GEOLOGY OF THE KAWAIHAE QUADRANGLE,

KOHALA MOUNTAIN, ISLAND OF HAWAII

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ABSTRACT

In the Kawaihae Quadrangle, alkali lavas of the Hawi Formation cap the Kohala Mountain shield-building lavas of the Pololu Formation, Kohala Mountain. A distinct soil horizon separates the two formations. The southern flank of Kohala Mountain is now buried by lavas of Mauna Kea's Hamakua Formation. Hawi activity was previously thought to have ended before the final burial of Kohala's southern flank. The Hawi Formation mugearite flow from Puu Loa, however, overlies a late Hamakua flow. The contact is well exposed in the Kawaihae quarry. The Puu Loa flow is 0.082 $\pm$ 0.006 m.y. old based on three potassium-argon age determinations. Pahala Ash 1.2 to 1.5 m in thickness, occurs over the entire map area with the exception of the Puu Loa flow. The flow is deflected around Puu Makela, a small volcanic dome of benmoreite composition.

The southwestern slope of Kohala Mountain is essentially unmodified by erosion. The absence of marine terraces and deposits, and the presence on the coast of Puu Ulaula, a Pololu cinder cone, suggests that sea level has not been higher than present sea level, at least since Puu Ulaula was formed.

All rock types mapped are members of the alkalic suite. Within the mapped area, the Pololu and Hamakua Formations consist of alkalic olivine basalts. The Hawi

Formation consists of mugearite, hawaiite and benmoreite; mugearite is the most abundant. Six new chemical analyses are reported in addition to previously published analyses. Chemical analyses show that Kawaihae lavas follow the average Hawaiian fractionation trend. Petrographic, microprobe and chemical analyses for Hawi lavas indicate that they are intergradational; the mugearite and hawaiite fields overlap. The hawaiite flow from Puu Kawaiwai topographically belongs to Kohala Mountain. Because the hawaiite is chemically, mineralogically, and texturally similar to Hawi mugearites, it is considered to have a Kohala source rather than a Mauna Kea source, as previously suggested by others.

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INTRODUCTION

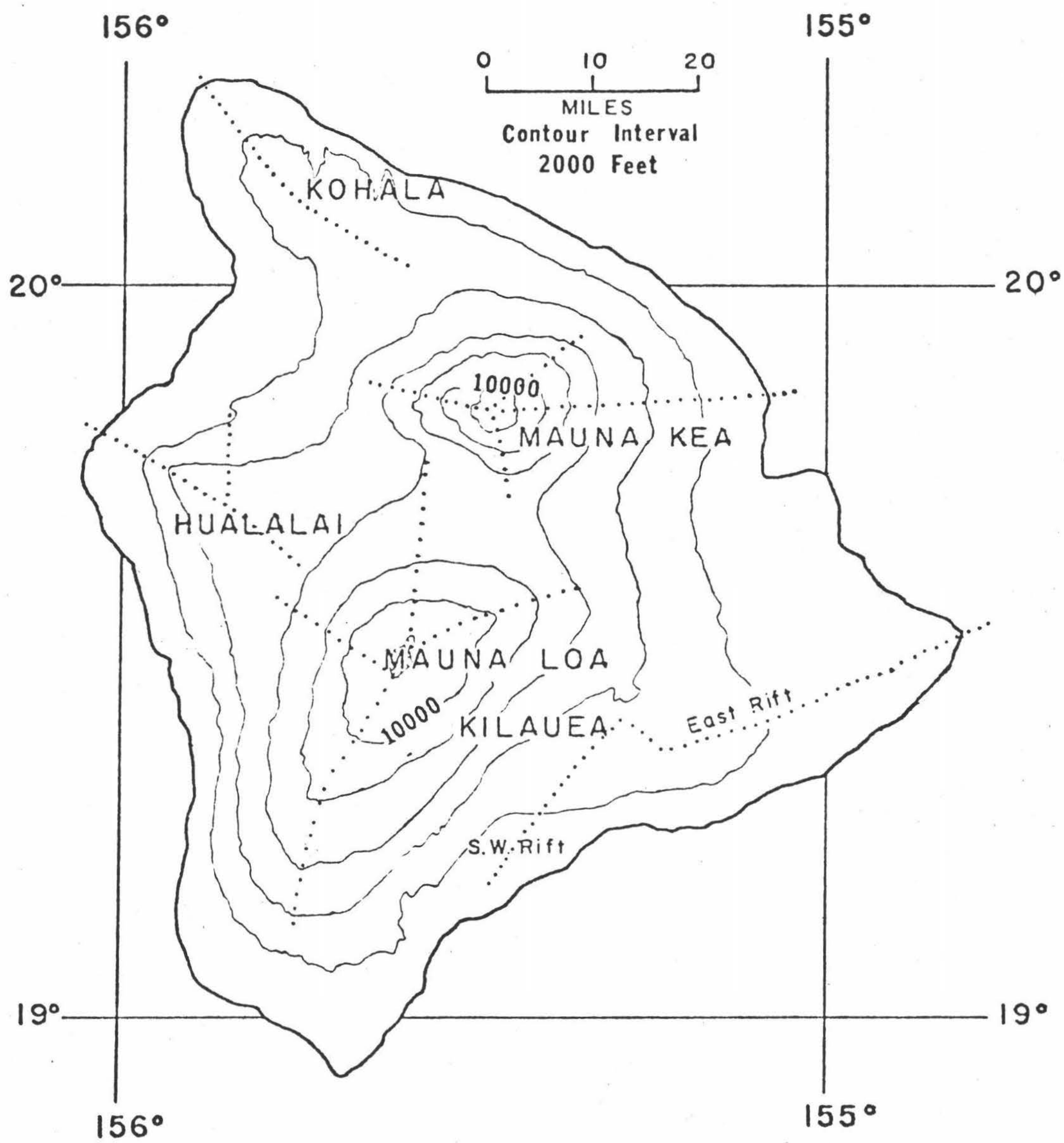
Purpose and Scope

The purpose of this study was to determine the geographic and stratigraphic rock type distribution and composition on Kohala Mountain within the Kawaihae Quadrangle, Island of Hawaii. The detailed map of the Kawaihae Quadrangle and the description of the petrology, petrography, and relative age relationships of rock units in this report are intended to add to the knowledge of the geology of Kohala Mountain and the Island of Hawaii.

General Characteristics

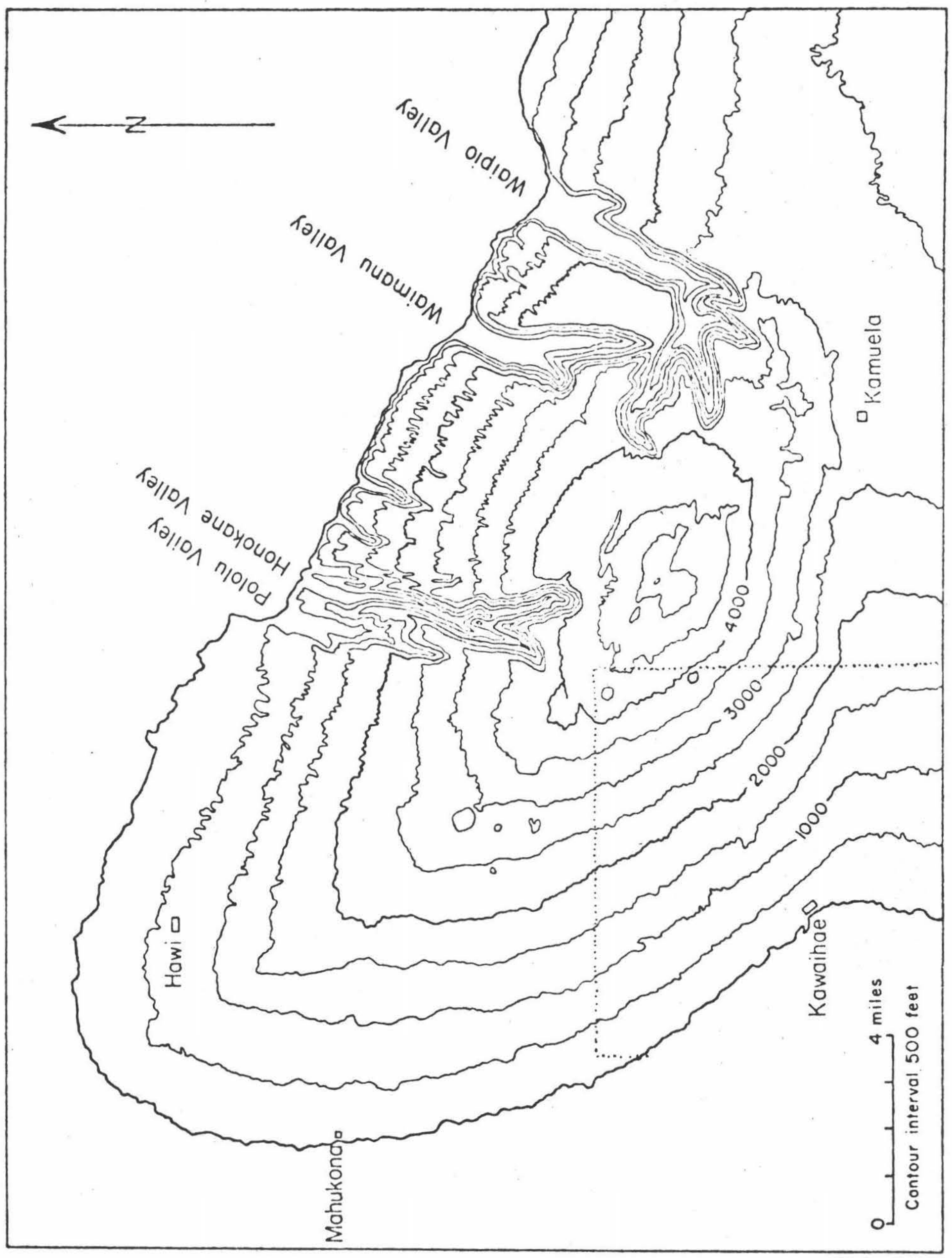
The Island of Hawaii is the youngest island of the Hawaiian Chain as evidenced by its continuing volcanic activity. Kohala Mountain, an elongate shield volcano which forms the northern portion of the Island of Hawaii, is considered to be the oldest volcano of the island (Stearns and Macdonald, 1946) (Fig. 1). The southern flank of Kohala is buried by late flows of the Hamakua Formation of Mauna Kea. Stearns and Macdonald (1946) recognized two periods of eruptive activity on Kohala Mountain. They named the rocks of the two periods the Pololu volcanic series and the Hawi volcanic series, but a revision of Hawaiian stratigraphic nomenclature presently being made alters the names to Pololu Formation

Figure 1. Volcanoes and rift zones on the Island of Hawaii. The rift zones are shown by dotted lines (after Macdonald and Abbott, 1970, Fig. 189).


156°
155°
0 10 20
MILES
Contour Interval
2000 Feet
KOHALA
20°
20°
10000
MAUNA KEA
HUALALAI
MAUNA LOA
10000
KILAUEA
East Rift
S.W. Rift
19°
19°
156°
155°

and Hawi Formation (Macdonald, verbal communication, 1977). The younger Hawi Formation forms a cap up to 153 m thick which thins rapidly away from the summit region, and is composed of alkalic lavas representing hawaiites, mugearites, and trachytes. Rocks of the alkalic suite make up less than 1% of the total volume of Kohala Volcano (Macdonald and Katsura, 1962). The two volcanic formations are separated by a thin soil layer on the western slopes, but by a marked erosional unconformity on the eastern slopes. The eastern part of the volcano is cut by canyons 305 m to 763 m deep, and has sea cliffs up to 427 m high. The western part, however, is not very altered by erosion (Macdonald and Abbott, 1970), and has, in places, a sea cliff no higher than 15 m high (Fig. 2). Two principal rift zones intersect on the Kohala summit, one trending N 35° W and the other S 65° E (Stearns and Macdonald, 1946). Most eruptive activity occurred along the northwest rift. At or near the end of the Pololu activity, collapse at the summit produced a trough or graben extending 10 km N 50° W, which is paralleled by en enchelon faults, whose curved character suggests the existence of an oval-shaped caldera at the end of Pololu activity (Stearns and Macdonald, 1946). The fault scarps were important in the distribution of Hawi Formation lavas. Those on the northwest and

Figure 2. Map of Koahla Mountain, showing the huge valleys cut into the windward (northeastern) slope, and the small degree of dissection of the leeward slope (after Macdonald and Abbott, 1970). Dotted line indicates area of Plate I of this report.


N
Waipio Valley
Waimanu Valley
Honokane Valley
Pololu Valley
Kamuela
4000
3000
2000
1000
Hawi
Kawaihae
Mahukona
0
4 miles
Contour interval 500 feet

southeastern sides of the caldera were buried and overrun by the Hawi lavas, but higher fault scarps on the northeastern side prevented the spread of Hawi lavas in that direction. Stearns and Macdonald (1946, p. 47) suggest that the extreme erosion of Kohala Mountain's northeast side was caused not only by the much higher rainfall typical on the windward side, but primarily by the uninterrupted erosion of Pololu lavas left uncovered by Hawi lavas.

The contrast in erosional dissection of Kohala Mountain's northeast and southwest flanks contributes to the question of the age of the volcano. Stearns and Macdonald (1946) believed that the Pololu Formation lavas were erupted during the Pliocene epoch and that the Hawi Formation lavas were erupted during the Pleistocene. Macdonald and Abbott (1970) now consider both Pololu and Hawi lavas to have erupted during Pleistocene time on the basis of recent potassium-argon dating studies. McDougall's potassium-argon studies of Kohala lavas (McDougall and Swanson, 1972; McDougall, 1964, 1969) indicate that the volcano became extinct in very late Pleistocene time.

McDougall's potassium-argon ages of flows from the predominantly tholeiitic Pololu Formation range from 0.33 m.y. to about 0.45 m.y. The subaerial part of the shield, therefore, was built over a period of 0.1 m.y. in the late Pleistocene and most of the Island of Hawaii is younger than 0.4 m.y. The mugearite flows from the younger Hawi Formation are between 0.06 m.y. and 0.25 m.y. old. The hiatus between the basalt shield-building stage of volcanism and the differentiated alkalic lava on Kohala is thus less than 0.2 m.y. (McDougall and Swanson, 1972). The Pleistocene age for Kohala is also favored because of paleomagnetic studies by Doell and Cox (1965) which indicate that both the Pololu and Hawi Formations have a normal direction of remanent magnetization and that the Pololu is probably less than 0.7 m.y. in age.

Potassium-argon dates on Hawi lavas provide some control as to the age of the Hamakua Formation lavas of Mauna Kea, because the lavas of this series are interbedded with and overlie Hawi lavas (Stearns and Macdonald, 1946, in McDougall, 1969). The later part of the building of MaunaKea's main shield is contemporaneous with the late Hawi activity of Kohala Volcano. Mauna Kea, however, continued to be active long after the cessation of Kohala Volcano. The canyons of Kohala had nearly reached their present size by the time of eruption of the late lavas of Mauna Kea, as shown by the Mauna Kea flow exposed in Hiilawe Canyon, a tributary of Waipio Valley (Macdonald and Abbott, 1970, p. 300). The author, however, disagrees that the Hawi lavas had ceased erupting before the late Hamakua lavas finished burying the southern flank of Kohala. Field relationships in the Kawaihae quarry indicate that a Hawi flow overlies a late Mauna Kea Hamakua flow. The stratigraphic relationships determined in the quarry will be discussed later. Potassium-argon studies completed by the author under the supervision of J. J. Naughton and V. Greenberg give an age of 0.08 m.y. for the young Hawi flow in the Kawaihae quarry. This age falls within McDougall's range for the eruption of Hawi Formation lavas.

The Kawaihae Quadrangle is the focus of this study of Kohala Mountain. (See Plate I.) The northeastern portion of the quadrangle includes Hawi Formation cinder cones, vents, and flows on the Kohala summit; the southern portion of the quadrangle shows the contact between Kohala Mountain and Mauna Kea; and the western portion shows the relationship of Hawi and Pololu lavas in numerous localities. The map area is virtually desert except for the upper part, which is lush grassland and in part, forest. Much of the area above 550 m (1800 feet) elevation is used as grazing land for cattle. Because streams are intermittent, a system of pipelines and water tanks brings water from the summit area to the dryer slopes below. The town of Kawaihae, for which the quadrangle is named, is built around a man-made harbor. The fill for the harbor was obtained from off-shore coralline reef material. The area also contains numerous remanents of the ancient Hawaiians. Ancient Hawaiian trails traverse the southwestern slope of Kohala Mountain and numerous house sites are seen along the coast. Puukohola Heiau, built by order of King Kamehameha I in 1790, is 1.3 km south of Kawaihae at the entrance to Spencer Park.

Previous Investigations

A reconnaissance map describing the distribution of lavas and structural features of Kohala Mountain was first completed by Harold T. Stearns (Stearns and Macdonald, 1946). Mauna Kea lavas were mapped similarly by Gordon A. Macdonald and are described in the same report. Earlier Kohala investigations are limited to observations and sampling of lavas along the Kohala-Waimea road and in the Mahukona area.

Cross (1915) reports that Dana and Hitchcock mentioned the Kohala region only with reference to its relative age and topography. Dana (1890) believed erosion could not be responsible for the origin of Waipio and Waimanu Valleys, because the upper stretches of their streams were bent parallel to the coast. Powers (1917) thought that faults determined the courses of those streams. Branner (1903) pointed to the flat floor of

Waipio Valley as proof of deep submergence. Stearns' (1946) field observations did not support Jaggar's (1920) theory that the high sea cliffs between Waipio and Pololu Valleys were caused by a downfaulted block and that a parallel block extending inland to the crest of Kohala Mountain had slipped eastward.

Early investigators found the late Hawi lavas to be very different from the "normal" Hawaiian basalts (Cross, 1915). Cohen (Cohen, 1880, in Cross, 1915, p. 33) examined several rocks from Kohala Volcano in 1880, and classified them into two groups: normal plagioclase basalts rich in olivine and another rock type transitional from basalt to augite andesite. Cross (1915) disagreed with Cohen's choice of "augite andesite" because augite was scarce in those rocks. Dutton (1884) remarked that the Kohala lavas were quite different from those of other volcanic centers on the island and thought they appeared similar to the andesites because of their less ferruginous, more feldspathic character. He thought they should be classified as augite andesites or normal basalts. The loss of his samples on the way to Washington prevented Dutton from confirming his suspicions petrographically. In 1896, Lyons published the chemical analyses of three Kohala lavas which included a basalt with feldspar phenocrysts, a basaltic fragment from a cinder cone, and a very salic rock which he thought was characteristic of the Waimea area lavas, apparently an oligoclase andesite (Macdonald, 1949b, p. 53). At Mahukona, Cross (1915) noted the lack of erosion on the west slope of Kohala and collected a single sample. From his macroscopic and microscopic description of the sample (Cross, 1915, p. 33-34), it appears to the author to have been a hawaiite, but no one since has been able to find a hawaiite at that location (Macdonald, verbal communication, January, 1977). Washington (1923) published the descriptions and chemical analyses of several specimens from the Kohala area. He recognized two major groups of lavas, basalts and andesites, which he preferred to name according to the dominant plagioclase present. Oligoclase andesite is the predominant andesite and Washington calls this rock type "oligoclasite," in preference to Iddings' (1913) term "kohalaite."

