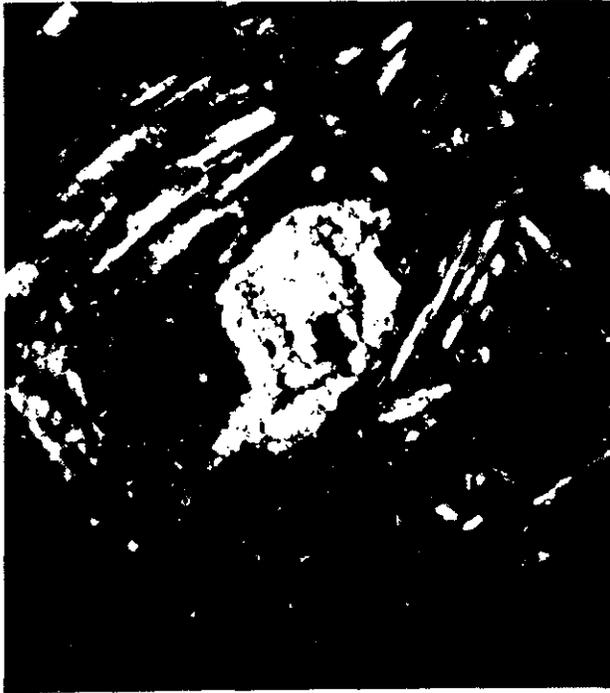


Photo 11.(a)-Zircon(?)(KV 24-2), pol., 25X,
0.30 mm.

APPENDIX I
Previous Chemical Analyses of Alkalic Kohala Lavas

	#3	#4	#5	#1	#2	#3	#4			
SiO ₂	58.06	47.33	49.01	52.27	51.99	47.39	45.33			
TiO ₂	1.88	4.84	3.93	2.13	3.02	2.83	2.45			
Al ₂ O ₃	18.21	17.96	16.29	17.05	16.30	16.46	16.52			
Fe ₂ O ₃	4.87	12.64	7.61	3.51	2.75	3.75	5.60			
MnO	0.36	0.64	0.27	0.16	0.11	0.09	0.10			
MgO	1.59	3.97	3.62	3.13	3.19	5.08	7.38			
CaO	3.29	6.29	9.79	5.82	6.67	7.37	7.89			
Na ₂ O	6.12	3.67	3.82	5.40	5.64	4.71	4.24			
K ₂ O	2.75	1.10	0.80	2.22	2.13	1.65	1.49			
P ₂ O ₅	0.65	1.05	0.49	0.62	1.25	2.22	2.32			
H ₂ O _t	-	-	-	0.52	0.36	0.37	0.33			
TOTAL	99.79	100.00	100.52	100.03	100.85	100.34	100.57			
Ref. Rock Type	1 feldspathic	1 vesicular	1 porphyritic	2 mugearite	2 mugearite	2 mugearite	2 mugearite			
Locality	Maimea	Maimea	Kohala	P. Makea	P. Kamae(?)	P. Kawaiwi	P. Lahikiola			
	C-70	C-69	C-68	62-1	C-210	C-211	C-212	F1-1	A-15-1	A-15-2
SiO ₂	47.48	45.54	50.52	58.27	51.80	48.80	48.73	47.15	49.65	48.65
TiO ₂	2.63	2.85	1.96	0.95	1.95	2.54	2.62	2.81	2.48	2.56
Al ₂ O ₃	17.42	17.61	19.43	19.12	17.07	15.77	15.85	15.45	16.51	16.44
Fe ₂ O ₃	3.59	3.56	4.03	5.60	3.12	5.06	5.13	7.57	6.32	4.64
FeO	8.10	8.25	5.36	1.51	6.93	6.41	6.99	4.94	4.98	6.91
MnO	0.18	0.17	0.20	0.26	0.22	0.22	0.22	0.24	0.25	0.25
MgO	6.74	6.42	3.38	1.30	3.10	3.91	3.80	4.46	3.45	3.96
CaO	8.54	10.82	5.82	2.98	6.01	7.21	7.27	7.52	6.56	6.98
Na ₂ O	3.12	2.74	5.35	6.54	5.78	5.38	5.45	5.20	5.27	5.08
K ₂ O	1.20	0.70	2.23	2.67	2.23	1.93	1.98	1.58	1.88	1.76
P ₂ O ₅	0.36	0.34	0.92	0.62	1.54	1.96	1.97	2.32	1.75	1.92
H ₂ O _t	0.62	0.70	0.52	0.43	0.89	0.86	0.43	0.23	0.44	0.44
TOTAL	99.98	99.70	99.72	100.25	100.64	100.05	100.64	99.47	99.55	99.59
Ref. Rock Type	3 AOB	3 AOB	3 Haw	3 Trach.	4 Mug.	4 Mug.	4 Mug.	5 Mug.	5 Mug.	5 Mug.
Locality	[All taken from Kamuela-Haw. Rd.]		Kamuela-Haw. Rd.]	Haw. Rd.]	Haw. Rd.]	Near Rd. P. Pili]	P. Pili]	P. Aiea	P. Lapolapa	P. Mala
	A-33-1	6-12-1	H-19-74	H-37-74	H-4-74	H-45-74	H-22-74	H-28-74	H-11-74	
SiO ₂	52.10	47.10	47.48	48.92	47.84	47.84	49.38	56.06	58.55	
TiO ₂	1.90	2.84	2.84	3.36	2.70	2.61	2.34	1.44	1.06	
Al ₂ O ₃	17.24	15.88	14.85	15.10	15.55	17.25	17.58	18.15	17.20	
Fe ₂ O ₃	4.36	7.51	3.61	4.99	5.62	4.92	6.07	3.51	4.68	
FeO	5.73	5.16	9.06	7.73	7.34	6.97	5.14	3.72	2.34	
MnO	0.24	0.24	0.18	0.19	0.22	0.22	0.23	0.22	0.22	
MgO	2.91	4.15	4.65	4.82	4.32	3.93	3.77	1.77	1.24	
CaO	5.27	7.22	9.18	9.45	7.19	6.55	6.40	3.40	3.08	
Na ₂ O	5.57	4.61	3.35	3.66	4.97	5.00	5.22	6.20	6.95	
K ₂ O	2.06	1.56	1.36	1.28	1.63	1.76	1.90	2.58	2.88	
P ₂ O ₅	1.45	2.21	0.44	0.65	2.15	1.78	1.60	0.65	0.73	
H ₂ O _t	0.42	0.57	0.31	0.20	0.52	0.48	0.47	1.88	0.33	
TOTAL	99.25	99.05	99.31	100.35	100.05	100.03	100.10	99.58	99.26	
Ref. Rock Type	5 Mug.	5 Mug.	6 AOB-Haw	6 AOB-Haw	6 Haw.	6 Mug.	6 Mug.	6 Ben.	6 Ben.	
Locality	P. Loo	P. Kawaiwi			P. Kawaiwi			P. Pelu	P. Mckea	
	MG-1	MG-1b	MG-2b	MG-4b	KH-12	KH-13	KH-1	KH-2	KH-19	
SiO ₂	47.89	48.25	47.27	53.18	53.65	55.88	62.83	60.80	59.72	
TiO ₂	3.75	3.21	3.10	2.14	2.08	2.10	1.36	1.36	0.82	
Al ₂ O ₃	14.77	16.30	14.96	18.15	18.83	18.43	19.68	19.29	20.18	
FeO	12.25	11.28	12.19	9.66	10.04	8.55	6.08	6.62	6.57	
MnO	0.19	0.16	0.23	0.26	0.25	0.16	0.20	0.25	0.33	
MgO	5.18	4.59	6.13	2.89	3.85	3.68	2.01	2.10	1.53	
CaO	9.47	9.51	9.84	5.40	5.70	5.72	3.45	3.87	2.80	
Na ₂ O	3.36	3.32	3.41	4.04	5.05	4.83	3.91	3.74	5.91	
K ₂ O	0.98	0.95	1.14	2.11	1.97	2.36	2.66	1.60	2.66	
P ₂ O ₅	0.61	0.68	0.60	1.48	1.24	1.22	0.45	0.66	0.51	
TOTAL	98.45	98.25	98.87	99.31	102.66	102.93	102.63	100.29	101.03	
Ref. Rock Type	7 Haw.	7 Haw.	7 Haw.	7 Mug.	7 Mug.	7 Mug.-Ben.	7 Ben.	7 Ben.	7 Ben.-Tr.	
Locality			Mamaewa Gulch				Waipio Valley			

REFERENCES

1. Lyons (1896)
2. Washington (1923)
3. Macdonald and Katsura (1964)
4. Macdonald (1968)
5. Malinowski (1977)
6. Sibray (1977)
7. Feigenson et al., (1981)

APPENDIX II

Sample Localities

Quadrangle maps divided into nine sections and nine subsections; for example, Section 5-3.

- Cone 1 Hokuula-Kamuela Quad, Section 9-2
 Samples A-C - Upper levels, hand-sized rocks in a cindery matrix
 Samples D-E - Lower level, loose boulders
- Cone 2 Puu Owaowaka Satillitic Cone - Kamuela, Section 9-3
 Samples A,B - Collected on cone slope next to reservoir
- Cone 3 Puu Ki - Kamuela, Section 9-3
 Sample A - Road cut
 Sample B - Road cut
 Sample 3-2 A,B - Strewn field, on slope
- Cone 4 Puu Manu - Kamuela Section 9-3
 Samples A,B,C - Collected from an exposed soil level at the head of a landslide
- Cone 5 Puu Kakaniha - Kamuela Section 9-2
 Sample 5-1 A,B, - From 3/4 way up cone, large boulders
 Sample 5-2 - Boulder at foot of cone
- Cone 6 Puu Lanikepu - Kamuela, Section 5-7
 Sample 6-1 - Boulder near hillside exposure
 Sample 6-2 - Wall outcrop
 Sample 6-3 - Boulder rubble, on slope
- Cone 7 Puu Kamoia - Kamuela, Section 4-6,9
 Samples 7-1 A,B - From on-slope boulders
 Sample 7-2 - From top section of cone
- Cone 8 Puu Kehena - Hawi, Section 8-1
 Samples 8-1 Series - Rock fragments on top and embedded in ground at the top of the cinder cone
 Sample 8-2 - Boulder rubble on slope
- Cone 9 Puu Lahikiola - Hawi, Section 8-6
 Sample 9-1 - Boulder embedded in ground, on slope
- Cone 10 Puu Aiea - Hawi, Section 8-9
 Sample 10-1 - Boulders along hill exposure
 Sample 10-2A - Boulder on slope inside top of cone summit
 Sample 10-2B - On slope, boulder

APPENDIX II (Continued)