There are petrographical and chemical analyses of Kohala rocks in Stearns and Macdonald (1946), Macdonald (1949), Macdonald and Katsura (1964), and Macdonald (1968). The 1946 and 1949 papers include Washington's (1923) analyses and Lyons' (1898) analyses. Muir and Tilley (1961) report an analysis of a Hawi lava 2.1 km ESE of Puu Kawaiwai. Of the 35 Kohala analyses reported in the above papers, 9 are of specimens collected within the Kawaihae

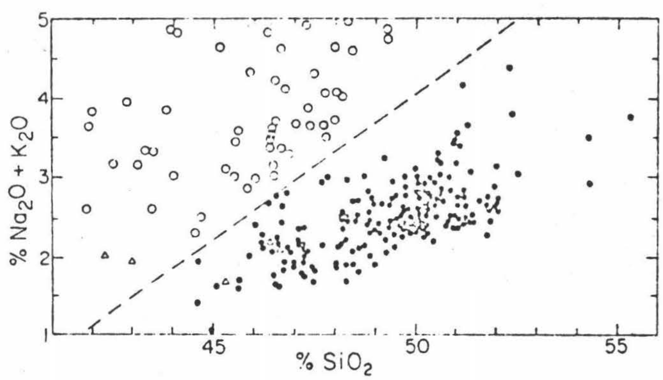
Quadrangle. Six new chemical analyses are presented in this report.

Nomenclature

Mugearite was first defined as a rock type on the Island of Skye by Harker in 1904 (Muir and Tilley, 1961, p. 186). Muir and Tilley state that today mugearite is recognized as a common, distinctive member of the alkali igneous rock series derived from alkali olivine basalt magma of some oceanic islands, including the Hawaiian Islands. Those rock types originally described as "oligoclase andesite" have the essential characteristics of mugearite and are linked to the alkali olivine basalt parent through intermediate rock types described by Macdonald (1949) as "andesine andesites." Iddings (1913) used the term "hawaiite" to describe the andesine andesites and "kohalaite" to describe the oligoclase andesites. Wells (1954) wanted the term "mugearite" limited to those oligoclase basalts with trachytic texture. He wanted those with mugearite composition but basaltic appearance to be called oligoclase basalts (*in* Muir and Tilley, 1961, p. 186). Williams, Turner, and Gilbert (1954) use Wells' (1954) terminology. Because the Hawaiian andesites are very distinct from the typical calc-alkaline andesites of continental margins, Macdonald (1960) proposed that the "andesite" term be dropped for oceanic alkali suite andesites, and that "hawaiite" be used in place of andesine andesite and "mugearite" be used in place of oligoclase andesite. Hawaiite is considered intermediate in composition between alkali olivine basalt and mugearite and grades into both (Macdonald, 1960). Wilkinson (1974) points out that igneous rock nomenclature should be based primarily on modal compositions, and that classifications must coordinate the mode with the rock chemistry. The difficulties of microscopically estimating modal alkali feldspar makes 'pigeon-hole' type classifications difficult to use, and "ternary feldspars tend to obscure the simplified twofold feldspar grouping (plagioclase vs. alkali feldspar) that such classifications demand" (Wilkinson, 1974, p. 71). Wilkinson's remarks support the use of Macdonald and Katsura's (1964, p. 88-89) classification of the oceanic alkalic basalt-trachyte association, which is adopted in this report, as follows:

1) Tholeiitic suite: rocks with tholeiitic mineral composition, falling below the boundary line in an alkali:silica diagram (Fig. 3).
    a) Tholeiitic basalt--containing less than 5% modal olivine.
    b) Tholeiitic olivine basalt--containing 5% or more modal olivine.
    c) Picrite basalt--contains less that 30% total

Figure 3. Alkali:silica diagram of Hawaiian basaltic rocks, showing the boundary (diagonal dashed line) between the tholeiitic and alkalic fields. Rocks with tholeiitic mineral composition are shown by solid dots, rocks with alkalic mineral composition by open circles, and ankaramites by triangles (from Macdonald and Katsura, 1964).



% Na2O + K2O
% SiO2
1
2
3
4
5
45
50
55

feldspar; abundant olivine phenocrysts.

2) Alkalic suite: rocks with alkalic mineral composition, falling above the line in an alkali: silica diagram (Fig. 3).

   a) Alkalic basalt--containing less than 5% modal olivine.

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

   e) Ankaramite (picrite basalt of ankaramite type)--containing very abundant phenocrysts of olivine and augite, less than 30% total feldspar, and augite more abundant than olivine.

   f) Hawaiite--a rock with moderate to high color index and frequently basaltic habit in which the normative and modal feldspar is andesine, and with soda:potash ratio greater than 2:1 (Macdonald, 1960, p. 175).

   g) Mugearite--a rock similar to hawaiite, with soda:potash ratio greater than 2:1, but the normative and modal feldspar is oligoclase.

   h) Trachyte--a rock composed essentially of alkalic feldspar and minor biotite, hornblende, or pyroxene. Small amounts of sodic plagioclase may be present.

i) Benmoreite--a trachyte trending toward mugearite.

Hawaiian volcanoes containing alkalic rocks are of two distinct types: "Kohala type" and "Haleakala type" (Macdonald and Katsura, 1964, p. 187-188). The Kohala-type volcano, which is under consideration in this study, has a thin cap of mugearite and trachyte separated by an erosional unconformity and commonly by a bed of ashy soil from the underlying basalts. Alkalic basalts appear in the uppermost part of the shield, beneath the erosional unconformity and are interstratified with tholeiitic rocks in places. In the Haleakala-type volcanoes there is no widespread unconformity. The alkalic basalts and related rocks appear in the middle or late part of the caldera-filling stage, commonly preceded by rocks of transitional nature. The transitional rocks are sometimes interbedded with tholeiitic rocks. Transitional and alkalic basalts with abundant large plagioclase phenocrysts are associated with both tholeiitic and alkalic rocks in the uppermost part of the shield of Kohala-type volcanoes, and in both the transitional and late stages of those of Haleakala type.

The names used for volcanic vents and other geomorphologic features on Plate I follow those on the 1956 U.S. Geological Survey topographic map of the Kawaihae

Quadrangle. Additional names come from a copy of a 1931 Kahua Ranch map by Harry H. Allen provided by Mr. J. White of the Hilton Head Company. Hawi Formation flows are often referred to by the name of the vent from which they issued, such as "Puu Loa flow." It should be noted that these are not intended to be formal stratigraphic names. They refer to the units mapped within the context of this report only.

Fieldwork

Fieldwork was conducted during two major time periods, the month of June, 1975 and from July 8-30, 1976. The final phase of fieldwork was completed January 3-6, 1977. The U.S.G.S. topographic map of the Kawaihae Quadrangle (1956) was used as a base map. Mapping was done directly on the base map and extensively on aerial photographs taken in 1965, obtained from the U.S. Department of Agriculture. Difficulties encountered with the base map included the mislocation on the map of several trails and a water tank, and the inconvenience of main roads not shown due to the 1956 date of the map. The new Kawaihae-Hawi and Kawaihae-Kona roads have been added to Plate I. A Brunton compass and pocket altimeter were used as location aides.

The author was accompanied by various field assistants 13 days of the total time spent conducting fieldwork.

Much of the coverage of the area was accomplished by hiking from the upper Kohala-Waimea road down the slope of the mountain to the lower Kawaihae-Hawi road. The total number of samples collected is 115. Of these, 60 have been thin sectioned and modally analyzed under the petrographic microscope.

Acknowledgments

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GEOMORPHOLOGY

The landforms in the Kawaihae Quadrangle are primarily constructional (Plate I). The mountainside is essentially the original land surface built by the volcano (Macdonald and Abbott, 1970, p. 295). The large volcanic vents in the northeastern portion of the area are cinder cones of the Hawi Formation. The cones are slightly asymmetrical as they are built higher on the southwest, the side which was downwind from the vent during eruption (Wentworth and Macdonald, 1953, p. 25). All of the cones (Puu Pili, Puu Honu, Puu Iki, Puu Lapalapa, and Puu Loa) have bowl-shaped craters, but that of Puu Mala was breached on the downhill side by a lava flow issuing from the vent. Puu Kaipuolelo, which is east of Puu Aiea, and Puu Mauu, which is east of Keanahalulu Gulch, are very small cinder cones (17 and 27 m high, respectively) that are surrounded by subsequent lava flows from Puu Waiakanonula and Puu Lapalapa, respectively. Puu Waiakanonula is not in the map area, but is located 2.55 km northeast of Puu Aiea. Puu Pili, the largest of the cones, is more than 275 m high. The total relief of the map area from sea level to the top of Puu Pili is 1,436 m.

The cinder cones have changed very little in form. The loose pyroclastic material is resistant to physical weathering and erosion because it is so permeable (Wentworth and Macdonald, 1953, p. 67).

Puu Makela is not a cinder cone, but a small volcanic dome of benmoreite that is partially buried by flows from Puu Loa.

There are only two cinder cones in the area representative of Pololu eruptive events. Puu Ulaula is a red horseshoe-shaped cone located on the northwest coast, and Puu Kamalii is a red cone northeast of Kawaihae. Both are gullied by erosion.

The slope topography formed by Pololu lavas is relatively smooth compared to the lumpy, hilly topography formed by Hawi lavas. Hawi flows often end with steep terminal margins such as that of the Puu Loa flow at Puu Kanane, 1.4 km north of Kawaihae. Along the coast, the Hawi and Pololu Formations are easily distinguishable. The Pololu Formation is characterized here by low topography, layered flows, and a rounded, smooth surface. The

Hawi Formation, however, appears tumbled and as sharp, jagged knife edges protruding into the sea. A viscous Hawi flow from Puu Lapalapa forms a prominent peninsula at the mouth of Honokoa Gulch. A small sea arch 1.0 km southwest of Puu Ulaula was formed in a Puu Aiea flow by the wave erosion of the lower flow breccia. In a deep, narrow inlet, 0.15 km northwest of the mouth of Kapae Gulch, are twin sea caves separated by a wall about 1.8 m thick. The caves are eroded about 6.0 m into the flow breccia of the Puu Pili flow, and expose the deep red soil horizon and feldspar-phyric basalt of the Pololu Formation in the floors of the caves.

Hamakua Formation flows from Mauna Kea form a hummocky topography. These flows bury the southern flank of Kohala Mountain along Makeahua Gulch, forming a gentle slope of 106 m per km (560 feet per mile), which is in sharp contrast with Kohala's slope of 218 m per km (1150 feet per mile). Along the southwest coast formed by Mauna Kea lavas are three sandy beaches: Kaunaoa Beach, Mauumae Beach and the beach at Spencer Park.

Erosional features of the area include stream valleys and sea cliff development. All stream valleys are in a youthful stage of development. There is no major deposition in any of the stream valleys except for large blocks and slightly rounded boulders that originated from the valley walls. Pololu lavas are more dissected by streams and gullies because these lavas are older, more deeply weathered, and more easily eroded than Hawi lavas. Hawi lavas followed former Pololu topography in several areas. Honokoa Gulch and its tributaries are the deepest erosional features on the southwest slope of Kohala. The gulch is 0.2 km wide on the average and has a maximum depth of approximately 85 m. The upper portion of the gulch, named Keawewai Stream, has an impressive sequence of waterfalls and plunge pools created where the stream leaves the younger, more resistant Hawi lavas and erodes into Pololu lavas. Plunge pools are common in most of the streams on the upper slopes. The presence of a large plunge pool is usually indicative of a Pololu-Hawi contact, or that the stream has eroded the less resistant flow breccia layer of a Hawi flow.

Sea cliff development along the west coast of Kohala is minimal. Cliffs formed in Pololu lavas are no more than 15 m high and are not continuous along the coast. The Hawi Puu Lapalapa flow which forms a peninsula at the mouth of Honokoa Gulch also has a sea cliff approximately 15 m high. Large jagged blocks are commonly found beneath sea cliffs formed in Hawi lavas.

Stearns (1973, p. 3484) postulates that Kohala Mountain and the Island of Hawaii were submerged at least 366 m and possibly as much as 520 m during Pleistocene time. He also describes marine deposits 12 m and 80 m above sea level near Mahukona, northwest of the map area of this report, and expresses surprise that similar deposits were not found within the Kawaihae Quadrangle (Stearns, verbal communication, April, 1977). The author found no evidence of marine deposits, or wave cut benches or terraces in the quadrangle. The presence of Puu Ulaula right on the coast is evidence that submergence here has not been higher than that seen today since the cone was built. Stearns originally indicates (Stearns and Macdonald, 1946, p. 175) that the cone lacks the sandy beds typical of a littoral cone and, therefore, must have formed during a lower stand of the sea and was brought to sea level by Pleistocene submergence. In the author's opinion, the cone would not have survived 80 m more of submergence.

ROCK DISTRIBUTION AND STRATIGRAPHY

Hamakua Formation

Hamakua Formation lavas (hmk) belong to the alkalic suite and comprise approximately 18% of the area mapped (Plate I). These Mauna Kea flows bury the southern portion of Kohala Mountain at Makeahua Gulch. Sampling along the Kawaihae-Kona road at roadcuts from the Hapuna Bay access road to the junction of the Kawaihae-Waimea road, and sampling in the Makeahua Gulch, Spencer Park and Kawaihae quarry area, reveals a sequence of three units that can be traced laterally. All the lavas are of the a'a type. The basal flow is a porphyritic alkali basalt with abundant plagioclase phenocrysts, and is separated from the center unit by a very red, oxidized clinker layer. The central unit is a massive alkalic olivine basalt with only occasional phenocrysts of plagioclase and olivine. The uppermost unit is separated from the center unit by a fresh-looking clinker layer. The upper unit varies locally from an ankaramite with abundant olivine and pyroxene phenocrysts to a porphyritic alkalic basalt with moderate amounts of olivine and pyroxene phenocrysts. This change in the abundance of phenocrysts within the upper unit may be explained by mechanical sorting during flowage (Macdonald, verbal communication, April, 1977). Phenocrysts are especially concentrated at the base of the upper unit. Macdonald (1972, p. 2974) suggests that crystal differentiation of magma in the volcanic conduit may be followed first by the eruption of the phenocryst-poor upper portion of the magma column and later by the eruption of the phenocryst-enriched lower portion. Perhaps the phenocryst-poor middle unit and the phenocryst-rich upper unit are two phases of the same flow.

Pololu Formation

Pololu Formation lavas (ppl) comprise approximately 20% of the area mapped. They underlie lavas of the Hawi and Hamakua Formations (Plate I). Those Pololu lavas belonging to the tholeiitic suite are not represented in the sampling and mapping study completed within the Kawaihae Quadrangle; the lavas sampled belong to the alkalic suite. It is suggested that tholeiitic basalts and/or basalts transitional to alkali basalts might be present in the lower section of the Pololu Formation exposed in Honokoa Gulch, the deepest erosional feature in the quadrangle. The bottom of the gulch was inaccessible to the author because of its vertical walls and great depth. Plunge pools and waterfalls made hiking up the gulch from its mouth impossible. Many flows and dark red intercalated ash beds in the section are visible from the rim of the gulch, indicating more explosive, less frequent eruptions in the last shield-building phases than in earlier stages (Macdonald and Katsura, 1962, p. 188). Pololu basalts are also exposed in many plunge pools of the upper gulches, some of the areas being too small to show on Plate I.

Pololu lavas are distinguished in hand specimen by abundant plagioclase phenocrysts, some greater than 5 mm in length. None of the lavas from the other volcanoes on the island of Hawaii has as great an abundance of feldspar phenocrysts as the Pololu lavas (Stearns and Macdonald, 1946, p. 197). Augite and olivine phenocrysts up to 4 mm in size are also present in some flows in modal abundances up to 5%.

Pololu flows are of both pahoehoe and a'a types. Pahoehoe flows are well exposed along the coast 0.5 km northwest of Honokoa Gulch and along the Kawaihae-Hawi road. Weathered pahoehoe rope and toe structures can be seen in the roadcuts 0.4 km northwest of Kapole Gulch. The pahoehoe flow units range in thickness from 5 cm to 0.6 m and are capped by a'a flows. The a'a flow units are about 1.2 m thick and fairly vesicular, with some vesicles near the base of the flow elongate in the direction of flow. A 3.7 m thick roadcut exposure of at least seven pahoehoe flow units can be seen in Kawaihae town about 0.8 km northwest of the Spencer Park access road. A red soil, which is present on all Pololu flows, is another identifying characteristic of this formation.

The Pololu lavas exposed along the upper Waimea-Kohala road southeast of Puu Makela are a'a type alkali olivine basalts but have a much less spinose clinker phase than typical a'a flows. These "clinker" phases are similar to the flow breccias typical of the more viscous alkalic Hawi lavas, which will be discussed later. The similarity of the flow structures of the alkalic Hawi lavas and these alkalic Pololu basalts indicates that flow structure may be influenced by composition, and greater viscosity and volatile content (Macdonald, verbal communication, January, 1977).

The only Pololu eruptive vents identified in the Kawaihae Quadrangle are Puu Kamalii and Puu Ulaula. Both cinder cones have a deep red color and are gullied by erosion. The north side of Puu Kamalii has been partially buried by a subsequent flow originating further upslope. Puu Ulaula has been eroded by the sea on the southwest leaving a horseshoe-shaped hill. The positions of these two cones do not coincide with either the southeast or the southwest rift zones.

Hawi Formation

Hawi Formation lavas comprise approximately 60% of the mapped area (Plate I). Flows extend from vents in the northeastern portion of the map to the sea, in most cases. Their exposures are easily seen along the upper Waimea-Kohala and lower Kawaihae-Hawi roads. They range in thickness from nearly 46 m at the summit to as little as 0.6 m near the coast. The average thickness is approximately 12 m. Lavas nearest the vents appear more fluid, displaying characteristics of pahoehoe flow. Vesicularity decreases away from the vent. On the whole, Hawi lavas are of a'a type, trending to block lavas in some cases. Stearns and Macdonald (1946) and the author consider the Puu Loa flow to be block lava.

The Hawi lavas are autobrecciated. This is the same flow mechanism as in a'a lavas, but the particles created by the autobrecciation are different. The a'a flows create clinker--very sharp and spinose fragments. The Hawi lavas, however, create larger, rounder, blocker fragments in the autobrecciation process, grading into block lava shapes. The best cross-section of a Hawi flow is in a roadcut along the Kawaihae-Hawi road less than 0.2 km northwest of the North Kohala-South Kohala District Boundary. The contact between the flow breccia and the dense, once liquid central portion of the flow is very sharp (Plate II, Fig. B). Many Hawi flows are composed of several "gushes" rather than just one. It is possible to discern the boundary between the upper flow breccia of the lower flow and the lower breccia of the upper flow in roadcuts by observing slight differences in texture and coloration (Plate III, Fig. A). Faulting occurs within the flow due to parts of the flow cooling and moving at different rates, creating structures such as shown in Plate III, Figure B.

The very viscous state of the Hawi lavas is responsible for the platy cleavage observed in many of the lavas of this formation (Plate IV, Fig. A). The platiness is the result of shearing caused by continued movement of the upper part of the flow over the lower part when the cooling lava lost most of its fluidity (Macdonald, 1972, p. 178). The platy cleavage is parallel to the direction of flow and is reflected in thin section by the parallel alignment of of uniform feldspar microlites. In hand specimen, the

Plate II. Fig. A. Exposure of Pololu pahoehoe flows along the Kawaihae-Hawi road. The soil horizon above the flows is Pololu derived, contains many rock fragments, and is bright red in color.

Fig. B. Cross-section of a Hawi flow in a roadcut along the Kawaihae-Hawi road less than 0.2 km northwest of the North-South Kohala District Boundary. Note sharp contact between the once liquid center of the flow and its flow breccia.