- Cone 11 Puu Kawaiwai - Kamuela, Section 4-7
 Sample 11-1 - From a bed approximately four feet off floor
 of excavation exposure
 Sample 11-2 Series - Longitudinal sampling (45 m) of an E-W
 trending excavated wall
- Cone 12 Puu Lala Kamuela, Section 6-9
 Sample 12-1 - Sample from soil horizon on hillside
 Sample 12-2 - Along foot trail along hillside
- Cone 13 Eke - Kamuela, Section 6-2
 Samples 13-1,2 - Embedded in mud
- Cone 14 Puu Loa-Kawaihae, Section 6-3
 Sample 14-1 - Outcrop along slope
 Sample 14-2 - Stream gully slope outcrop
- Sample 15 Found along foot trail of Upper Hamakua ditch trail, at the
 head of Alakahi Valley, Section 5, 3 Kamuela Quad.
- Sample 16 Puu Pelu - Kamuela, Section 5-8
 Sample collected along ridge, south part of a lava flow
 from P. Pelu (Cone 17)
- Cone 17 Puu Pelu - Kamuela, Section 5-8
 Boulders on east side of cone slope
- Cone 18 Puu Lep-Hawi, Section 6-7
 Sample westward slope boulder
- Cone 19 Puu o Lani-Hawi, Section 5-9
 Samples 19-1 - Outcrop on hill
 Samples 19-2 - Boulder on slope
- Cone 20 Puu Mala-Kawaihae, Section 3-6
 Samples 20-1 A,B - Boulder outcrop on slope
- Cone 21 Puu Lapalapa-Kawaihae, Section 3-6
 Sample 21-1 - Fragment embedded in soil of an on-slope ero-
 sion scarp
 Sample 21-2A - Outcrop on a hill
 Sample 21-2B - Stream outcrop, from horizon below 21-2A
 Sample 21-3 - Outcrop on slope
- Cone 22 Puu Pala-Kawaihae, Section 3-6
 Sample from on-slope boulder
- Cone 23 Puu Pili-Kawaihae, Section 3-2
 Sample 23-1 - Hillside scarp outcrop
 Sample 23-2 - Flat lavaflow outcrop

APPENDIX II (Continued)

- Cone 24 Puu Iki-Kawaihae, Section 3-5
 Samples 24-1,2 - On-slope boulders
- Cone 25 Puu Honu-Kawaihae, Section 3-5
 Samples 25-1 - On-slope boulder
 Samples 25-2 - On-slope boulder inside cone summit
- Cone 26 Ahu Noa-Hawi, Section 9-8
 Sample from scarp exposure
- Cone 27 Waia Kanonula-Hawi, Section 9-7
 Sample from scarp exposure

APPENDIX III

Sample Petrography

- KV 1-1A Holocrystalline, fine-grained, allotriomorphic to hypidiomorphic (groundmass) with idiomorphic phenocrysts of olivine and plagioclase, porphyritic, localized flow textures, plag.-cpx-opaques-olivine.
- KV 1-1B Holocrystalline, medium-grained, allotriomorphic (groundmass) to idiomorphic (amphibole, apatite, some plagioclase), porphyritic (amphibole), localized flow textures, plag.-amphibole-opaques-olivine-apatite, An₂₂ to An₁₉.
- KV 1-1C Holocrystalline, medium-grained, allotriomorphic to hypidiomorphic (plagioclase, olivine), slightly porphyritic (plagioclase, opaques, olivine), plag.-opaques-olivine-apatite, An₂₅.
- KV 1-1D Holocrystalline, coarse, allotriomorphic to hypidiomorphic (olivine, plagioclase, cpx, opaques), slightly vesicular, plag.-opaques-cpx-olivine, An₄₄ to An₃₇.
- KV 1-1E Holocrystalline, medium-grained, allotriomorphic to idiomorphic (apatite), porphyritic (olivine, plagioclase), slightly vesicular, plag.-cpx-opaques-olivine-apatite, An₃₉ to An₂₄.
- KV 2-1A Hypocrystalline, fine-grained, hypidiomorphic, slightly porphyritic (olivine, cpx, plagioclase), plag.-opaques-olivine-cpx.
- KV 2-1B Holocrystalline, medium-grained, hypidiomorphic, vesicular, porphyritic (olivine), flow textures, plag.-opaques-olivine-cpx, An₃₂.
- KV 3-1 Holocrystalline, fine-grained, allotriomorphic to idiomorphic (olivine), porphyritic (olivine), flow textures, plag-opaques-olivine.
- KV 3-2B Holocrystalline, medium-grained, hypidiomorphic to idiomorphic (apatite), porphyritic (olivine), slightly vesicular, plag.-opaques-olivine-apatite, An₃₃.
- KV 4-1 Hypocrystalline, fine-grained, hypidiomorphic, oxidized, vesicular, slightly porphyritic (plagioclase, olivine), plag.-glass-opaques-olivine-apatite.
- KV 5-2 Holocrystalline, medium-grained, allotriomorphic to hypidiomorphic, vesicular, porphyritic (olivine), flow textures, plag.-cpx-opaques-olivine-apatite, An₄₀ to An₂₈.

APPENDIX III (Continued)

- KV 6-1 Holocrystalline, fine-grained, hypidiomorphic, slightly oxidized, plag.-cpx-opaques-olivine, An₄₆.
- KV 6-2 Holocrystalline, medium-grained, allotriomorphic to hypidiomorphic, slightly oxidized, slightly vesicular, slightly porphyritic (olivine, cpx, plagioclase), plag.-opaques-cpx-olivine-biotite, An₂₄.
- KV 6-3 Holocrystalline, fine-grained, allotriomorphic to hypidiomorphic, slightly vesicular, resorption of plagioclase cores, porphyritic (plagioclase), plag.-opaques-olivine-amphibole, An₂₁.
- KV 7-2 Holocrystalline, fine-grained, allotriomorphic to hypidiomorphic, slightly vesicular, flow texture, plag.-olivine-cpx-apatite.
- KV 8-1#2B Hypocrystalline, medium-grained, allotriomorphic to idiomorphic (olivine), vesicular, porphyritic (olivine, plagioclase, opaques), plag.-opaques-olivine-cpx-glass-K-spar, An₄₇.
- KV 8-1#2C Holocrystalline, fine-grained, hypidiomorphic, vesicular, flow texture, slightly porphyritic (plagioclase, olivine, cpx), plag.-cpx-opaques-olivine-apatite, An₂₃.
- KV 8-2 Hypocrystalline, medium-grained, hypidiomorphic, vesicular, porphyritic (olivine), plag.-glass-olivine-cpx-alkali feldspar, An₄₃ to An₃₈. Glass obscures detail.
- KV 9-1 Hypocrystalline, fine-grained, allotriomorphic to hypidiomorphic, vesicular, slightly porphyritic (plagioclase), plag.-opaques-glass-cpx-olivine-alkali feldspar.
- KV 11-1A Hypocrystalline, medium-grained, hypidiomorphic to idiomorphic (olivine), quite vesicular, plag.-glass-opaques-olivine-apatite, An₃₈.
- KV 11-2E Hypocrystalline, fine-grained, hypidiomorphic, quite vesicular, slightly porphyritic (opaques), plag.-opaques-cpx-apatite-K-feldspar-biotite.
- KV 11-2H Hypocrystalline, medium-grained, hypidiomorphic, quite vesicular, porphyritic (olivine, plagioclase), plag.-opaques-olivine-cpx-apatite, An₃₈ to An₃₃.
- KV 12-1A Holocrystalline, fine-grained but equant, allotriomorphic, nonporphyritic, plag.-cpx-opaques-apatite-olivine-biotite.

APPENDIX III (Continued)

- KV 13-1 Holocrystalline, medium-grained, basically hypidiomorphic, porphyritic (olivine, plagioclase, cpx), plag.-opaques-cpx-olivine-K-feldspar, An₄₁ to An₃₅.
- KV 14-1 Holocrystalline, fine- to medium-grained, hypidiomorphic to idiomorphic (olivine), slightly vesicular, slightly porphyritic (microphenocrysts of olivine, plagioclase, opaques), plag.-opaques-olivine-cpx-apatite, An₄₇.
- KV 14-2 Hypocrystalline, fine- to medium-grained, hypidiomorphic to idiomorphic (olivine, opaques, cpx?), vesicular, slightly porphyritic (olivine, opaques, cpx?), plag.-opaques-olivine-cpx-apatite-K-feldspar, An₂₉, oxidized, splotchy appearance.
- KV 15-1 Holocrystalline, medium- to coarse-grained, hypidiomorphic to idiomorphic (olivine, opaques, apatite), slightly vesicular, porphyritic (olivine, plagioclase), plag.-opaques-olivine-cpx-apatite, An₂₄ phenocrysts to An₃₇ groundmass.
- KV 16-1 Hypocrystalline, medium-grained, hypidiomorphic to idiomorphic (kaersutite), pilotaxitic, slightly porphyritic (kaersutite, plagioclase, olivine), plag.-kaersutite-opaques-olivine, An₂₀.
- KV 17-1 Holocrystalline, medium-grained, hypidiomorphic to idiomorphic (kaersutite), opacite rims, some resorption, porphyritic (kaersutite, plagioclase, olivine), plag.-opaques-cpx-kaersutite-olivine-apatite, An₂₃.
- KV 18-1 Holocrystalline, medium-grained, hypidiomorphic to idiomorphic (olivine), slightly vesicular, very porphyritic (olivine, plagioclase, opaques), plag.-opaques-olivine-cpx-K-feldspar, An₅₁ (phenocrysts) to An₄₂-An₃₂ groundmass.
- KV 19-1 Hypocrystalline, fine-grained, hypidiomorphic, very vesicular, slightly porphyritic (olivine), oxidized, altered look, plag.-olivine-opaques-K-feldspar. Minerals obscured by alteration.
- KV 21-1 Hypocrystalline, very fine-grained, hypidiomorphic to idiomorphic (olivine), pilotaxitic, vesicular, slightly porphyritic (opaques), oxidized, plag.-opaques-olivine-cpx-apatite-zircon(?).
- KV 21-2A Holocrystalline, medium-grained, hypidiomorphic to idiomorphic (kaersutite, plagioclase), relict mineral structures (kaersutite), porphyritic (plagioclase, one large

APPENDIX III (Continued)

- cpx, kaersutite), pilotaxitic, plag.-opaques-cpx-kaersutite-olivine, An₂₈ to An₂₂.
- KV 21-2B Hypocrystalline, fine-grained, hypidiomorphic, vesicular, pilotaxitic, and slightly porphyritic (opaques, olivine), plag.-cpx-opaques-olivine-apatite, An₃₀ to An₂₇.
- KV 21-3 Hypocrystalline, fine-grained, hypidiomorphic, vesicular, pilotaxitic, oxidized, slightly porphyritic (microphenocrysts of olivine, plagioclase, opaques), plag.-opaques-olivine-K-feldspar, slide rather altered.
- KV 22-1 Hypocrystalline, fine-grained, hypidiomorphic, vesicular, oxidized, altered, splotchy appearance, plag.-opaques-olivine-K-feldspar.
- KV 23-1 Holocrystalline, fine- to medium-grained, hypidiomorphic to idiomorphic (olivine, K-feldspar), quite vesicular, slightly porphyritic (microphenocrysts of olivine), plag.-opaques-olivine-apatite-K-feldspar, An₄₇.
- KV 23-2 Holocrystalline, fine-grained, hypidiomorphic, quite vesicular, porphyritic (microphenocrysts, plagioclase, olivine), plag.-opaques-olivine-apatite-K-feldspar-cpx, An₄₁ to An₂₈ (groundmass), slight oxidation.
- KV 24-1 Hypocrystalline, fine-grained, hypidiomorphic, vesicular, oxidized, altered, slightly porphyritic (microphenocrysts-olivine, opaques, plagioclase), plag.-opaques-olivine-cpx-apatite.
- KV 24-2 Holocrystalline, medium-grained, hypidiomorphic, vesicular, pilotaxitic, slightly porphyritic (plagioclase, cpx), plag.-cpx-opaques-apatite-biotite-zircon(?), An₂₃.
- KV 25-1 Hypocrystalline, medium-grained, hypidiomorphic to idiomorphic (olivine), vesicular, porphyritic (olivine), plagioclase-cpx-opaques-glass-olivine-apatite.
- KV 25-2 Hypocrystalline, medium-grained, hypidiomorphic, vesicular, pilotaxitic, porphyritic (olivine?), Fe-Mg minerals are quite altered with heavy opaque rims obscuring identification, plag.-opaques-ferromagnesian minerals-apatite.
- KV 26-1 Hypocrystalline, medium-grained, hypidiomorphic to idiomorphic (olivine), vesicular, oxidized, grungy slide, plag.-olivine-opaques-apatite.