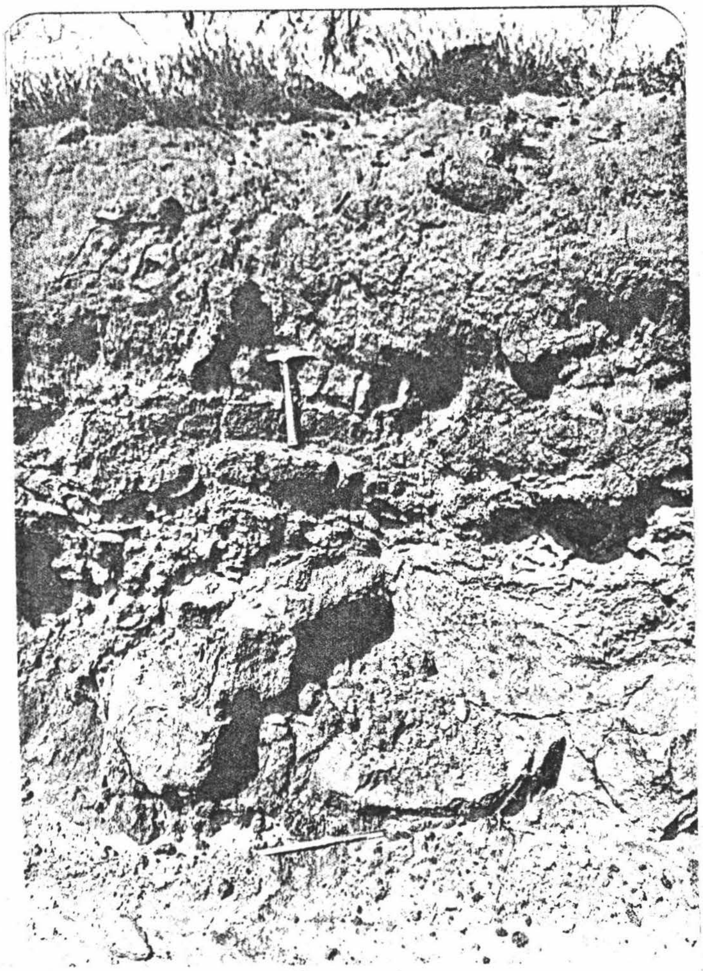


Figure A.

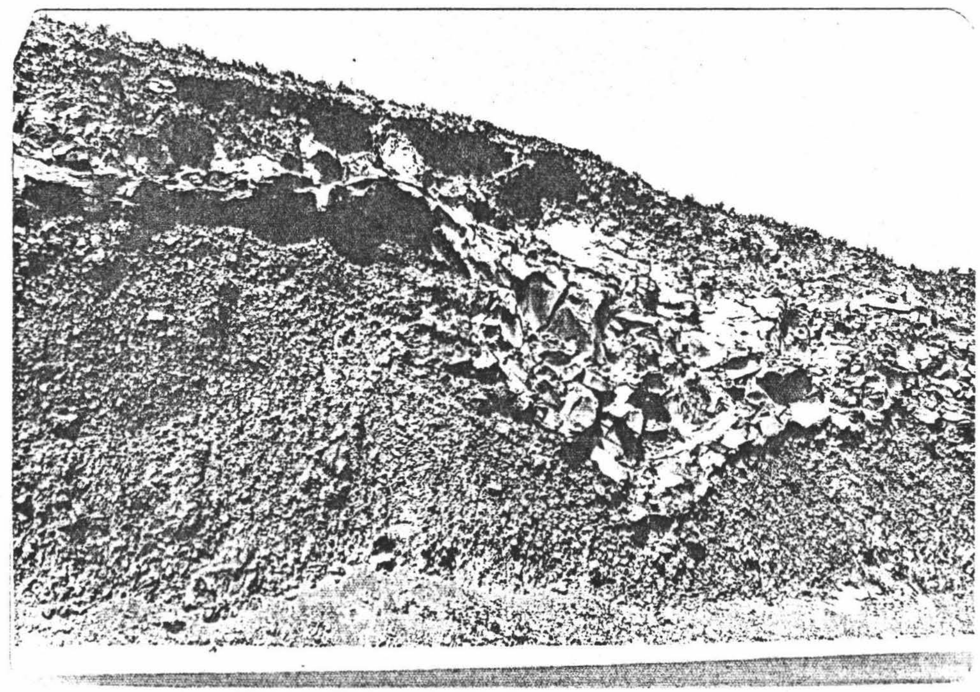


Figure B.

Plate III. Fig. A. The hammer lies on the contact of two "gushes" of a Hawi flow. Differences in color and texture distinguish the upper flow breccia of the first flow from the lower flow breccia of the upper flow.

Fig. B. Faulting within a Hawi flow due to differential cooling and movement of the lava.

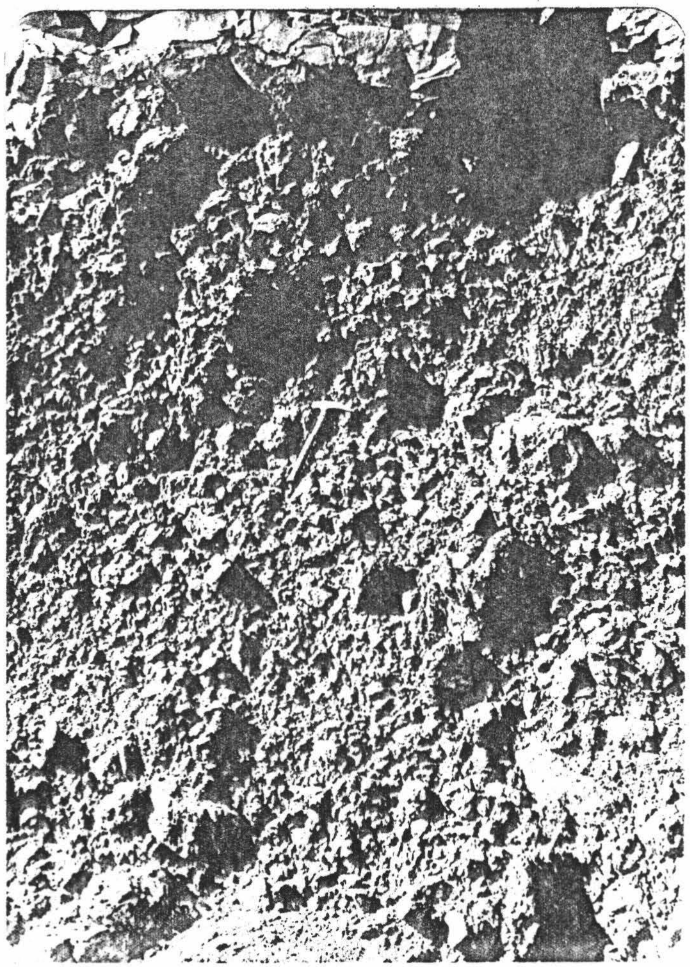


Figure A.

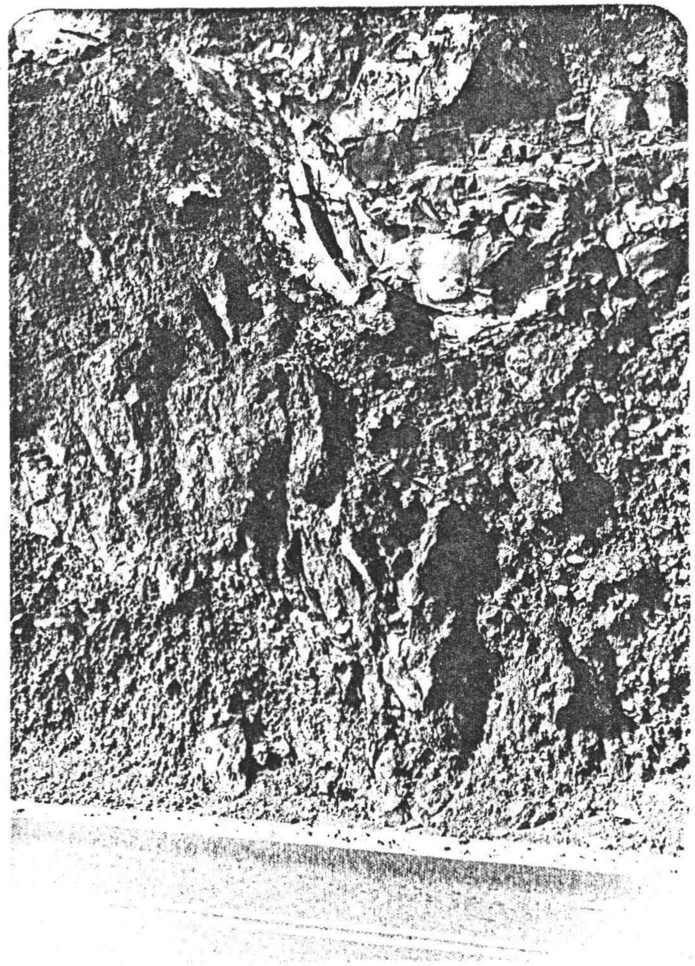


Figure B.

Plate IV. Fig. A. Platy cleavage in Hawai lava observed in a roadcut immediately northwest of Honoloa Gulch along the Kawaihae-Hawi road.

Fig. B. Fusiform bomb in the quarried cinder cone of Puu Kawaiwai.

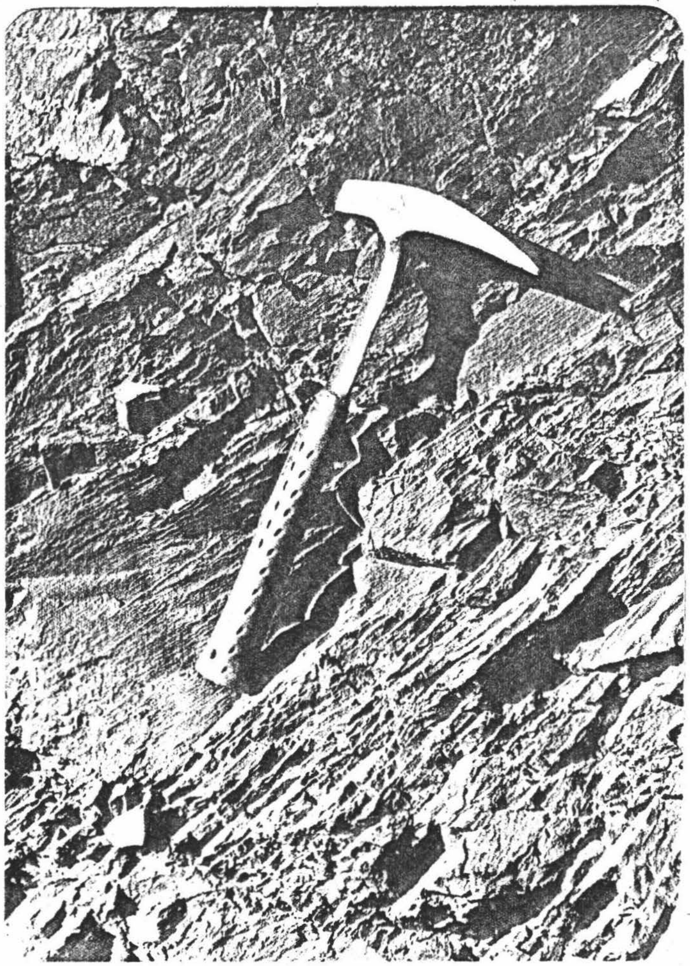


Figure A.

Figure B.

parallel alignment of feldspar gives the rocks a distinct sheen. Cleavage of this type was observed most commonly in the roadcuts of the Puu Lapalapa flow along the lower Kawaihae-Hawi road and along the coast, near the terminations of the flows. The roadcut immediately northwest of Honokoa Gulch shows the best example of shearing and cleavage. In these same areas, vesicularity is minimal, with the vesicles being most abundant near the contact with the flow breccia. The vesicles are so elongate in the direction of the flow that in many cases they are stretched flat by the movement of the viscous lava.

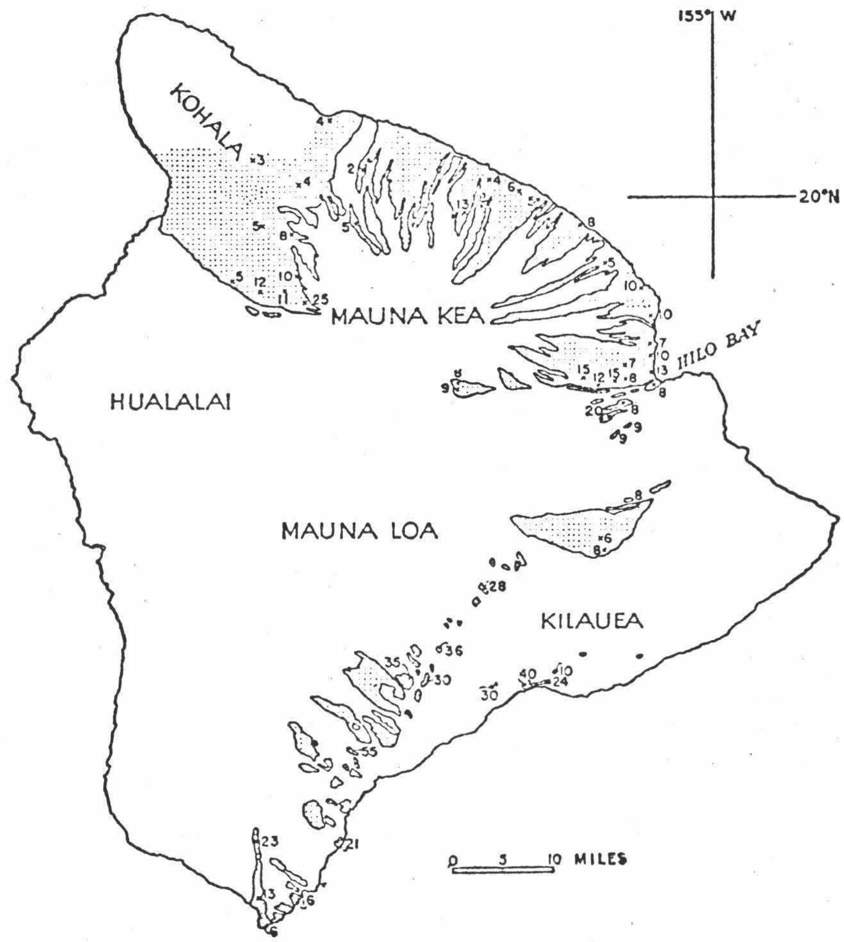
The flow from Puu Ahia is distinguishable by its greater abundance of plagioclase phenocrysts. The phenocrysts are generally about 3 mm long and have a blocky habit. The benmoreite dome of Puu Makela is distinguished by its very light grey color and coarser texture. It has plagioclase phenocrysts as long as 1 cm and numerous xenoliths of dunite up to 5 cm in length. The Puu Lapalapa flow also contains dunite xenoliths from 3mm to 8cm in diameter.

The cinder cones formed at vents by the explosive eruption of viscous Hawi lavas are composed largely of unconsolidated reddish scoria from 1 to 2.5 cm in diameter. Lapilli and ash, and larger fragments of grey scoria up to 30 cm in diameter are also present. The large fragments of scoria are most abundant near the lower slopes of Puu Lapalapa and Puu Pala. A vertical cut along a trail on the south flank of Puu Pili reveals crude size sorting of vent material with the coarser fragments at the bottom. Large, extremely weathered, nodular dunite inclusions up to 15 cm in diameter, are also seen in this trail cut. There is very little spatter and welded material incorporated in the cinder cones. The greatest abundance of spatter is observed at Puu Loa. Occasional bombs of the bipolar fusiform type are observed at most of the cones. A huge bomb, 1.2 m in diameter, and one slightly smaller in size were observed at Puu Kawaiwai; they have distinguishable bipolar fusiform shapes, which indicate that they were at least partially liquid upon ejection (Plate IV, Fig. B). The quarrying away of much of the center of Puu Kawaiwai has exposed its inner structure. Beds of cinder dip steeply away from the center of the cone. The cinder is quarried for use as road metal.

Pahala Ash

The Pahala Ash covers portions of Kilauea, Mauna Loa, Mauna Kea, and Kohala (Fig. 4). Because it was probably erupted over a considerable span of time and from several sources, it should not be used as a strict time indicator. Both the Pololu and Hawi Formations, however, are considered to be older than the Pahala Ash (Stearns and Macdonald, 1946; Macdonald and Abbott, 1970). In the Waimea area the

Figure 4. Map of Hawaii showing distribution and thickness in feet of Pahala Ash (after Stearns and Macdonald, 1946).


155° W
20°N
KOHALA
MAUNA KEA
HILO BAY
HUALALAI
MAUNA LOA
KILAUEA
0 5 10 MILES

Pahala Ash is about 1.2 to 1.5 m thick and was postulated (Stearns and Macdonald, 1946) to be mostly derived from eruptions on Mauna Kea from the time of eruption of the late Hamakua lavas to the close of volcanic activity on Mauna Kea. Demonstration by the writer of at least partial contemporaneity of Hawi and Hamakua volcanism makes it possible that some Pahala Ash also came from Kohala. Lower atmospheric winds from the northeast distributed much of Mauna Kea-derived ash. These winds would have been more favorable in distributing Kohala-derived ash on Kohala's southwestern slope (G. A. Macdonald, verbal communication, July, 1977). Pahala Ash deposits are present along the upper Waimea-Kohala road on top of Hawi lavas. The deposits consist of thin layers of sand-sized pumice shards. The ash blankets the previous topography, but some deposits are thicker in topographic depressions. Plate V, Figures A and B, illustrate blanketing ash layers on the southwest flank of Puu Makela. The ash is yellowish brown in color and has been altered to limonite, goethite, and possibly palagonite in some cases.

Much of the soil in this area appears to be derived from ash. Approximately 1.2 m of soil is found above a continuous layer of sand-size ash about 0.2 km southeast of Kilohana Gulch. The ash is slightly consolidated, but very friable. Microscopic examination of soil sampled 0.6 m above the definite ash layer reveals shards of pumice,

Plate V. Figs. A and B. Pahala Ash deposits on the northwest flank of Puu Makela.

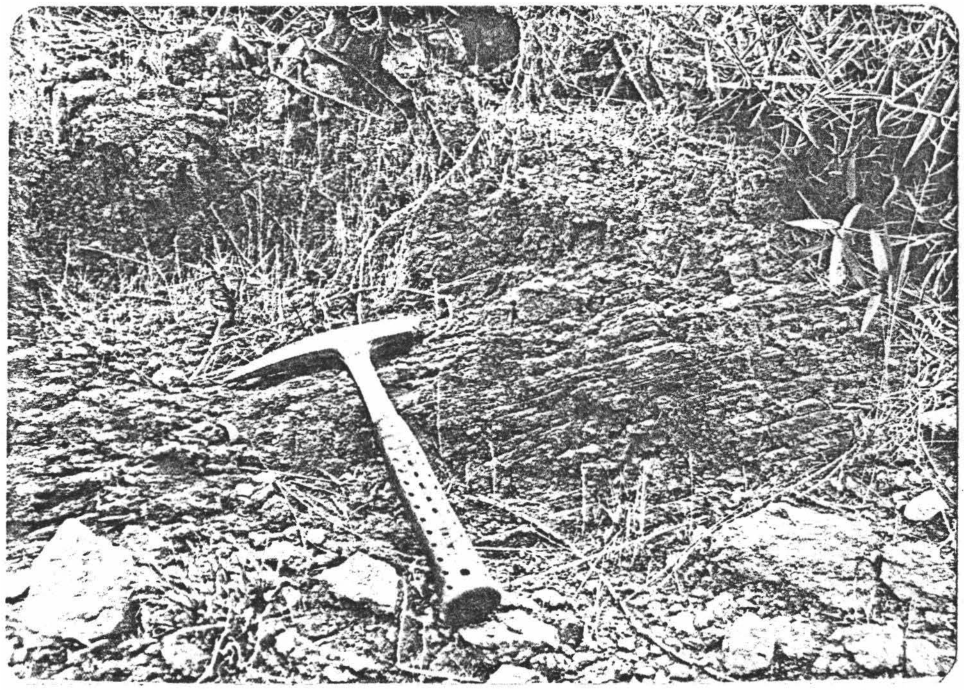


Figure A.