APPENDIX III (Continued)

KV 27-1 Holocrystalline, medium-grained, hypidiomorphic to allotriomorphic (olivine, opaques), vesicular, porphyritic (microphenocrysts of plagioclase), plag.-opaques-olivine-apatite-biotite, An₂₉.

APPENDIX IV

Instrumental Parameters for Geochemical Analysis

XRF

<u>Oxide</u>	<u>X-Ray Tube</u>	<u>2θ Peak (°)</u>	<u>Kv</u>	<u>mA</u>	<u>Analyzing Crystal</u>	<u>Counting Time (sec.)</u>
SiO ₂	Cr	79.225	44	30	PET	20
TiO ₂	Cr	6.600	25	20	PET	10
FeO _T	Cr	57.350	45	9	PET	10
CaO	Cr	15.150	24	11	PET	10
K ₂ O	Cr	20.625	20	20	PET	10

ATOMIC ABSORPTION

<u>Oxide</u>	<u>Wavelength (nm)</u>	<u>Lamp Current</u>	<u>Detector Voltage</u>	<u>Slit Width</u>	<u>Oxidizer</u>
Al ₂ O ₃	309.00-309.3	10	530	160	N ₂ O + acetylene
MnO	279.2	16	700	80	air
MgO	284.80-285.4	5	530	320	air
Na ₂ O	588.75-589.4	-	530	160	air
Rb	780.0	-	-	150	air
Ni	232.0	5	800	80	air

SPECTROPHOTOMETRY

<u>Oxide</u>	<u>Wavelength (nm)</u>
P ₂ O ₅	420.0

APPENDIX V

Dissolving Procedure for Atomic Absorption Analysis

1. Prepare the following solutions:
 - A. 1:3 HCl:HF (50 ml/sample)
 - B. 1:1:8 HCl:HNO₃:H₂O (50 ml/sample)
2. Weigh 0.500 gm powdered sample into Teflon beaker.
3. Measure 50 ml solution A into plastic graduated cylinder. Add 10 ml to sample, swirl to ensure wetting, then add rest.
4. Cover with Teflon watchglass and heat for 12 hours (i.e., overnight).
5. Remove watchglass, increase heat to just below boiling point and remove beaker from heat after sample evaporates to dryness (3-4 hours). Do not burn or sample will be difficult to redissolve.
6. Measure 50 ml solution B into graduated cylinder. Add approximately 100 ml to dried sample, wetting well, and break up sample with Teflon rod. Add remaining solution while rinsing rod.
7. Replace beaker on hot plate and evaporate to 35 ml (approximately 1 hour).
8. Let cool, then transfer to 50 ml volumetric flask. Rinse beaker twice with deionized water, adding rinse to flask.
9. Dilute to 50 ml with deionized water, mix well, and store solutions in plastic bottles.
10. Run a blank (add all reagents but no sample) with each set of samples.

Full strength, 1% by weight, rock solutions used for trace-element analyses. Solutions diluted by 50 times (2 ml diluted to 100 ml) used for major-element analyses. All determinations must be corrected for weight by dividing by the factor $\left(\frac{\text{sample wt.}}{0.5000}\right)$.

APPENDIX VI

Partial Chemical Analyses

	<u>1-1B</u>	<u>3-2A</u>	<u>5-1B</u>	<u>7-1A</u>	<u>7-1B</u>	<u>8-1^{#1}</u>	<u>10-1</u>	<u>10-2B</u>	<u>11-2B</u>	<u>11-2C</u>
SiO ₂	50.55	48.94	50.31	52.58	52.77	49.44	48.96	48.03	48.90	48.84
TiO ₂	-	2.85	2.48	2.14	2.11	3.61	3.02	3.17	2.80	2.85
FeO _T	10.84	10.98	10.00	9.41	9.09	13.60	11.53	11.89	11.60	11.96
CaO	7.01	11.04	5.87	5.42	5.44	9.10	7.75	7.35	7.01	6.94
K ₂ O	1.82	0.86	1.96	2.14	2.14	0.83	1.59	1.37	1.63	1.70
Rock Type	H-M	H(-AOB)	M	M	M	H(-AOB)	H	H	H	H