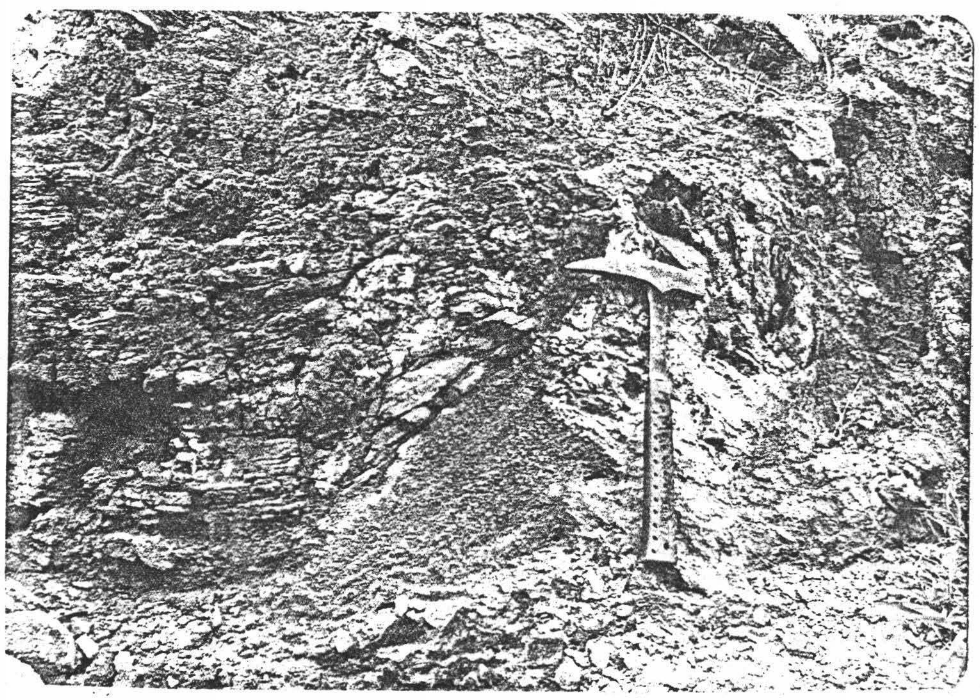


Figure B.

microlites of pyroxene, and glass, which confirms its derivation from the weathering of the ash. The average thickness of soil overlying all the Hawi Formation lavas is 1.2 to 1.5 m with one exception. There is very little soil and no trace of Pahala Ash on the flow from Puu Loa. Ash was not observed on the late Hamakua Formation lavas which bury the southern flank of Kohala Mountain. According to Stearns and Macdonald (1946), the wind blew away most of the ash in this particular area because of the lack of sufficient vegetation to hold ash and soil in place.

Sedimentary Rocks

Unconsolidated stream alluvium consisting of mud and gravel occurs in some plunge pools and pockets in stream gulches, but none of the deposits are extensive enough to be shown on Plate I. The floor of most gulches appears to consist of lava flow surfaces covered in places by a thin veneer of wet mud deposited by intermittent streams. The gravel is derived from Hawi flow breccia fragments. Large blocks and boulders derived from the valley walls are commonly found in stream channels.

Beach sand deposits are found along the coast underlain by Mauna Kea lavas. The sand, which is derived from offshore coralline and other calcareous material, is very fine grained and nearly white in color. No beaches are present along the southwest Kohala coast. A beach previously existed at Kawaihae, as indicated on the 1956 topographic map, but is now covered by the coralline fill of the Kawaihae harbor.

A very small, isolated deposit of beach rock was discovered along the Kohala coast 0.3 km southeast of Kamilo Gulch on a small jagged peninsula formed by the Puu Aiea flow. The deposit, 1.8 m above sea level, comprises several small discontinuous patches in eroded pockets on the surface of the flow. The largest of these deposits is approximately 1.5 m long and 0.3 m thick. The beach rock is composed of fragments of flow breccia in a calcareous cementing matrix, and appears to have formed during present sea level.

An unconsolidated stream-laid sedimentary breccia is exposed in the south wall of Makeahua Gulch, 0.3 km directly north of Benchmark 1562 on the Kawaihae-Waimea road. The exposure consists of two layers of weathered water-laid ash alternating with two layers of pebble to cobble size angular fragments of predominantly Hawi Formation flow material. There are some Pololu fragments incorporated in the breccia. The floor of the gulch at this location is the surface of a flow from Puu Kawaiwai and a Hamakua Formation alkali olivine basalt caps the sedimentary breccia. The exposure is approximately 0.2 km long. At the easternmost boundary of the exposure, the sequence above the floor consists of a 0.6 m layer of sedimentary breccia, topped by a 15 cm layer of sedimentary breccia, followed by 0.8 m of water-laid ash and soil, and finally, the 3 m-thick Hamakua lava flow. The sedimentary breccias die out toward the west leaving the entire section below the lava to consist of ash and soil incorporating only a few large lithic fragments. Bedding in ash is parallel to the breccia, but is distinct only where there are changes of color. Microscopic examination of the stream-laid ash indicates that it is a more weathered, finer grained version of the wind-laid ash found on the upper slopes of Kohala. The water-deposited ash contains some pyroxene grains and weathered shards of pumice.

Many calcified tree root molds are observed in the Makeahua Gulch deposit at the westernmost end of the exposure in a massive, 1.8 m soil horizon. There is no baking evident along the base of the Hamakua flow. Therefore, it is suggested that this deposit marks a former location of Makeahua Gulch, which was filled by a late Hamakua flow. The lava destroyed the vegetation growing there, but did not disturb the unconsolidated sediments. The present gulch was then carved at the new boundary between Kohala Mountain (the Puu Kawaiwai flow, at this location) and Mauna Kea flows.

Stratigraphic Relationships

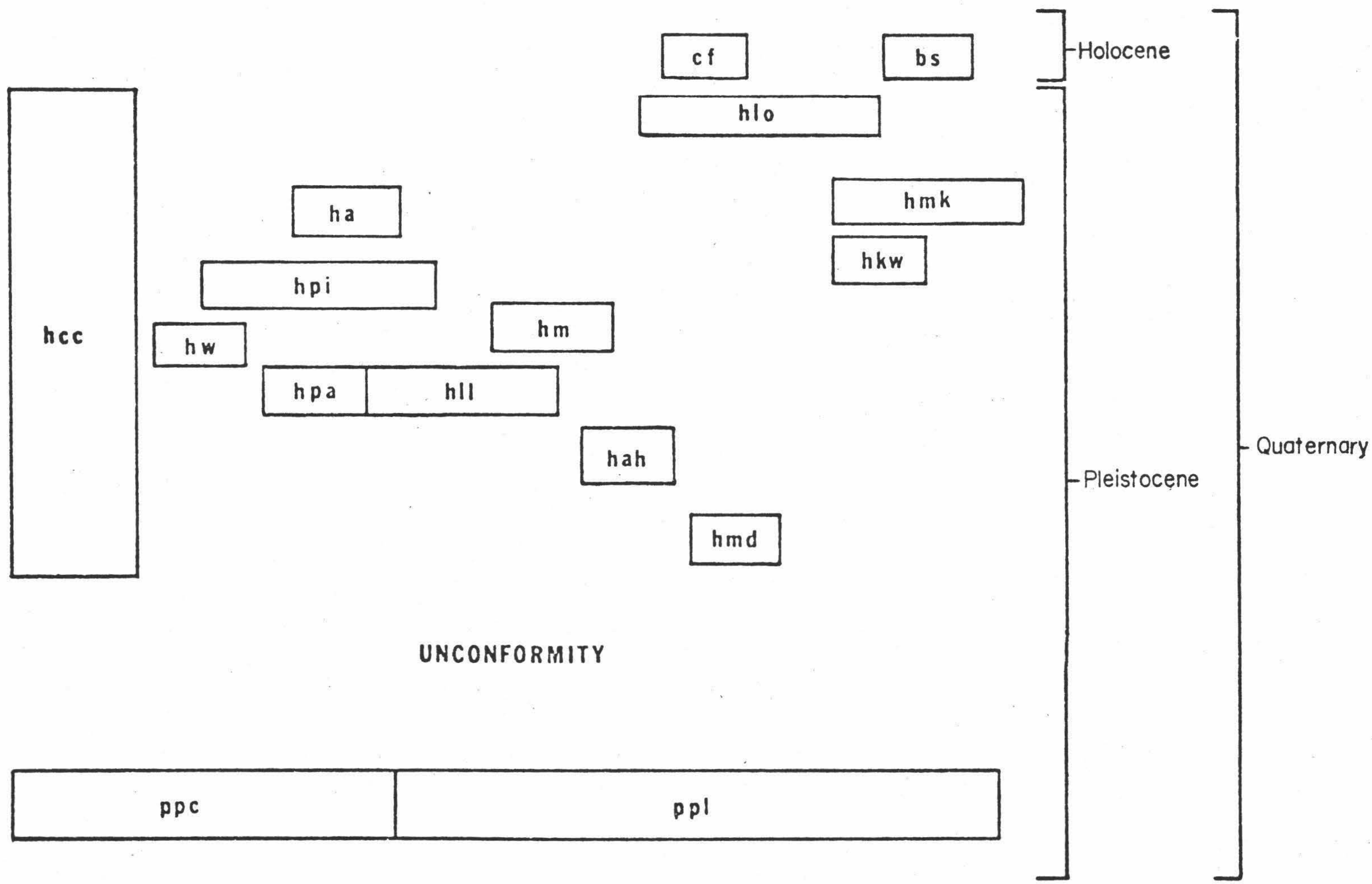
The primary criterion used for determining relative age of rock units in this investigation is the superposition of flow units. Relative age is also determined by the presence of unconformities; the degree of soil development, weathering, erosional dissection, and coastal cliff development; the presence or absence of the Pahala Ash on flow units; and deflection of surficial lava flows around obstacles.

The correlation of map units in this study is shown in Figure 5 as well as on Plate I. The Pololu Formation (ppl) of Late Pleistocene age is the oldest rock unit exposed in the map area. It represents the last stages of shield building on Kohala Volcano. The thickest exposed section of Pololu lava is in Honokoa Gulch where there is a sequence of nearly 55 m of a'a and pahoehoe flows intercalated with red ash units. The Pololu lavas are covered by a red, ashy lateritic soil up to 0.4 m thick which marks the unconformity between the Pololu shield-building lavas and the late-stage Hawi alkalic lavas.

The Hawi Formation lavas were erupted during the Late Pleistocene and Early Holocene, and rest unconformably on the Pololu Formation lavas. During the same time period, lavas of the late Hamakua Formation (hmk) were erupted, interfingering in part with the Hawi lavas, but continuing somewhat after the cessation of most Kohala volcanism and

Figure 5. Correlation of map units in the Kawaihae Quadrangle. Symbols are the same as those used on Plate I.

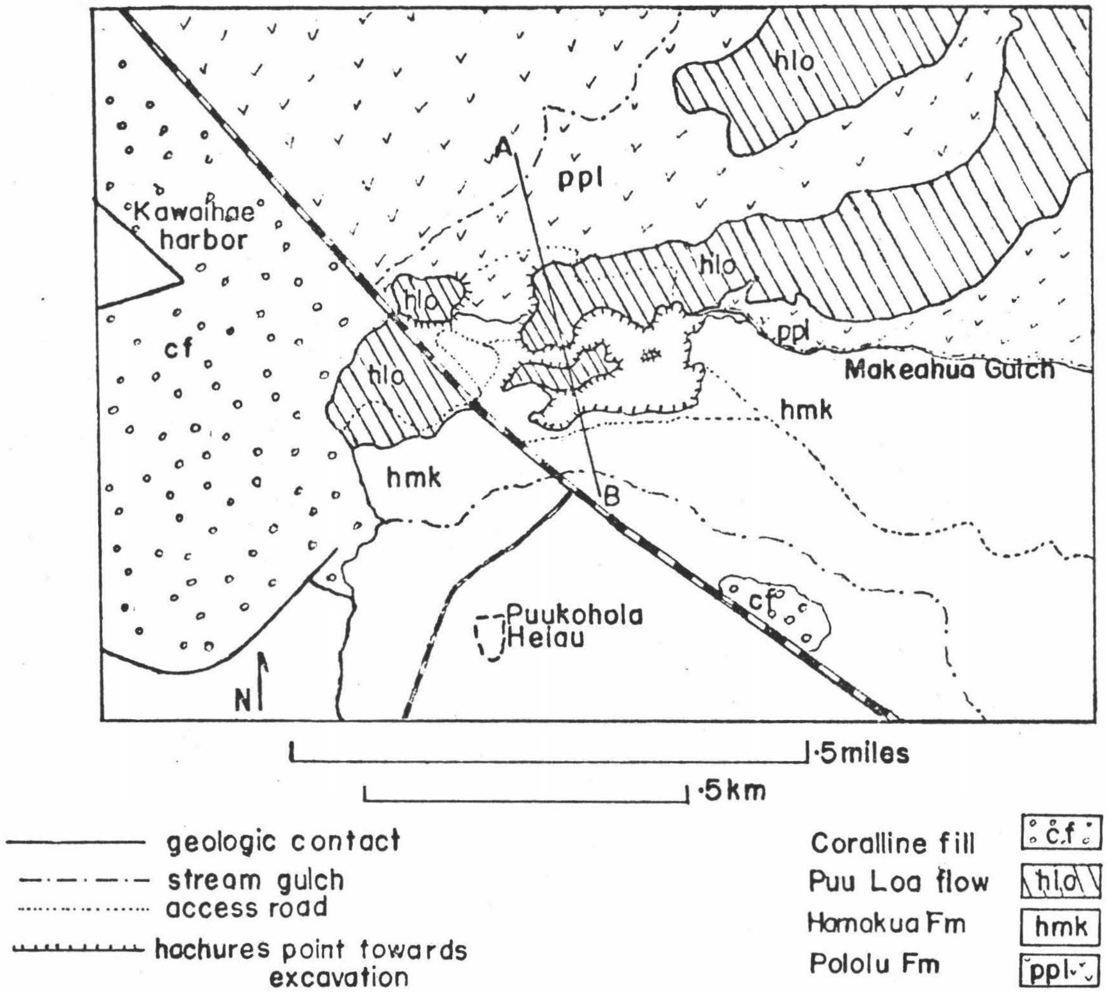
CORRELATION OF MAP UNITS

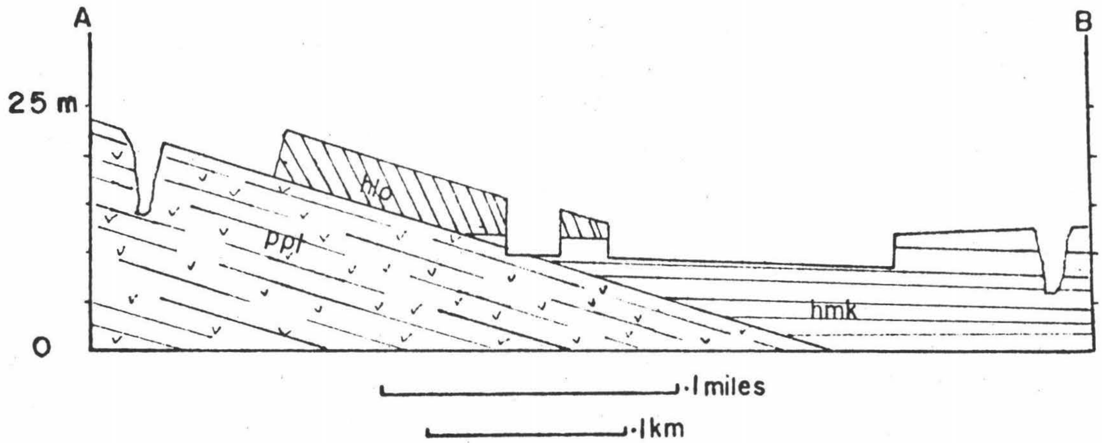


largely burying the southern flank of Kohala (Macdonald and Abbott, 1970). It is demonstrated, however, that Hawi volcanism did not cease before the burying of Kohala's south flank. The flow from Puu Loa (hlo) is the youngest Hawi unit mapped within the Kawaihae Quadrangle. It lies unconformably on Pololu lavas (ppl) and conformably on a late Hamakua flow (hmk). The exposures that show this stratigraphic relationship are within the Kawaihae quarry at the mouth of Makeahua Gulch, which is at the contact between Kohala Mountain and Mauna Kea. Plate VI shows a map and cross-section of the quarry. The Hamakua rock exposed beneath the Hawi flow is massive, with phenocrysts of olivine, pyroxene and feldspar, whereas the Hamakua rocks exposed higher in the section, in the northeastern and southeastern walls of the quarry, have a greater abundance of olivine and pyroxene. In the gulch just south of the Kawaihae-Hawi road and west of the Spencer Park road, the massive Hamakua rock is underlain by thin olivine basalt pahoehoe units with flow-to-flow contact without intervening soil or weathering. Farther south, the lava beneath Puukohola Heiau at road level is also similar to the massive Hamakua lava, though with more olivine. It appears to be part of the same flow.

When Stearns mapped this area in 1946, he indicated that the flow from Puu Loa ended approximately 229 m (750 feet) above sea level. However, mapping during this

Plate VI. Geologic map and cross-section of the Kawaihae quarry area.


hlo
A
ppl
Kawaihae harbor
hlo
hlo
ppl
Makeahua Gulch
cf
hlo
hmk
hmk
B
cf
Puukohola Heiau
N
.5 miles
.5 km
geologic contact
stream gulch
access road
hachures point towards excavation
Coralline fill
c.f
Puu Loa flow
hlo
Hamakua Fm
hmk
Pololu Fm
ppl


A
B
25 m
0
hlo
ppl
hmk
.1 miles
.1 km

study clearly indicates that the flow does extend to the ocean, and covers part of a Hamakua flow. The Puu Loa flow near the coast is now buried under the Kawaihae harbor coralline fill. Near the Puu Loa vent, the flow is in contact with the Pololu Formation in the Keawewai Stream in a plunge pool just south of Kawaihae Uka site. This contact is also present along the southeastern boundary of the flow.

The flow from Puu Loa appears to be relatively recent based on the extreme freshness and blocky character of its surface and by the fact that both the vent and the flow are the least vegetated of all the Hawi flows and cones. Most important is the fact that the flow is post-Pahala Ash; it is not covered by the ash or any significant amount of soil, unlike the other Hawi lavas in the map area. The Puu Loa flow is deflected around the benmoreite dome of Puu Makela (hmd) and is banked against the northeast flank of the dome (Plate VII, Fig. A). Macdonald, in 1974, described Puu Makela as "a thick short flow of 'benmoreite', erupted at Puu Loa, which is a cinder cone built at the vent." Puu Loa and Puu Makela, however, represent two separate vents, two different rock types, and two separate eruptive events, the dome being considerably older. To the southwest, the dome is cut by the Waimea-Kohala road, exposing a major portion of the dome (Plate VII, Fig. B).

Plate VII. Fig. A. Photo taken from the top of Puu Honu shows the profiles of Puu Loa (left) and Puu Makela (right). The Puu Loa flow deflected around Puu Makela dome, banking against its northern flank.

Fig. B. Waimea-Kohala roadcut through Puu Makela dome, looking southeast.

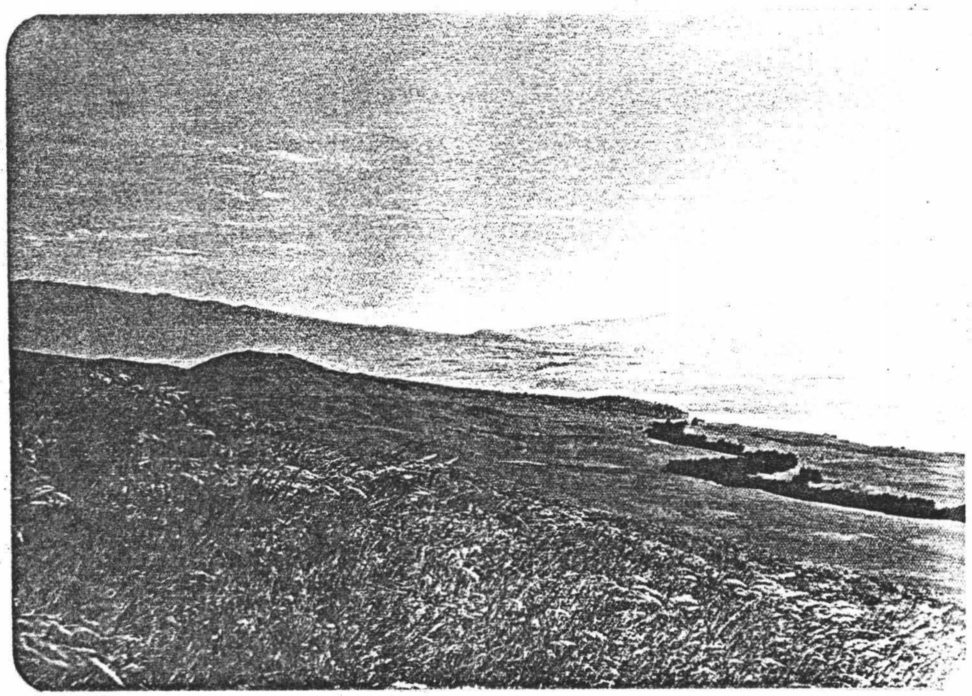


Figure A.

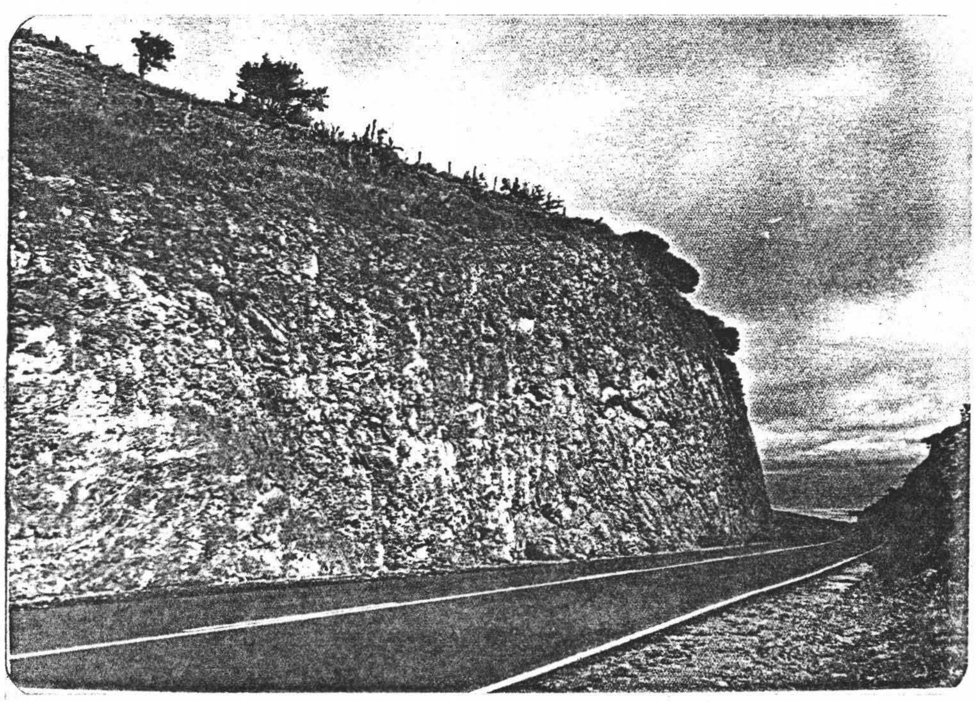


Figure B.

The interpretation that Puu Makela is a dome is suggested by the roughly concentric structure of rock indicative of dome expansion, the lack of flow breccia and the very massive character of the rock, and the broken up surface on the top, characteristic of spiny brittle dome skin that is broken during expansion. At the very top of the dome, joints dip very steeply. The greater age of Puu Makela is indicated by the presence of Pahala Ash on the gentler slopes of the dome and by the more weathered character of the lavas.

The contacts between flow units of Hawi lavas were mapped based on the assumption that stream courses tend to develop between surface flow units in recent volcanic areas. Therefore, the stratigraphic succession of the Hawi lavas was determined by observing the superposition of flow units at these contacts in the appropriate gulches.

The flow from Puu Ahia (hah) is overlain to the southeast by the flow from Puu Loa, and to the northwest by the flow from Puu Mala (hm). The flow from Puu Mala is also younger than the flows from Puu Lapalapa (hll) and Puu Pala (hpa). The eruptions at Puu Lapalapa and Puu Pala may have occurred simultaneously because the cinder of the two cones is interbedded. The Lapalapa flow is quite extensive and is deflected around both Puu Iki and Puu Honu (hcc), spilling between the two vents and burying any lavas that may have issued from those vents. Puu Iki may have preceded Puu Honu since the ash and soil on Puu Iki is thicker and more weathered. Flow ridges of the Lapalapa flow extend to the northwest and southwest sides of the Puu Lapalapa cinder cone, demonstrating that the flow did originate from that vent. The flow from Puu Pili (hpi) is younger than the flows from Puu Lapalapa, Puu Pala, and Puu Waiakanonula (hw). The flow from Puu Aiea (ha) is, in turn, younger than the Pili flow. Evidence indicates that several of these flows possibly erupted simultaneously. The similar thicknesses of ash and soil horizons overlying these lavas suggest that they were erupted over a relatively short span of time. The flow from Puu Loa, however, is by far the youngest of the Hawi lavas erupted in this area.

POTASSIUM-ARGON DATING

Purpose and Scope

Potassium-argon dating was conducted by the author under the supervision of J.J. Naughton and V. Greenberg. The purpose of the potassium-argon dating study was to obtain absolute ages by radiometric methods as a supplement to relative ages determined during fieldwork. Of particular interest were the age relationships of the Mauna Kea and Kohala units observed in the Kawaihae quarry.

It was also of interest to compare the results with radiometric ages obtained for Kohala Mountain in previous investigations (Table 1).

Summary of Previous Investigations

McDougall (1964) used K-Ar ages to show that the exposed part of the Pololu Formation is no older than 0.8 m.y. and therefore, of Pleistocene age. Dalrymple (1971) also confirmed that the Pololu Formation is Pleistocene in age, although his results were somewhat different from McDougall's. Dalrymple reported five K-Ar ages ranging from 0.46 ± 0.36 m.y. to 1.28 ± 0.46 m.y.; he used a weighted mean age of 0.7 ± 0.15 m.y. as the best estimate of the age of the Pololu Formation. Potassium-argon ages obtained for the Hawi lavas range from 0.06 m.y. to 0.25 m.y. (McDougall, 1969; McDougall and Swanson, 1972). Dalrymple's evidence indicates that there is a hiatus of about 0.5 m.y. between the Pololu and Hawi Formations, but McDougall believes that the hiatus is less than 0.2 m.y.

Pololu lavas are difficult to date using the K-Ar method because of their young age and very low (about 0.1% for tholeiites) K_2O content (Dalrymple, 1971). Besides being very young, Hawi lavas are very fine grained (less than 0.2 mm) and may be expected to lose radiogenic argon by diffusion (McDougall, 1964). McDougall suggests that argon loss by diffusion is probably minimal because the lavas have not been buried or deformed.

Table 1. K-Ar Age Determinations, Kohala Mountain

Sample	Source	Rock Type and Locality	K-wt%	%Rad Ar	Calculated Age (m.y.)
		Hawi Formation			
62-1	Sample:Macdonald and Katsura, 1964;K-Ar age:McDougall, 1969	Benmoreite, 1.1 km S by W of Puu Loa,below Puu Makela,altitude 3420'	2.42 2.42	9.7 10.0 11.2	0.149 ± 0.006 0.137 ± 0.005 0.135 ± 0.005
C-210	Sample:Macdonald, 1968; K-Ar age:McDougall, 1969	Mugearite, 1.4 km WNW of Puu Loa, near Keawewai Stream,altitude 3480' Puu Ahia flow	1.785 1.794	14.1 18.2 18.5	0.166 ± 0.005 0.148 ± 0.003 0.144 ± 0.003
C-68	Sample:Macdonald and Katsura, 1964; K-Ar:McDougall, 1969	Mugearite, 3.5 km ESE of Puu Kawaiwai	1.96 2.02	10.0 14.1	0.203 ± 0.009 0.190 ± 0.009
HW-21	McDougall and Swanson, 1972	Roadcut 8.8 km S of Mahukona, Puu Aiea flow, mugearite	1.353 1.356	12.4	0.181 ± 0.003
HW-22	McDougall and Swanson, 1972	Mugearite, roadcut near Keawewai Stream, 5 km N of Kawaihae, Puu Aiea flow	1.925 1.916	11.7	0.184 ± 0.003
M-2	Malinowski, 1976, unpubl.	Mugearite, Puu Loa flow, Kawaihae quarry	1.766 ±.051	2.4 2.3	0.087 ± 0.003 0.077 ± 0.002
M-4	Malinowski, 1976, unpubl.	Mugearite, Puu Loa flow, flow ridge between P. Loa and P. Makela	1.775 ±.042	2.9	0.082 ± 0.002
		Pololu Formation			
11	Samples: Doell (Doell and Cox, 1965); K-Ar ages: Dalyrmple, 1971	Lowest part of section of tholeiites in Waipio Canyon described by Macdonald and Stearns (1946)	0.096 0.097	3.3	0.94 ± 0.42
33		Samples are within 135 m to 270 m of the top of the Pololu Formation.	0.058 0.058	4.0	1.28 ± 0.46
39			0.150 0.162	1.8	0.46 ± 0.36

Table 1. (continued) K-Ar Determinations, Kohala Mountain

Sample	Source	Rock Type and Locality	K-wt%	%Rad Ar	Calculated Age (m.y.)
		<u>Pololu Formation</u>			
47	Samples: Doell (Doell and Cox, 1965); K-Ar ages: Dalrymple, 1971	Lowest part of section of tholei-ites in Waipio Canyon described by Stearns and Macdonald (1946).	0.120 0.121	4.3	0.72 ± 0.24
50		Samples are within 135 m to 270 m of top of Pololu Formation	0.068 0.065	5.6	0.70 ± 0.15
HW-16	McGougall and Swanson (1972)	Basalt, roadcut 3.2 km S of Hawi, altitude 430 m	0.770 0.773	5.0	0337 ± 0.013
HW-18		Basalt, roadcut 1.6 km S of Mahukona, altitude 49 m	0.776 0.771	5.5	0.382 ± 0.016
HW-17		Feldspar-phyric basalt, roadcut in Mahukona, altitude 52 m	0.768 0.767	9.4	0.400 ± 0.008
P71-4		Olivine basalt, trail into Pololu Valley 110 m below top of Pololu Formation, second or third flow unit above valley floor	0.098	1.4	0.403 ± 0.141
P71-10		Olivine basalt, E wall, Waipio Valley, uppermost Pololu flow	0.929 1.256	1.7 1.9	0.296 ± 0.089 0.400 ± 0.066

Methods and Sample Preparation

The method followed for potassium-argon analysis is that of John Gramlich (1970). A "Reynolds type" mass spectrometer, single focusing instrument, utilizing a 60 degree magnetic deflection and a 4.5 degree radius of curvature, was used for argon analysis. The system makes use of an ^{38}Ar tracer for calibration with periodic accuracy checks with U.S.G.C. Interlaboratory Standard Muscovite P207. Potassium analyses were determined by atomic absorption spectrometry using standard addition. Duplicate runs were made for both potassium and argon analyses of each sample.

Samples were examined in this section and chosen for analysis on the basis of their freshness and lack of weathering or alteration. Alteration of olivine to iddingsite is acceptable because potassium is negligible in olivine, and the alteration takes place during and immediately after eruption (McDougall, 1964, p. 109). Rocks were broken in an iron mortar to 43 mesh size, rinsed in deionized water and left to stand 45 minutes in a 1% dilute solution of HNO_3 to help remove fine particles. Samples were finally cleaned in an ultrasonic bath to further remove fine particles. Samples were oven dried and then split into an argon portion of at least 10 grams, and a potassium portion of about 1 gram. The potassium split was then crushed to a powder in an agate mortar. One hundred milligrams of powdered sample were used for each potassium determination.

Results

Results for Kawaihae samples were only obtained for one flow--the very young flow from Puu Loa. The three age determinations for the Puu Loa flow are: 0.087 ± 0.003 m.y. and 0.077 ± 0.002 m.y. for a sample taken from the Kawaihae quarry exposure, and 0.082 ± 0.002 m.y. for a sample taken from the flow ridge between Puu Loa and Puu Makela. It must be noted that the three ages compare quite well and that the error given here is not a standard deviation, but the estimated standard deviation (error propagation) calculated for a single K-Ar age determination derived by Cox and Dalrymple (1967 _in_ Gramlich, 1971). Calculating a standard deviation for these three results gives an average age of 0.082 ± 0.006 m.y. for the Puu Loa flow. Further age determinations were not possible due to mechanical problems with the mass spectrometer. Table 1 shows previously published potassium-argon dates determined for lavas of the Pololu and Hawi Formations. Hawi samples dated are from the Kawaihae Quadrangle.

PETROLOGY

PETROGRAPHY

Methods and Sample Preparation

A major difficulty encountered during fieldwork was the great similarity in hand specimen of rocks having different chemical compositions. In the field it was impossible to distinguish between the alkalic rock types represented in the Hawi Formation. On rare occasions there was some difficulty in telling Pololu Formation rocks from Hawi rocks in hand specimen, but stratigraphic relationships usually prevented any confusion. Hamakua lavas appeared similar in hand specimen to both Pololu and Hawi lavas.

Over one hundred samples were collected during fieldwork. Of these 60 were chosen for petrographic and chemical analyses on the basis of freshness and field location in order to corroborate flow contacts established by mapping. Thin sections were made by Western Petrographic, Tucson, Arizona. Modes were determined by point counting at least 200 points for one section of each major flow and visual modes were estimated for the remainder. The estimate of probable error at the 95.4 level of confidence in point counting is 3% to 7% for 200-225 points counted and 2% to 5% for 400-425 points counted (Galehouse, 1971, p. 398). Point count modal analyses are listed in Table 2. Detailed descriptions of thin sections

Table 2. Modal Point Count Analyses for Hawi, Pololu and Hamakua Formations*

Sample	Oligoclase	Andesine	Labradorite	Alkali feldspar	Olivine**	Clino-pyroxene	Hornblende	Biotite	Magnetite	Ilmenite	Hematite	Apatite	Glass	Points counted
<u>HAWI FM</u>														
A-12-1	57	11	--	tr	17	6	--	--	6	--	1	2	--	202
A-15-1	59	--	--	5	12	6	--	3	12	--	1	2	--	200
A-18-2	51	2	--	6	18	7	--	2	12	--	--	2	--	214
A-20-3	65	--	--	4	10	10	--	tr	9	tr	tr	2	--	229
A-33-1	59	6	--	3	17	3	--	--	9	tr	tr	3	--	214
A-33-2	64	5	--	3	16	4	--	--	4	1	1	2	--	211
A-34-1	73	--	--	9	6	6	--	--	3	--	1	1	1	204
A-35-1	69	2	--	3	12	3	--	tr	7	tr	2	1	tr	202
A-42-2	60	6	--	1	16	5	--	--	6	--	2	4	tr	403
A-60-1	70	tr	--	8	8	6	2	--	5	tr	2	1	--	429
B-1-1	57	tr	--	3	19	7	--	1	11	--	1	1	--	209
C-12-1	27	36	--	2	24	5	--	--	4	tr	2	2	--	225
F-1-1	60	7	--	2	14	7	--	--	9	--	tr	1	--	214
F-4-2	54	2	--	3	19	10	--	--	9	--	1	2	--	411
<u>POLULU FM</u>														
A-27-1	--	--	58	tr	22	13	--	1	5	1	--	tr	--	225
A-100	--	--	47	3	22	13	--	2	13	--	--	tr	--	214
C-18-1	--	--	62	tr	15	13	--	--	7	2	--	tr	tr	216
B-4-2	--	--	56	tr	20	13	--	--	10	--	--	1	--	201

Table 2. (continued) Modal Point Count Analyses for Hawi, Pololu and Hamakua Formations*

Sample	Oligoclase	Andesine	Labradorite	Alkali feldspar	Olivine**	Clino-pyroxene	Hornblende	Biotite	Magnetite	Ilmenite	Hematite	Apatite	Glass	Points counted
HAMAKUA FM														
C-11-1	--	--	53	--	16	16	--	--	15	--	--	tr	--	203
C-14-1b	--	--	53	--	25	12	--	--	9	tr	tr	tr	--	236
D-1-1	--	--	44	--	19	17	--	--	17	--	--	tr	--	205
D-3-2	--	--	55	--	18	17	--	--	10	--	--	tr	--	231
D-3-3	--	--	50	--	18	18	--	--	14	--	--	tr	--	225
D-7-1	--	--	54	--	16	17	--	--	13	--	tr	tr	--	211

*Vesicularity not included, see the Appendix for % vesicularity; symbol tr means less than 1%.

**Iddingsite is included with olivine.

representing major flows are found in the Appendix. Sample designations, such as A-60-1, refer to a geographic region within the map area by letter, a station number, which is recorded on aerial photographs of the area, and a number indicating which specimen it is of a possible group taken at a particular station. Letter 'A' refers to the area northwest of the upper Waimea-Kohala road; area 'B' is southeast of the North Kohala-South Kohala District Boundary and northwest of the Kawaihae-Kawaihae Uka trail; area 'C' is southeast of the trail and north of the Kawaihae-Waimea road; area 'D' is south of the road and southeast of Spencer Park road; area 'E' is southwest of the upper Waimea-Kohala road, northwest of the North Kohala-South Kohala District Boundary, and northeast of the major fenceline which goes through a large corral at 1360 ft elevation; and area 'F' is southwest of the fenceline and northwest of the District Boundary.

The identification of minerals was made in this section using the data tables of Tröger (1971), Bloss (1961), and Heinrich (1965). Angles of 2V were measured from Bxa and Bxo intereference figures. Feldspar compositions were estimated by extinction angle methods. Microscopic identification of minerals was hampered by the extremely fine grained character of the Hawi lavas. Several attempts to stain Hawi thin sections for alkali feldspar, using the standard method described by Hutchinson (1974), were unsuccessful. Ten samples were also examined by electron microprobe quantometer to determine crystal compositions. Tables of data and results are discussed under "Mineralogy." The microprobe analyses were conducted by Carlton Allen on the ARL Electron Microprobe Quantometer, Lunar and Planetary Laboratory, University of Arizona, Tucson. Samples were prepared by the author by mounting thick sections of rock in bakelite collars with epoxy. Samples were then polished to 0.05 microns and examined under reflected light to ensure a smooth, flat surface for microprobe analysis. A map was made of each thick section indicating the grains to be analyzed.

Pololu Formation

The Pololu lavas sampled in this study are mostly porphyritic alkalic olivine basalts. They contain feldspar, olivine and augite phenocrysts, but feldspar phenocrysts are by far the most abundant, comprising up to nearly 15% of the mode in some samples. The various phenocrysts are often found as cumulocrysts. The groundmass texture is generally intergranular, but locally is subophitic. Most lavas are vesicular with the exception of the massive flows sampled along the Waimea-Kohala road at the eastern boundary of the map. These massive Pololu rocks, also porphyritic, have a very fine grained groundmass (nearly as fine grained as the Hawi lavas) and exhibit a weak flow structure.

The Pololu Formation samples are identified as alkalic olivine basalts on the basis of their containing groundmass olivine, distinctly brownish groundmass augite, and minor amounts of interstitial alkali feldspar.