	<u>11-2D</u>	<u>11-2G</u>	<u>12-2</u>	<u>12-2F</u>	<u>12-2A</u>	<u>15-1</u>	<u>16-1</u>	<u>20-1</u>	<u>25-1</u>	<u>25-2</u>
SiO ₂	48.72	48.81	48.15	48.90	48.79	51.70	51.89	47.90	51.44	51.59
TiO ₂	-	2.88	2.89	2.82	2.91	2.30	1.71	2.66	2.21	2.14
FeO _T	11.60	11.71	12.14	11.81	11.69	9.91	7.44	11.03	9.97	9.89
CaO	7.23	7.04	6.64	7.11	7.10	-	2.13	5.67	4.67	4.90
K ₂ O	1.54	1.64	1.55	1.61	1.60	2.02	2.60	1.75	2.06	2.07
Rock Type	H	H	H	H	H	M	M-B	H-M	M	M

APPENDIX VII

Published Sr Isotope Ratios for Hawaiian Rocks

	<u>Rock Type</u>	<u>Sr⁸⁷/Sr⁸⁶</u>	<u>Reference</u>
<u>ISLAND OF HAWAII</u>			
<u>Kilauea Volcano</u>			
1955	ol. basalt	0.7033	1
1955	basalt	0.7035	1
Prehistoric	basalt	0.7034	1
3 Kilauea Iki	basalt	0.7032	1
Kahuku Pali	basalt	0.7035	1
Kilauea Iki	tholeiite	0.7024	2
Kilauea Iki	tholeiite	0.7032	2
Kilauea Iki	tholeiite	0.7032	2
H-11-61 1960 Kapoho	tholeiite	0.7046	3
H-15-61 1959 Kilauea Iki	tholeiite	0.7056	3
Kilauea Rift-Tholeiites 1	tholeiite	0.70364	7
Kilauea Rift-Tholeiites 2	tholeiite	0.70357	7
Kilauea Rift-Tholeiites 4,5	tholeiite	0.70358	7
Kilauea Rift-Tholeiites 6	tholeiite	0.70357	7
<u>Mauna Loa</u>			
1881 Flow (JP-12)	tholeiite	0.7041	5
<u>Hualalai</u>			
Puu Waawaa	trachyte	0.7028	1
Puu Anahulu	trachyte	0.7029	1
Puu Anahulu (JP-15)	trachyte	0.7043	5
Puu Anahulu H-8-61	trachyte	0.7059	3
Puu Anahulu 17	trachyte	0.7054	3
Puu Waawaa 18	trachyte glass	0.7052	3
Puu Waawaa H-8-61	trachyte glass	0.7072	3
<u>Mauna Kea</u>			
JP-10	hawaiite	0.7043	5
H-6-61	hawaiite	0.7048	3
H-7-61	hawaiite	0.7043	3
Paauilo Quarry	hawaiite	0.7046	3
No Locality	picrite	0.7026	1
No Locality	hawaiite	0.7027	1
<u>Kohala</u>			
16	mugearite	0.7045	3
61-104 Puu Makea	mugearite	0.7052	3
No Locality	mugearite	0.7028	1

APPENDIX VII (Continued)

<u>ISLAND OF MAUI</u>	<u>Rock Type</u>	<u>Sr⁸⁷/Sr⁸⁶</u>	<u>Reference</u>
<u>Haleakala</u>			
H-5-61	ankaramite	0.7033	2
<u>ISLAND OF OAHU</u>			
<u>Waianae V.S.</u>	average	0.7030	4
C-16	tholeiite	0.7029	4
C-47	alkalic basalt	0.70305	4
C-170	hawaiite	0.7033	4
---	rhyodacite	0.70285	4
<u>Koolau V.S.</u>	7 thd., 1 alk.	0.70385	4
<u>Honolulu V.S.</u>	neph. basalts	0.7029	4
JP-16	mel. neph. I	0.7030	5
JF-30	mel. neph. II	0.7031	5
JP-13	neph. basalt	0.7031	5
JP-11	basanitoid	0.7033	5
61-66	linosaite	0.7045	3
61-127	tuff	0.7038	3
61-131	neph. basalt	0.7044	3
---	melilite basalt	0.7026	1
---	melilite basalt	0.7026	1
68-SAL-7	xenolith	0.7031	8
68-SAL-25	xenolith	0.7035	8
68-SAL-24	xenolith	0.7029	8
68-KEE-1	nephelinite	0.7036	8
68-PY-1	nephelinite	0.7033	8
Sea Water	gulf stream	0.7081	2
Diamond Head, Oahu	shell & coral rock	0.7088	4
<u>ISLAND OF MOLOKAI</u>			
<u>East Molokai</u>			
Mo-12-72	mugearite	0.7035	6
Mo-10-72	mugearite	0.7024	6

REFERENCES

1. Gast (1967)
2. Hedge and Walthall (1963)
3. Lessing and Cantanzaro (1964)
4. Powell and DeLong (1966)
5. Powell et al. (1965)

APPENDIX VII (Continued)REFERENCES (Continued)

6. Hlava (1974)
7. Hart (1973)
8. O'Neill et al. (1970)

APPENDIX VIII

Non-conclusive fractionation diagrams. See text and Fig. 18.