Olivine occurs in significant amounts in all the basalts studied, with phenocrysts up to 3 mm in size. Some phenocrysts and microphenocrysts are euhedral in shape but most show some partial resorption indicated by rounding and embayment. Freshest euhedral olivines are found in the massive lavas along the upper road. Alteration of olivine to reddish brown iddingsite is very common. The iddingsite is usually present as a rim around a core of olivine that extinguishes simultaneously with the core, or as a compound rim in which the outer rim extinguishes at a different orientation from the inner rim and olivine core. Olivine also alters to iddingsite irregularly, in streaks along crystallographic directions, along fractures, or in patches which creates a mottled extinction. Some olivine is completely altered to iddingsite. Many microphenocrysts exhibit an overgrowth of olivine in the same optical orientation as the core olivine, giving the microphenocrysts a euhedral outline, even though the core had been partially resorbed before alteration to iddingsite. The rims were too narrow to measure the 2V in these samples, but very slight increase in birefringence of the overgrowths in a few cases indicates a slight increase in fayalite content. The olivine is biaxial negative or neutral with $2V_z$ ranging from -85° to 90°. This indicates a compositional range of Fo 79 to Fo 88.

Augite phenocrysts, up to 3 mm in size, generally comprise 1 to 2% of the mode. They are biaxial positive, buff to greenish brown in color, range in birefringence from 0.012 to 0.028, and in $2V_z$ from 49° to 60°. Twinning is very common and microphenocrysts are often glomerocrystic. Interpenetration twins are observed in C-18-1. The augite is not altered, but does often occur as slightly rounded, embayed grains indicating resorption. The groundmass pyroxene is also augite with $2V_z$ ranging from 50° to 55°. It is generally buff colored and anhedral. Orthopyroxene and pigeonitic pyroxene were not found.

Plagioclase phenocrysts up to 1 cm in length are found in Pololu lavas. They are euhedral to subhedral laths, commonly ragged and fractured and clustered together as glomerocrysts. Normal zoning is quite common. Reversed zoning was observed in A-100 with a core of An50 and a rim of An64. Carlsbad, albite, and pericline twinning are observed as well as a few interpenetration twins. Plagioclase composition was estimated by combined Carlsbad-albite twins and Michel-Levy statistical methods. Compositions range from calcic labradorite (An66) to sodic labradorite (An56 to An58). Groundmass plagioclase occurs as euhedral to subhedral laths averaging 0.1 mm in size.

Composition of the groundmass plagioclase is sodic labradorite (An50 to An58). It is generally more sodic than the phenocrysts. Alkalic feldspar is present interstitially in minor amounts. It is distinguished by a refractive index less than that of basalm. Much of the alkali feldspar is found in vesicles, suggesting late crystallization and the possibility of volatile transfer of alkalis.

Anhedral plates of biotite up to 0.12 mm in size comprise about 1% of the mode of massive basalts along the Waimea-Kohala road. They often are found protruding into vesicles or associated with magnetite and hematite.

The opaque fraction of Pololu Formation alkalic basalt consists largely of magnetite. Ilmenite, identified as long jagged needles, makes up nearly 5% of the mode in sample C-2-1. Magnetite grains, which are found throughout the groundmass and associated with strongly altered olivines, are equidimensional. A few platy anhedral grains of red hematite also are present. Colorless needles of apatite occur in trace amounts throughout the groundmass.

Hawi Formation

The alkalic lavas of the Hawi Formation in the Kawaihae Quadrangle comprise mugearites, hawaiites, and benmoreites. Each of these rock types will be discussed individually.

Mugearites

Most of the Hawi Formation lavas in the Kawaihae Quadrangle are mugearites. Typically, they are massive and very fine grained, and less vesicular than the alkali basalts. Texture is almost always intergranular, locally intersertal, rarely porphyritic, and strongly pilotaxitic to trachytic. Samples collected near vents show a very weak pilotaxitic texture which becomes more pronounced away from the vent area, and finally quite extreme near the terminal margins of flows. The most extreme examples of trachytic flow texture were collected along the lower Kawaihae-Hawi roadcuts in the flow from Puu Lapalapa. These samples exhibit a double fabric of feldspar orientation which under crossed nicols gives the appearance of a striped "herringbone" fabric. The general parallel alignment of feldspars is caused by flowage of the viscous lava. The uniformly sized feldspars are parallel to each other within each "stripe," but not quite parallel to those in an adjacent "stripe," i.e., alternating stripes extinguish simultaneously. The hand specimens of these samples exhibit extreme platy cleavage and shearing (Plate IV, Fig. A). It is possible that as the flow was losing its fluidity, the double fabric was caused by the shearing along cleavage, dragging plates of feldspar past each other and slightly changing the orientation of the feldspars within each plate (stripe).

Intersertal texture occurs locally in samples collected near the vents. Small patches of glassy, highly vesicular scoria occasionally are observed in thin sections.

Mineralogically the mugearites are characterized by 50 to 60% modal oligoclase, minor andesine and alkali feldspar, groundmass olivine, clinopyroxene, magnetite apatite, and minor biotite. Olivine strongly predominates over pyroxene.

The composition of the plagioclase was estimated by extinction angle using the Michel-Levy and microlite statistical methods (Heinrich, 1965). The angle of extinction for the plagioclase was generally close to 0°, giving compositions in the range of calcic to medium oligoclase, An20-An28. The grains are euhedral to subhedral laths and microlites with albite and Carlsbad twinning. Laths of sodic andesine, An33-An 38, based on extinction angles of 15-20°, are also found in amounts up to 7%. These grains are slightly larger in size than the surrounding oligoclase grains. Alkali feldspar is present interstitially and as small grains in amounts up to 6%. Alkali feldspar has a refractive index less than 1.54. Some of the mugearites contain large ragged phenocrysts of plagioclase which appear to be oligoclase with more sodic oligoclase rims, or sodic andesine with oligoclase rims.

Olivine comprises 10 to 20% of the mode of Hawi Formation mugearites. The great majority of the olivine is in the groundmass although some samples such as F-4-2, A-33-1 and A-35-1 contain microphenocrysts up to 0.7 mm in size. The greatest number of olivine microphenocrysts, averaging 0.35 mm, occur in the lava flow from Puu Loa (samples A-33-1, A-33-2). Many olivine grains are elongated parallel to the x-axis and range in shape from euhedral to anhedral, with the majority being subhedral. Angles of $2V_z$ range from 80° negative to 90°. Iddingsite alteration varies from sample to sample, even within the same flow. Total or partial alteration is common, but distinct iddingsite rims are found only in the Puu Pili flow, where several rounded grains of olivine have heavy, sharp rims of iddingsite containing some small grains of magnetite. Because these grains are so distinctly rimmed and are larger than the unrimmed olivines in the sample ($2V_z$ -85°), it appears that they may be xenocrysts. The presence of numerous dunite nodules and inclusions in the vent material at Puu Pili also favors a xenocrystic origin for the olivine.

A xenocrystic clinopyroxene was found in a sample from the Puu Pili flow. It is 0.8 mm in size, birefringence 0.031 and has an extinction angle between 35 and 40°. Under crossed nicols it exhibits brightly colored thin lamellae, possibly indicating exsolution.

The pyroxene in the Hawi mugearites is confined to the groundmass and is pale green augite, biaxial positive, with $2V_z$ of about 50° to 55°. It comprises up to 10% of the mode and has an average size of 0.04 mm. Euhedral and subhedral shapes are common in needles and prismatic forms. Aegirin-augite occurs in A-20-3, a sample from the Puu Ahia flow. It is pleochroic from pale yellow to brownish yellow-green, has a birefringence up to 0.039, and negative $2V_z$ of about 60°. Birefringence is higher in an outer rim, which indicates compositional zonation.

The opaque fraction of Hawi mugearites consists largely of magnetite. Ilmenite also occurs as long jagged needles as well as minor amounts of goethite and hematite. The magnetite grains are equidimensional and average 0.027 mm in size in the groundmass, often forming clumps and aggregates. The numerous tiny euhedral grains commonly have a "dusty" appearance. Large microphenocrysts up to 0.32 mm also occur.

Accessory apatite occurs in two forms in amounts up to 4%. It appears in its common form as tiny groundmass needles, colorless to pale green in color. It also occurs as large, euhedral, pinkish-brown crystals up to 0.4 mm in length. These pinkish-brown crystals are often pleochroic. Basal sections tend to be hexagonal in outline and the prismatic sections are rectangular, commonly exhibiting poor basal (0001) cleavage. Rows of tiny dark inclusions are parallel to the "c" crystallographic direction. The occurrence of these large brown apatite crystals is quite commonly associated with the occurrence of the large magnetite phenocrysts. Apatite is among the late forming minerals. Because iron oxide is often enclosed in late minerals, apatite is associated primarily with biotite, hornblende, magnetite, and alteration products (Moorhouse, 1959). Most apatite occurs at or near grain boundaries.

Biotite also is found as an accessory mineral in modal amounts up to 3%. It is pleochroic from pale yellow to reddish brown with high birefringence, "birdseye maple" structure, parallel extinction, and $2V_z$ negative less than 10°. Biotite is seen as anhedral cleavage pieces and basal sections, averaging 0.03 mm in size, but reaching a maximum size of 0.28 mm. Samples A-15-1 from the Lapalapa flow and A-18-1 from the Mala flow, exhibit the greatest abundance of biotite. It is often found projecting into vesicles and associated with large magnetite grains. In the Puu Ahia flow, anhedral biotite xenocrysts up to 0.8 mm across have deeper colors and higher birefringence (0.060) than other biotite grains, and are surrounded by heavy opaque rims (samples A-35-1, A-20-3).

Benmoreite

Benmoreite occurs at only one location within the Kawaihae Quadrangle; the dome of Puu Makela. The texture of the dome rock is porphyritic with an intergranular groundmass with strong trachytic texture and an average grain size of about 0.4 mm. Two samples from the dome were studied in detail. In A-60-1, from the center of the dome at the Puu Makela roadcut, feldspar occurs in three size groupings: phenocrysts 6.0 mm in length, groundmass feldspar averaging 0.40 mm in length, and very small, almost fibrous grains 0.02 mm in length. Except for grains of aegirine-augite, hornblende, olivine, and magnetite comparable in size to the middle-sized feldspar grains, the rock appears in plane light to be composed totally of feldspar and "dusted" with tiny grains of aegirine-augite, hornblende, olivine, magnetite, apatite, and hematite. Both the hornblende and the aegirine-augite are anhedral grains averaging 0.22 mm in size. The aegirine-augite is yellowish-green, has a birefringence of 0.012, negative $2V_z$ of about 70°, and hourglass extinction, with $\gamma \Lambda c$, 28°. Olivine grains are subhedral and average 0.12 mm to 0.20 mm in size. They are altered irregularly to iddingsite. Sample A-34-1, from the very top of the dome, differs from A-60-1 only in that it contains no hornblende or aegirine-augite, and it contains 1% glass. The clinopyroxene in A-34-1 occurs as pale green needles.

There is a complete gradation in the composition of the groundmass feldspar from oligoclase An20 to calcic albite An5. Alkali feldspar having a negative $2V_z$ of 50° comprises some of the tiny grains. Large phenocrysts of oligoclase with Carlsbad and albite twinning are very rounded and embayed by resorption, and enclosed by a thin shell of calcic albite. Rounded andesine phenocrysts up to 1cm in size are also present.

Hawaiite

The only hawaiite in the Kawaihae Quadrangle is the flow from Puu Kawaiwai. The hawaiite has an appearance very much like that of mugearite. It has a fine grained, intergranular texture, and a very trachytic flow texture. Andesine (An38 to An41) dominates oligoclase (An20) by only 9%. The andesine grains have more albite twinning and are more euhedral than the oligoclase grains. Euhedral to anhedral groundmass olivine (Fo82-Fo85) comprises 20% of the rock. There is extensive alteration to iddingsite. Clinopyroxene occurs as colorless to pale green needles. Iron ore minerals include abundant magnetite, some hematite, and traces of ilmenite. Subhedral magnetite microphenocrysts up to 0.34 mm are commonly associated with altered olivine. Large brown apatite crystals are also present.

Hamakua Formation

The sequence of lavas of the Hamakua Formation in the Kawaihae Quadrangle is from a lowest feldspar-phyric unit to a fine grained, massive unit with only occasional olivine and pyroxene phenocrysts, to a unit of abundant pyroxene and olivine phenocrysts. The middle and upper units may be phases of the same flow. All three units are alkali olivine basalts. The composition of feldspars, pyroxene, and olivine is very similar among the units, but the abundance and condition of the phenocrysts varies greatly.

The feldspar-phyric unit is porphyritic intergranular and contains 11% plagioclase phenocrysts of labradorite (An56 to An67). Phenocrysts occur up to 3.0 mm in length and many are euhedral to subhedral ragged laths. Groundmass feldspar, 0.24 mm in size, is sodic labradorite (An50 to An54). Groundmass and phenocrystic olivine has a negative $2V_z$ of about 85° and composition of Fo78. Olivine phenocyrsts average 1.5 mm in size. Augite phenocrysts comprise 2% of the mode and are buff to greenish yellow in color, up to 0.8 mm in size, with positive $2V_z$ of 50°, and are twinned. Groundmass clinopyroxene grains are pale green, euhedral to anhedral, and have a positive $2V_z$ of 45 to 50°.

The middle unit is a subporphyritic, intergranular, equigranular rock with cumulocrysts of pyroxene and plagioclase. The phenocrysts are calcic labradorite (An65) and the groundmass is sodic labradorite (An55). Augite is pale green to buff, with positive $2V_z$ of 55°. Olivine has the same composition as in the preceding unit.

The upper unit has 4% phenocrysts of medium labradorite (An60). Some of the phenocrysts appear quite "motheaten" and have normal zoning. Groundmass plagioclase is more sodic (An57).

All three units have 10-15% magnetite and needles of apatite in trace amounts. Vesicularity for the lower and upper units is approximately 8%. Olivine and augite occur within each sample, in nearly equal amounts.

The Hamakua alkali olivine basalt that lies directly below the flow from Puu Loa in the Kawaihae quarry appears to be the middle unit described above. Measurement of extinction angles of combined Carlsbad-albite twins gives 19° and 36° and calcic labradorite composition (An67) for large, sometimes frayed, rounded and zoned feldspar phenocrysts. Groundmass feldspar is sodic labradorite (An52). Olivine phenocrysts up to 3.0 mm in length comprise up to 10% of the mode and vary in their amount of alteration to iddingsite. Some are fractured, rounded, and embayed without alteration to iddingsite, while others show altered centers, or rims mantled with fresh olivine. Augite phenocrysts up to 2.0 mm in size are buff to pale yellow to pinkish in color, and have inclined extinction of 51° to 55°. The pinkish color may indicate slightly titaniferous augite. They are euhedral to subhedral in shape, show some rounding and embayment and commonly form clots, or cumulocrysts with plagioclase and occasionally olivine. The groundmass clinopyroxene is also probably augite. It is buff colored to pinkish, has inclined extinction, birefringence of

0.012, and subhedral to anhedral shape. The usual $2V_z$ for this clinopyroxene is about 45°, but several off-center Bxa interference figures show 2V's that are probably lower. Magnetite is present in amounts up to 10% of the mode, giving a "dusty" appearance in places. Ilmenite and apatite are present in trace amounts, and vesicularity is only 4%.

MINERALOGY

Ten samples representing the major mappable units in the Kawaihae Quadrangle were analyzed in reconnaissance using an ARL-SEMQ electron microprobe by Carlton Allen of the Lunar and Planetary Laboratory, University of Arizona, Tucson. Chemical analyses were reported for feldspar, pyroxene, olivine, and spinel as shown in Table 3. Feldspar compositions are plotted in Figure 6. To distinguish among spinel compositions along the ulvospinel-magnetite join and those along the ilmenite-hematite join, total FeO was recalculated and is presented as Fe_2O_3 and FeO in the table. Analyses are considered accurate if totals are between 98% and 101%. Because of the reconnaissance nature of the probe analyses and the limited number of samples probed, the results are used here largely as a comparison with petrographic results.

The samples that were probed are as follows:

Table 3. Results of Microprobe Analyses

Weight %	27 mp	28 mp	30 mp	33 mp	34 mp	47 gm	48 gm	59 gm	50 gm	51 gm
	Sample A - 33 - 2					Sample F - 4 - 2				
Na_2O	0.04	5.44	6.59	6.94	0.00	0.04	7.75	6.73	6.98	6.70
K_2O	0.16	0.34	0.82	1.55	0.02	0.04	1.36	6.03	0.71	5.54
CaO	0.18	10.28	7.73	6.82	0.27	0.00	5.06	1.27	6.63	2.53
Al_2O_3	2.60	27.20	24.75	24.00	0.27	5.44	22.75	17.77	24.99	17.30
SiO_2	0.34	55.34	58.29	57.64	36.85	0.20	59.95	64.78	58.24	62.93
MgO	2.45	0.07	0.07	0.02	33.92	4.27	0.19	0.41	0.31	1.11
TiO_2	22.42	--	--	--	0.15	14.36	--	--	--	--
Cr_2O_3	0.12	--	--	--	0.06	0.00	--	--	--	--
FeO	17.86	0.43	1.40	0.87	27.80	39.05	1.28	1.91	1.01	1.59
Fe_2O_3	52.70	--	--	--	--	36.72	--	--	--	--
Total	98.77	99.10	99.90	98.12	99.34	100.12	98.61	99.47	99.10	98.29
Mineral	TI-MAGT	PLAG	PLAG	PLAG	OLIVINE	ULVO-SPINEL	PLAG	PLAG	PLAG	PLAG
Composition		Ab 48 Or 2 An 50	Ab 58 Or 5 An 37	Ab 59 Or 9 An 32	Fo 69 Fa 31		Ab 68 Or 8 An 24	Ab 59 Or 35 An 6	Ab 63 Or 4 An 33	Ab 57 Or 31 An 12

Table 3. (continued) Results of Microprobe Analyses

Weight %	Cyrstal # 11 mp	14 mp	15 mp	16 gm	1A mp				
		Sample A - 42 - 2			Sample A - 20 - 3				
Na_2O	0.00	8.70	5.69	7.49	7.06	6.80	6.75	7.61	6.55
K_2O	0.04	1.97	0.37	1.31	0.79	0.72	0.73	1.01	0.58
CaO	0.00	4.57	9.93	5.72	6.62	7.06	6.91	5.37	7.52
Al_2O_3	4.62	25.88	27.36	23.03	25.65	25.65	24.69	23.73	26.62
SiO_2	0.20	54.77	55.30	60.14	58.47	57.35	59.08	61.98	58.48
MgO	4.58	0.00	0.03	0.02	0.03	0.01	0.03	0.01	0.03
TiO_2	20.15	--	--	--	--	--	--	--	--
Cr_2O_3	0.03				--	--	--	--	--
FeO	13.47	4.40	0.66	0.84	0.39	0.40	0.41	0.37	0.43
Fe_2O_3	56.67	--	--	--					
Total	99.76	100.44	99.53	98.83	99.03	98.10	98.62	100.22	100.40
Mineral	TI-MAGT	PLAG	PLAG	PLAG MATRIX	PLAG	PLAG	PLAG	PLAG	PLAG
Composition		Ab 70 Or 10 An 20	Ab 50 Or 2 An 48	Ab 65 Or 8 An 27	Ab 63 Or 5 An 33	Ab 61 Or 4 An 35	Ab 61 Or 4 An 35	Ab 68 Or 6 An 26	Ab 59 Or 3 An 37

Table 3. (continued) Results of Microprobe Analyses

Chemical %	Crystal # 3A mp		4A mp		2A mp	
	Sample A - 20 - 3 (continued)					
Na_2O	7.64	7.40	7.53	7.37	0.05	0.05
K_2O	0.77	0.81	0.76	0.79	0.02	0.01
CaO	5.22	5.51	5.47	5.38	0.19	0.20
Al_2O_3	24.36	24.42	24.38	24.22	0.25	0.04
SiO_2	60.71	60.12	60.43	61.17	36.87	37.61
MgO	0.04	0.04	0.02	0.04	34.33	34.25
TiO_2	--	--	--	--	0.02	0.09
Cr_2O_3	--	--	--	--	0.05	0.00
FeO	0.18	0.18	0.32	0.22	29.04	29.41
Total	98.95	98.53	98.94	99.20	100.81	101.66
Mineral	PLAG	PLAG	PLAG	PLAG	OLIVINE	OLIVINE
Composition	Ab 69 Or 5 An 26	Ab 67 Or 5 An 28	Ab 68 Or 5 An 27	Ab 68 Or 5 An 27	Fo 68 Fa 32	Fo 67 Fa 33

Table 3. (continued) Results of Microprobe Analyses

Weight %	Crystal # 7A mp		8A mp		9A mp		5A mp	6A mp
				Sample A - 35 - 1				
Na_2O	7.58	7.30	7.74	7.50	7.03	7.21	0.09	0.01
K_2O	0.69	0.67	0.72	0.78	0.74	0.72	0.04	0.01
CaO	5.50	5.71	5.43	5.36	6.22	6.37	0.00	0.00
Al_2O_3	24.34	24.75	24.23	23.80	25.73	24.83	2.35	3.05
AiO_2	61.09	60.19	61.60	61.47	59.22	60.87	0.21	0.00
MgO	0.02	0.04	0.03	0.01	0.07	0.03	3.58	3.83
TiO_2	--	--	--	--	--	--	19.50	18.67
Cr_2O_3	--	--	--	--	--	--	0.00	0.00
FeO	0.22	0.17	0.36	0.48	0.19	0.22	13.06	12.11
Fe_2O_3	--	--	--	--	--	--	61.70	62.24
Total	99.49	98.95	100.20	99.40	99.23	100.32	100.53	99.92
Mineral	PLAG	PLAG	PLAG	PLAG	PLAG	PLAG	TI-MAGT	TI-MAGT
Composition	Ab 68 Or 4 An 27	Ab 67 Or 4 An 29	Ab 69 Or 4 An 27	Ab 68 Or 5 An 27	Ab 64 Or 4 An 31	Ab 64 Or 4 An 31		

Table 3. (continued) Results of Microproge Analyses

Weight %	Crystal # 36 mp	37 mp	43 gm	39 mp	40 mp
			Sample A - 60 - 1		
Na_2O	7.98	7.52	7.63	0.05	0.00
K_2O	0.89	0.94	4.36	0.05	0.01
CaO	5.14	5.70	0.78	0.40	0.45
Al_2O_3	24.16	24.41	20.32	0.04	0.00
SiO_2	61.22	60.52	62.65	33.68	33.79
MgO	0.00	0.02	0.00	21.70	22.23
TiO_2	--	--	--	0.05	0.06
Cr_2O_3	--	--	--	0.02	0.00
FeO	0.33	0.33	0.67	42.30	43.19
Total	99.76	99.50	96.58	98.29	99.73
Mineral	PLAG	PLAG	PLAG MATRIX	OLIVINE	OLIVINE
Composition	Ab 70 Or 5 An 25	Ab 67 Or 5 An 28	Ab 70 Or 26 An 4	Fo 48 Fa 52	Fo 48 Fa 52

Table 3. (continued) Results of Microprobe Analyses

Weight %	Crystal 3						
	14A mp		15A mp		19A mp	12A mp	
			Sample C - 12 -1				
Na_2O	6.83	6.15	6.23	5.85	5.76	0.02	0.04
K_2O	1.10	0.53	0.99	1.04	0.38	0.02	0.04
CaO	6.29	7.99	7.56	7.76	9.02	0.22	0.22
Al_2O_3	25.15	27.10	26.74	26.77	27.16	0.13	0.00
SiO_2	60.34	57.97	58.10	57.83	55.65	40.69	39.46
MgO	0.01	0.04	0.09	0.09	0.11	44.43	42.74
TiO_2	--	--	--	--	--	0.02	0.11
Cr_2O_3	--	--	--	--	--	0.02	0.04
FeO	0.75	0.72	0.69	0.86	0.97	14.28	17.03
Total	100.53	100.77	100.64	100.44	99.28	99.83	99.68
Mineral	PLAG	PLAG	PLAG	PLAG	PLAG	OLIVINE	OLIVINE
Composition	Ab 62 Or 7 An 32	Ab 56 Or 3 An 40	Ab 56 Or 6 An 38	Ab 54 Or 6 An 40	Ab 52 Or 2 An 45	Fo 85 Fa 15	Fo 82 Fa 18

Table 3. (continued) Results of Microprobe Analyses

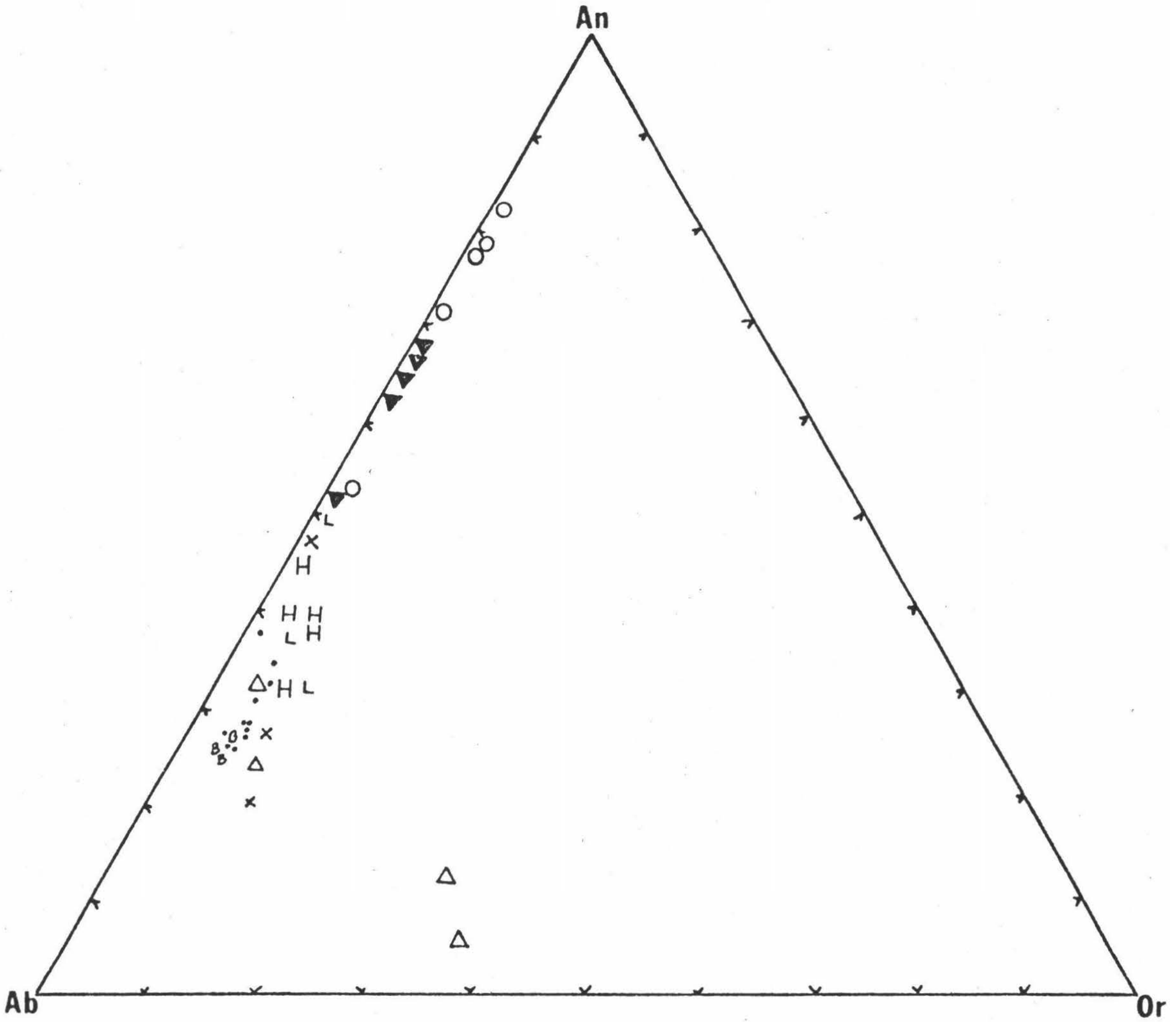
Weight %	Crystal # 1 p	3 p	5 gm	6 p	9 p	2 p	4 gm	7 p
				Sample C - 18 - 1				
Na_2O	3.73	3.84	5.29	4.03	4.10	0.26	0.18	0.23
K_2O	0.21	0.18	0.37	0.22	0.22	0.04	0.03	0.04
CaO	13.98	13.77	11.03	13.53	12.61	18.23	19.31	18.24
Al_2O_3	30.64	31.52	28.43	30.68	30.80	1.75	2.11	1.68
SiO_2	51.27	51.86	55.88	52.94	52.12	50.42	51.44	51.36
MgO	0.23	0.19	0.10	0.20	0.15	15.66	16.19	15.06
TiO_2	--	--	--	--	--	1.18	0.73	1.25
Cr_2O_3	--	--	--	--	--	0.01	0.17	0.04
FeO	0.48	0.58	0.59	0.57	0.58	12.05	8.61	11.16
Total	100.54	102.02	101.72	102.35	100.76	99.60	98.77	99.06
Mineral	PLAG	PLAG	PLAG	PLAG	PLAG	PYX	PYX	PYX
Composition	Ab 31 Or 1 An 67	Ab 33 Or 1 An 66	Ab 46 Or 2 An 52	Ab 35 Or 1 An 64	Ab 37 Or 1 An 62	Wo 37 En 44 Fs 19	Wo 40 En 46 Fs 14	Wo 38 En 44 Fs 18

Table 3. (continued) Results of Microprobe Analyses

Weight %	Crystal # 17 mp	18 mp	19 mp	20 mp	24 mp	26 gm	21 mp	23 mp
				Sample C - 14 - 1				
Na_2O	2.38	3.35	2.42	1.88	2.46	5.20	0.02	0.01
K_2O	0.15	0.18	0.14	0.11	0.16	0.47	0.02	0.08
CaO	16.78	15.50	16.45	17.54	16.62	11.22	0.38	0.26
Al_2O_3	31.80	30.33	31.68	32.75	31.41	27.52	0.00	0.11
SiO_2	48.46	50.33	47.32	48.19	47.96	55.26	38.33	37.66
MgO	0.11	0.06	0.09	0.10	0.13	0.20	38.90	39.19
TiO_2	--	--	--	--	--	--	0.00	0.14
Cr_2O_3	--	--	--	--	--	--	0.00	0.00
FeO	0.64	0.66	0.82	0.48	0.71	0.86	22.22	22.38
Total	100.51	100.58	99.04	101.18	99.62	100.93	99.87	99.83
Mineral	PLAG	PLAG	PLAG	PLAG	PLAG	PLAG MATRIX	OLIVINE	OLIVINE
Composition	Ab 20 Or 1 An 79	Ab 28 Or 1 An 71	Ab 21 Or 1 An 78	Ab 16 Or 1 An 83	Ab 21 Or 1 An 78	Ab 44 Or 3 An 53	Fo 76 Fa 24	Fo 76 Fa 24

Notation: gm = groundmass; mp = microphenocryst; TI-MAGT = titaniferous magnetite; p = phenocryst.

Figure 6. Ternary diagram showing feldspar compositions determined from microprobe analyses.



• A-20-3, Mugearite, hah
• A-35-1, Mugearite, hah
ʟ A-33-2, Mugearite, hlo
× A-42-2, Mugearite, hm
B A-60-1, Benmoreite, hmd
△ F-4-2, Mugearite, hll
H C-12-1, Hawaiite, hkw

○ C-14-1, Alkali olivine basalt, hmk
▼ C-18-1, Alkali olivine basalt, ppl

Mugearites:	A-33-2, Puu Loa flow
	F-4-2, Puu Lapalapa flow
	A-20-3 and A-35-1, Puu Ahia flow
	A-42-2, Puu Mala flow
Hawaiite:	C-12-1, Puu Kawaiwai flow
Benmoreite:	A-60-1, dome of Puu Makela
Alkali olivine basalts:	C-18-1, Pololu Formation
	C-14-1, Hamakua Formation

Locations and petrography for these samples are given in the Appendix.

The flow from Puu Loa shows two groupings of feldspar compositions: calcic andesine (An51) and sodic andesine (An32). Andesine microphenocrysts were seen in thin section, but oligoclase was the dominant feldspar. The olivine analysis reported has a forsterite component of Fo69, which is richer in iron than any compositions obtained by optical means for this sample.

The flow from Puu Lapalapa also shows two groupings of feldspar composition: calcic oligoclase (An24) to sodic andesine (An33), and feldspar showing a high enough Or component to be considered anorthoclase (Or31-Or35). These results agree with thin section observations; alkali feldspar was found optically. The plagioclase matrix appears to have an oligoclase composition.

The Puu Mala flow shows medium to calcic oligoclase (An20 and An27) and calcic andesine (An48). Optically estimated compositions compare closely: medium to calcic oligoclase (An20 to An28) and calcic andesine (An49 and An47).

The analyses run on the samples from the Puu Ahia flow show compositions for several points within single crystals. Grain 1A from A-20-3 shows variation from sodic andesine, An37, to calcic oligoclase, An26. Grains 3A and 4A appear to be uniformly calcic oligoclase. Grains 7A and 8A in A-35-1 are calcic oligoclase, and 9A is sodic andesine. Olivine compositions (Fo67 and Fo68) for this sample are in the same range as that reported for Puu Loa. Stearns and Macdonald (1946, p. 178) refer to the flow from Puu Ahia as a trachyte. Chemical and petrographic evidence above are inconsistent with that interpretation. The chemistry (Macdonald, 1968, p. 492, sample C-210) and mineralogy of this sample is typical of Hawaiian mugearites.

The benmoreite dome of Puu Makela (A-60-1) contains plagioclase mostly in the range of calcic oligoclase (An25-30), but the analysis of the plagioclase matrix shows a K_2O content of 4.36 weight per cent and an Or component of 26. This high potassium content in the groundmass agrees with the high modal content of alkali feldspar observed in thin section in samples A-60-1 and A-34-1. Olivine is iron rich (Fo44 to Fo48).

The hawaiite flow from Puu Kawaiwai (C-12-1) shows plagioclase that is dominantly sodic to medium andesine (An32 to An40), which agrees quite well with compositions estimated optically (An37 to An41). Olivine compositions (Fo81 to Fo85) also agree with optical determinations (Fo82 to Fo85). A Mauna Kea origin has been suggested for Puu Kawaiwai (Macdonald, 1946, p. 196), but the cone and its flow belong geographically to Kohala Mountain.

The Puu Kawaiwai lava does not resemble the Mauna Kea lavas of the area studied, either chemically or petrographically, but is similar to Kohala Mountain mugearites.

Probe results for Pololu Formation sample C-18-1 give plagioclase compositions ranging from calcic to sodic labradorite (An67 to An53) as seen in thin section (An66 to An52). An augite composition (En44) for clinopyroxenes agrees with both probe and petrographic results.

The Hamakua Formation sample analyzed (C-14-1) shows feldspar phenocryst compositions in the bytownite range (An71 to An83), while optical determinations give compositions in the labradorite range (An60 to An67). Probe data shows the groundmass to be calcic labradorite. The grains probed are very rounded and show wavy extinction. They were not in equilibrium with the rest of the magma and perhaps represent xenocrysts rather than phenocrysts. Olivine has a composition of Fo76 compared to the petrographic estimation of Fo78.

In summary, mineral compositions given by reconnaissance microprobe analyses generally agree with compositions determined optically. Figure 6 illustrates the overlapping nature of mugearite, hawaiite and benmoreite feldspar compositions. The probe analyses help to show the possible range of feldspar composition in Hawi lavas and to point out that Kohala mugearites, benmoreites and hawaiites are gradational.

GEOCHEMISTRY

Methods

Six new chemical analyses are reported here for rocks in the Kawaihae Quadrangle. The samples were analyzed for major elements by the Analytical Laboratory, Department of Earth Sciences, University of Manitoba. A summary of methods used at the Analytical Laboratory is found in Table 4. Table 5 defines the precision and accuracy of major elemental analyses. Samples were chosen to represent as many of the major units mapped as possible without duplicating previously published analytical results. The six samples analyzed were chosen on the basis of their freshness in hand sample and in thin section. All available chemical analyses of samples from the Kawaihae Quadrangle are presented in Table 7. C.I.P.W. norms, differentiation index and Al_2O_3/SiO_2 and FeO/Fe_2O_3 ratios also are presented in Table 7. Differentiation Index, D.I., is defined as Q + OR + AB + LC + NE + KP + HL + C + Z + TH + NC. 'A' is defined as $Na_2O + K_2O$; 'F' is defined as $FeO + 0.89981 \times Fe_2O_3 + MnO$; 'M' is defined as MgO. Table 6 reports sample numbers, plotting symbols, flow unit and location, and source of the chemical analyses. A location map of chemically analyzed samples is shown in Plate VIII. It should be noted that C-69 and C-70 in Macdonald and Katsura (1964) were labeled as part of the Hawi Formation

Table 4. Summary of Methods Used in the Analytical Laboratory, Department of Earth Sciences, University of Manitoba

Element	Method
Si Al Fe (Total) Mg (High) Ca K Ti Mn Zr	X-ray Fluorescence Spectrometry. Weighted sample plus $Li_2B_4O_7$ plus La_2O_3 heated in a graphite crucible at about 1100°C for a half hour. Resulting glass bead with H_3FO_3 (total weight, 2.1000 grams) ground to -200 mesh and then compressed to 50,000 p.s.i. Elements then simultaneously analyzed on multi-channel ARL X-ray Spectrometer.
Na_2O, Mgo (Low) and Trace Metals	Atomic Absorption Spectrophotometry. Rock dissolves with Hf, H_2SO_4, and HNO_3 in platinum crucibles. Perkin Elmer 303 A.A.S. used for determinations.
P_2O_5	Colorimetry. Solution as for Na_2O above. The absorption at 430 m of molybdivanado-phosphoric acid complex. Unicam sp 500 spectrophotometer.
FeO	Rock decomposed with HF and 1:4 H_2SO_4 solution titrated with $K_2Cr_2O_7$ using Sodium Diphenylamine Sulfonate as indicator.
H_2O^-	Determined by heating sample to constant weight at 110°C.
H_2O (Total)	Determined by heating sample in a stream of dry oxygen in an induction furnace (Temp. 1100°C). H_2O collected on Anhydrone and weighed.
H_2O^+	H_2O (Total) - H_2O^-.
S	Determined by heating samples in an induction furnace with oxygen flowing through combustion chamber. SO_2 evolved is then tritated. Leco Induction Furnace and automatic Titrator.

Table 4. (continued) Summary of Methods Used in the Analytical Laboratory, Department of Earth Sciences, University of Manitoba

Element	Method
CO_2	Sample decomposed by HCl and heat. CO_2 evolved passed through drying train and collected on Ascarite.
CO_2 (Low S samples)	Determined simultaneously with H_2O (Total). CO_2 collected on Ascarite; small amounts of SO_2 removed on MnO (act).