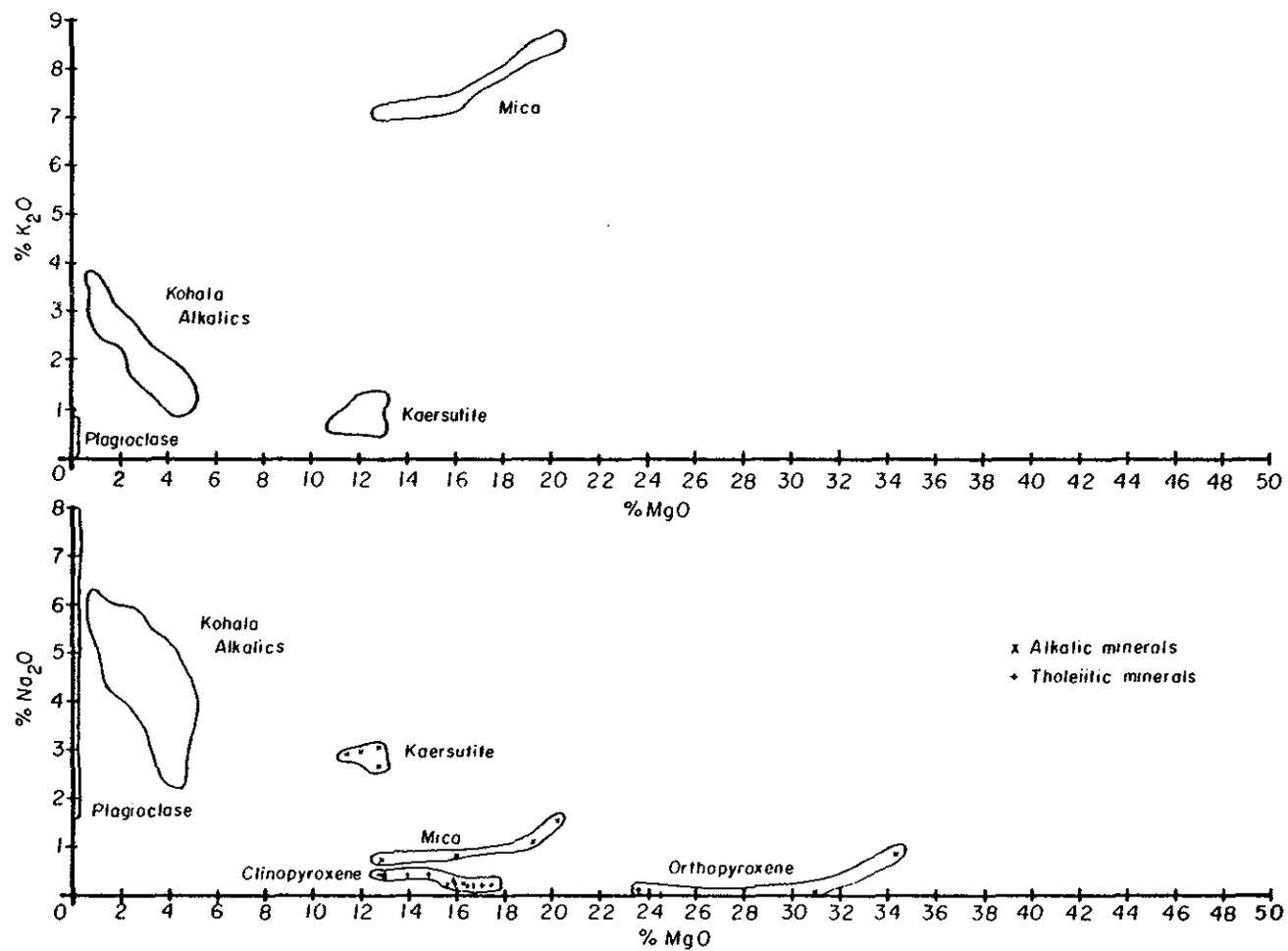


Fig. VIIIa. (top) Potash vs. magnesia. VIIIb. (bottom) Soda vs. magnesia.

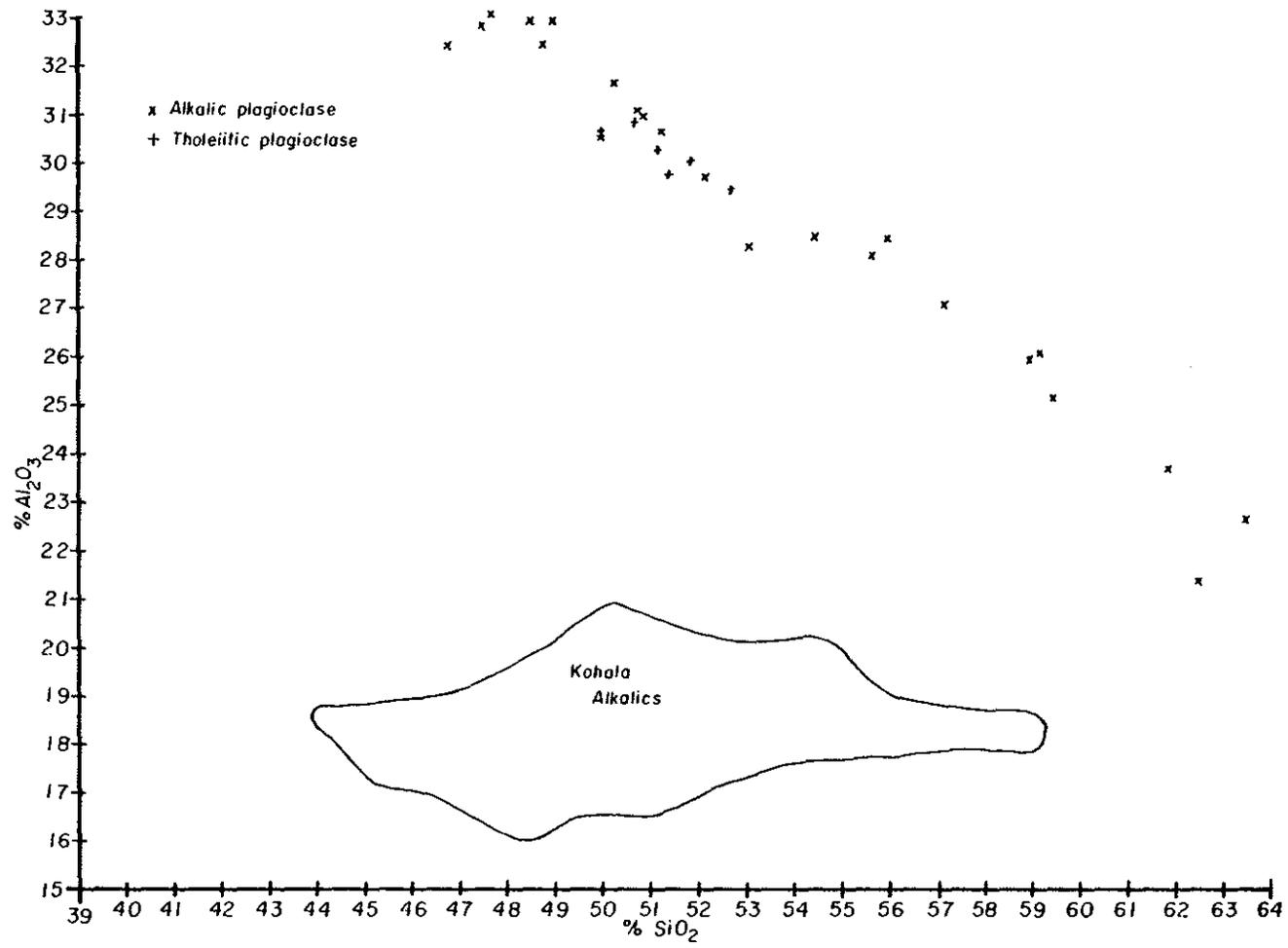


Fig. VIIc. Alumina vs. silica.

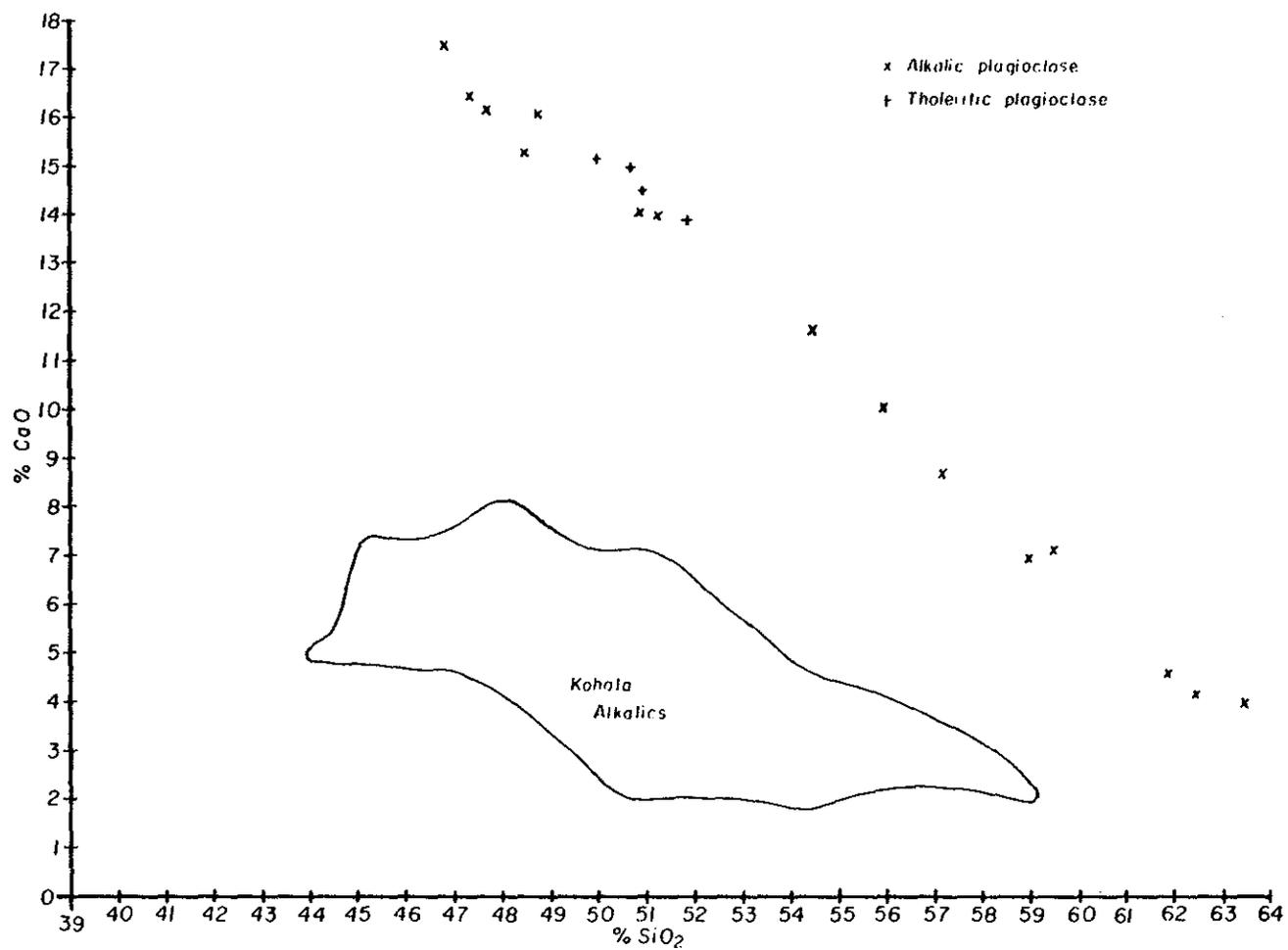


Fig. VIIIId. Lime vs. silica