Table 5. Precision and Accuracy of Major Element Determinations, Department of Earth Sciences, University of Manitoba

Constituent	Concentration %	Instrument Precision, σ	Accuracy of Replicates, σ
SiO_2	59.60	.12	.20
Al_2O_3	9.34	.05	.13
Fe_2O_3 (Total)	10.08	.017	.03
MgO	.404	.04	.10
CaO	10.22	.02	.07
K_2O	2.69	.01	.01
MnO	.41	.01	.01
TiO_2	.48	.02	.02
Na_2O	4.20	.01	.05
H_2O (Total)	1.60	.03	.06
CO_2	1.15	.05	.12
P_2O_5	0.20	.01	.01
FeO	10.92	--	.04
S	0.185	.003	.005

Table 6. Symbols, Locations and Sources of Chemically Analyzed Samples

Plot Symbol	Sample No.	Rock Type	Map Unit Represented and Location	Source
A	F1-1	Mugearite	Puu Aiea flow; roadcut, Kawaihae-Hawi road 1.2 km (0.75 mi) NW of Kapole Gulch.	Malinowski, 1977
B	C-211	Mugearite	Puu Pili flow; 92 m upslope from Waimea-Kohala road, due west of Puu Honu.	Macdonald, 1968
C	C-212	Mugearite	Puu Pili flow; in gulch below Waimea-Kohala road 0.8 km (0.5 mi) SE of Puu Aiea	Macdonald, 1968
D	A15-1	Mugearite	Puu Lapalapa flow; Waimea-Kohala road 0.7 km (0.45 mi) SE of North/South Kohala District Boundary.	Malinowski, 1977
E	A18-2	Mugearite	Puu Mala flow; Waimea-Kohala road 0.2 km (0.1 mi) NW of Kilohana Gulch, 3564' elevation marker.	Malinowski, 1977
F	C-210	Mugearite	Puu Ahia flow; Waimea-Kohala roadcut NW of Puu Loa at head of 1st gulch N of Keawewai Gulch.	Macdonald, 1968
G.	62-1	Benmoreite	Dome of Puu Makela; deep roadcut on Waimea-Kohala road 0.4 km (0.25 mi) SE of Puu Loa.	Macdonald and Katsura, 1964
H	WAS12	Mugearite	Puu Loa flow; 1098 m (3600 ft) altitude near Puu Makela.	Washington, 1923
I	A33-1	Mugearite	Puu Loa flow; flow ridge between Puu Loa and Puu Makela.	Malinowski, 1977
J	C-68	Mugearite	Hawi flow; Waimea-Kohala road 3.5 km (2.2 mi) ESE of Puu Kawaiwai.	Macdonald and Katsura, 1964

Table 6. (continued) Symbols, Locations and Sources of Chemically Analyzed Samples

Plot Symbol	Sample No.	Rock Type	Map Unit Represented and Location	Source
K	WASH4	Hawaiite	Puu Kawaiwai flow; near Puu Kawaiwai at 976 m (3200 ft) altitude	Washington, 1923
L	C12-1	Hawaiite	Puu Kawaiwai flow; N side of Makeahua Gulch, E boundary of map, 0.15 mi N of Waimea-Kawaiwai road.	Malinowski, 1977
Q	C14-1	Alkali ol. basalt	Hamakua Formation; Kawaihae quarry, below Puu Loa flow.	Malinowski, 1977
X	C-69	Alkali ol. basalt	Pololu Formation; Waimea-Kohala road 1.4 km (0.9 mi) E of Puu Kawaiwai.	Macdonald and Katsura, 1964
Y	C-70	Alkali ol. basalt	Pololu Formation; Waimea-Kohala road 2.1 km (1.3 mi) NW of Puu Kawaiwai.	Macdonald and Katsura, 1964
Z	WASH5	Alkali ol. basalt	Pololu Formation; 1037 m (3400 ft) altitude in Kawaihae Gulch.	Washington, 1923
①	Thole	--	Average Hawaiian Tholeiite	Macdonald, 1968
②	Ankar	--	Average Hawaiian Ankaramite	Macdonald, 1968
③	Alolb	--	Average Hawaiian Alkali Olivine Basalt	Macdonald, 1968
④	Hawai	--	Average Hawaiian Hawaiite	Macdonald, 1968
⑤	Mugea	--	Average Hawaiian Mugearite	Macdonald, 1968
⑥	Benmo	--	Average Hawaiian Benmoreite	Macdonald, 1968
⑦	Natra	--	Average Hawaiian Soda-Trachyte	Macdonald, 1968

Table 7. Results of Chemical Analyses and Norm Calculations*

SAMPLE	F1-1	C-211	C-212	A15-1	A18-2
SYMBOL	A	B	C	D	E
SIO2	47.15	48.80	48.93	49.65	48.65
AL2O3	15.45	15.77	15.65	16.51	16.44
FE2O3	7.57	5.06	5.13	6.32	4.64
FEO	4.94	6.41	6.99	4.98	6.91
MGO	4.46	3.91	3.80	3.45	3.96
CAO	7.52	7.21	7.27	6.56	6.98
NA2O	5.20	5.38	5.45	5.27	5.08
K2O	1.59	1.93	1.98	1.88	1.76
TIO2	2.81	2.54	2.62	2.48	2.56
P2O5	2.32	1.96	1.97	1.76	1.92
MNO	0.24	0.22	0.22	0.25	0.25
H2O	0.23	0.53	0.24	0.44	0.44
CO2	0.11			0.15	0.08
TOTAL	99.58	99.72	100.45	99.70	99.67
			NORMS (CIPW)		
Q					
C					
OR	9.4	11.4	11.6	11.1	10.4
AB	42.1	40.1	39.1	44.7	41.9
AN	14.2	13.2	12.9	15.9	16.9
NE	1.1	3.0	3.7		0.7
WO	3.1	4.1	4.3	1.8	2.0
EN	2.6	2.7	2.7	4.6	1.2
FS		1.1	1.3	0.2	0.6
FO	6.0	4.9	4.7	2.8	6.1
FA		2.1	2.6	0.1	3.5
MT	8.6	7.4	7.4	9.2	6.7
HM	1.7				
IL	5.4	4.8	5.0	4.7	4.9
AP	5.5	4.7	4.6	4.2	4.6
CC	0.3			0.3	0.2
TOTAL	99.9	99.6	99.9	99.7	99.7
SALIC	66.8	67.8	67.3	71.8	69.9
FEMIC	33.1	31.8	32.6	27.9	29.7
DI	5.7	7.9	8.3	3.3	3.8
DIWO	3.1	4.1	4.3	1.8	2.0
DIEN	2.6	2.7	2.7	1.5	1.2
DIFS		1.1	1.3	0.1	0.6
HY				3.2	
HYEN				3.1	
HYFS				0.1	
OL	6.0	7.1	7.3	2.9	9.5
OLFO	6.0	4.9	4.7	2.8	6.1
OLFA		2.1	2.6	0.1	3.5
D.I.	52.6	54.6	54.4	55.9	53.0
AL2O3/SIO2	0.33	0.32	0.32	0.33	0.34
FEO/FE2O3	0.65	1.27	1.36	0.79	1.49

*See Table 6 for sources of data.

Table 7. (Continued) Results of Chemical Analyses and Norm Calculations*

SAMPLE	C-210	62-1	WAS12	A33-1	C-68
SYMBOL	F	G	H	I	J
SIO2	51.80	58.27	52.27	52.10	50.52
AL2O3	17.07	19.12	17.05	17.24	19.43
FE2O3	3.12	5.60	3.51	4.36	4.03
FEO	6.93	1.51	7.20	5.73	5.36
MGO	3.10	1.30	3.13	2.91	3.38
CAO	6.10	2.98	5.82	5.27	5.82
NA2O	5.78	6.54	5.40	5.57	5.35
K2O	2.23	2.67	2.22	2.06	2.23
TIO2	1.95	0.95	2.13	1.90	1.96
P2O5	1.54	0.62	0.62	1.45	0.92
MNO	0.22	0.26	0.16	0.24	0.20
H2O	0.48	0.24		0.42	0.37
CO2				0.32	
TOTAL	100.32	100.06	99.51	99.57	99.57
NORMS (CIPW)					
Q		3.4			
C		1.5		0.5	
OR	13.1	15.8	13.2	12.2	13.2
AB	43.5	55.3	43.0	47.3	40.4
AN	14.0	10.7	15.8	14.7	22.5
NE	2.8		1.6		2.7
WO	2.6		3.8		0.2
EN	1.3	3.2	1.9	5.5	0.1
FS	1.2		1.8	3.2	0.1
FO	4.5		4.1	1.3	5.8
FA	4.7		4.1	0.8	2.8
MT	4.5	3.0	5.1	6.3	5.9
HM		3.6			
IL	3.7	1.8	4.1	3.6	3.7
AP	3.6	1.5	1.5	3.4	2.2
CC				0.7	
TOTAL	99.6	99.8	100.0	99.7	99.7
SALIC	73.5	86.8	73.6	74.8	78.9
FEMIC	26.1	13.0	26.5	24.9	20.8
DI	5.1		7.5		0.4
DIWO	2.6		3.8		0.2
DIEN	1.3		1.9		0.1
DIFS	1.2		1.8		0.1
HY		3.2		8.7	
HYEN		3.2		5.5	
HYFS				3.2	
OL	9.2		8.3	2.1	8.6
OLFO	4.5		4.1	1.3	5.8
OLFA	4.7		4.1	0.8	2.8
D.I.	59.5	74.5	57.8	59.6	56.4
AL2O3/SIO2	0.33	0.33	0.33	0.33	0.38
FEO/FE2O3	2.22	0.27	2.05	1.31	1.33

*See Table 6 for sources of data.

Table 7. (Continued) Results of Chemical Analyses and Norm Calculations*

SAMPLE	WASH4	C12-1	C14-1	C-69	C-70
SYMBOL	K	L	Q	X	Y
SIO2	47.39	47.10	47.20	45.54	47.48
AL2O3	16.46	15.88	13.62	17.61	17.42
FE2O3	3.75	7.51	4.69	3.56	3.59
FEO	8.42	5.16	8.12	8.25	8.10
MGO	5.08	4.15	7.41	6.42	6.74
CAO	7.37	7.22	9.37	10.82	8.54
NA2O	4.71	4.61	3.08	2.74	3.12
K2O	1.65	1.56	1.09	0.70	1.20
TIO2	2.83	2.84	3.44	2.85	2.63
P2O5	2.22	2.21	0.59	0.34	0.36
MNO	0.09	0.24	0.21	0.17	0.18
H2O	0.28	0.57	0.58	0.60	0.40
CO2		0.33	0.18		
TOTAL	100.25	99.38	99.68	99.60	99.76
NORMS (CIPW)					
Q		0.1			
C					
OR	9.7	9.3	6.5	4.2	7.1
AB	37.4	39.3	26.1	23.3	26.5
AN	18.9	18.1	20.2	33.8	30.1
NE	1.3				
WO	1.3	0.5	9.0	7.5	4.2
EN	0.8	10.4	13.5	4.8	6.9
FS	0.5		4.2	2.4	3.3
FO	8.3		3.5	7.9	7.0
FA	5.7		1.2	4.2	3.6
MT	5.4	9.2	6.8	5.2	5.2
HM		1.2			
IL	5.4	5.4	6.6	5.4	5.0
AP	5.2	5.3	1.4	0.8	0.9
CC		0.8	0.4		
TOTAL	99.8	99.5	99.4	99.4	99.6
SALIC	67.3	66.7	52.9	61.3	63.6
FEMIC	32.6	32.8	46.6	38.2	36.0
DI	2.6	1.0	17.2	14.4	8.1
DIWO	1.3	0.5	9.0	7.5	4.2
DIEN	0.8	0.5	6.3	4.7	2.7
DIFS	0.5		1.9	2.3	1.3
HY		9.9	9.5	0.2	6.2
HYEN		9.9	7.2	0.1	4.2
HYFS			2.3	0.1	2.0
OL	14.0		4.7	12.1	10.6
OLFO	8.3		3.5	7.9	7.0
OLFA	5.7		1.2	4.2	3.6
D.I.	48.4	48.6	32.6	27.4	33.6
AL2O3/SIO2	0.35	0.34	0.29	0.30	0.37
FEO/FE2O3	2.25	0.69	1.73	2.32	2.26

*See Table 6 for sources of data.

Table 7. (Continued) Results of Chemical Analyses and Norm Calculations*

SAMPLE	WASH5	THOLE	ANKAR	ALOLB	HAWAI
SYMBOL	Z	1	2	3	4
SIO2	47.98	49.40	44.10	45.40	47.90
AL2O3	15.32	13.90	12.10	14.70	15.90
FE2O3	2.49	3.00	3.20	4.10	4.90
FEO	8.86	8.50	9.60	9.20	7.60
MGO	6.16	8.40	13.00	7.80	4.80
CAO	10.28	10.30	11.50	10.50	8.00
NA2O	3.56	2.20	1.90	3.00	4.20
K2O	1.08	0.40	0.70	1.00	1.50
TIO2	3.53	2.50	2.70	3.00	3.40
P2O5	0.22	0.30	0.30	0.40	0.70
MNO	0.12	0.20	0.20	0.20	0.20
H2O	0.62				
CO2					
TOTAL	100.22	99.10	99.30	99.30	99.10
			NORMS (CIPW)		
Q		1.9			
C					
OR	6.4	2.4	4.2	6.0	8.9
AB	25.9	18.8	11.6	20.5	34.9
AN	22.6	27.1	22.6	23.9	20.3
NE	2.3		2.5	2.7	0.5
WO	11.2	9.4	13.7	10.8	6.3
EN	6.8	21.1	9.5	6.9	4.2
FS	3.8	9.5	3.2	3.2	1.6
FO	6.0		16.2	8.8	5.5
FA	3.7		6.0	4.5	2.4
MT	3.6	4.4	4.7	6.0	7.2
HM					
IL	6.7	4.8	5.2	5.7	6.5
AP	0.5	0.7	0.7	1.0	1.7
CC					
TOTAL	99.4	100.0	100.0	100.0	100.0
SALIC	57.1	50.2	40.9	53.0	64.6
FEMIC	42.3	49.8	59.2	47.0	35.4
DI	21.8	18.1	26.4	21.0	12.2
DIWO	11.2	9.4	13.7	10.8	6.3
DIEN	6.8	6.0	9.5	6.9	4.2
DIFS	3.8	2.7	3.2	3.2	1.6
HY		21.8			
HYEN		15.1			
HYFS		6.7			
OL	9.7		22.2	13.3	7.9
OLFO	6.0		16.2	8.8	5.5
OLFA	3.7		6.0	4.5	2.4
D.I.	34.5	23.1	18.3	29.2	44.3
AL2O3/SIO2	0.32	0.28	0.27	0.32	0.33
FEO/FE2O3	3.56	2.83	3.00	2.24	1.55

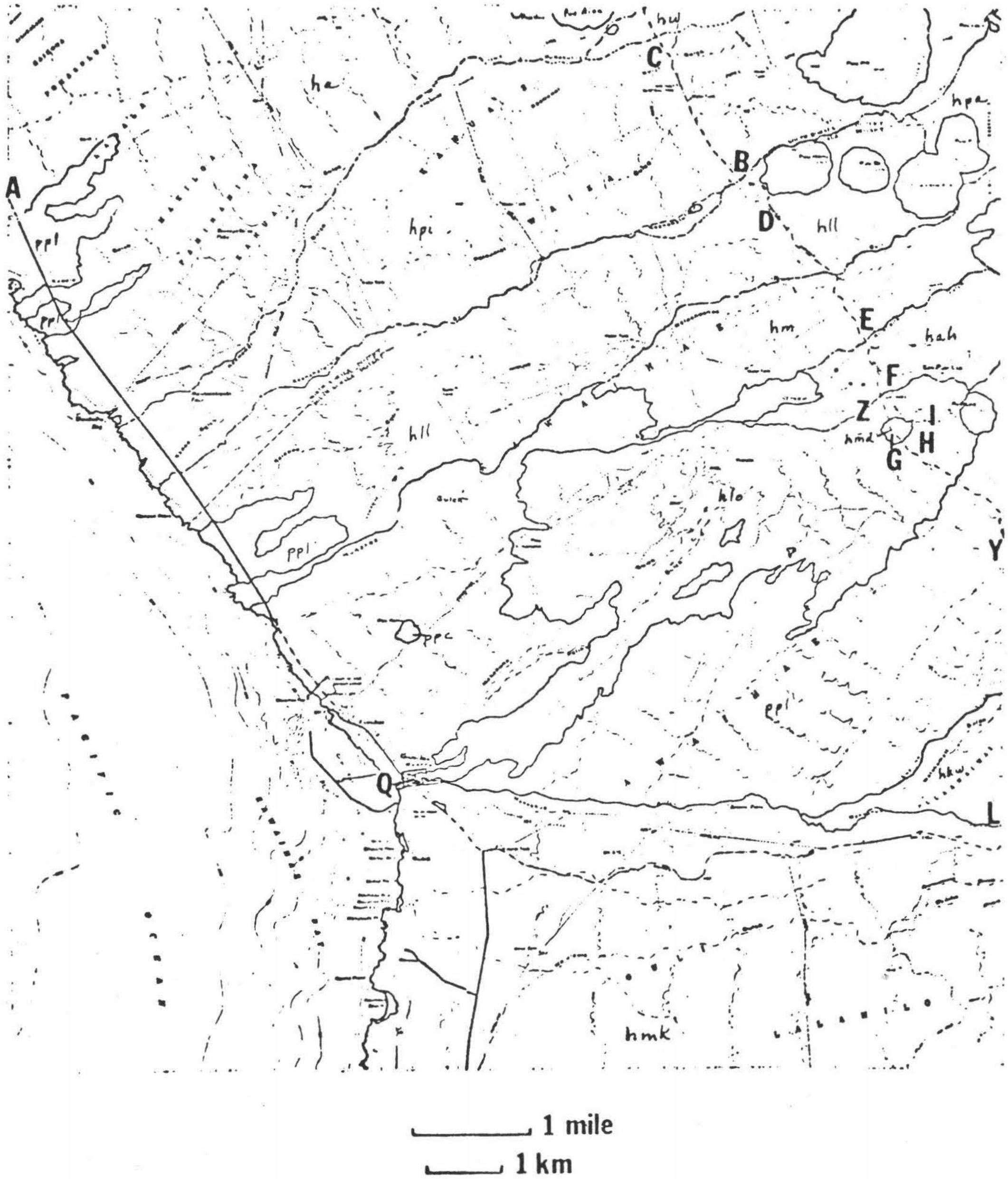
*See Table 6 for sources of data.

Table 7. (Continued) Results of Chemical Analyses and Norm Calculations*

SAMPLE	MUGEA	BENMO	NATRA
SYMBOL	5	6	7
SIO2	51.60	57.10	61.70
AL2O3	16.90	17.60	18.00
FE2O3	4.20	4.80	3.30
FEO	6.10	3.00	1.50
MGO	3.30	1.60	0.40
CAO	6.10	3.50	1.20
NA2O	5.40	5.90	7.40
K2O	2.10	2.80	4.20
TIO2	2.40	1.20	0.50
P2O5	1.10	0.70	0.20
MNO	0.20	0.20	0.20
H2O			
CO2			
TOTAL	99.40	98.40	98.60
		NORMS (CIPW)	
Q		4.2	0.2
C		0.2	
OR	12.5	16.8	25.2
AB	45.1	50.7	63.5
AN	15.8	13.0	3.5
NE	0.5		
WO	3.1		0.5
EN	1.9	4.0	1.0
FS	1.0		
FO	4.4		
FA	2.5		
MT	6.1	7.0	4.1
HM		0.1	0.5
IL	4.6	2.3	1.0
AP	2.6	1.7	0.5
CC			
TOTAL	100.1	100.0	100.0
SALIC	73.8	85.0	92.5
FEMIC	26.3	15.1	7.6
DI	6.0		0.9
DIWO	3.1		0.5
DIEN	1.9		0.4
DIFS	1.0		
HY		4.0	0.6
HYEN		4.0	0.6
HYFS			
OL	6.9		
OLFO	4.4		
OLFA	2.5		
D.I.	58.0	71.8	88.9
AL2O3/SIO2	0.33	0.31	0.29
FEO/FE2O3	1.45	0.62	0.45

*See Table 6 for sources of data.

PLATE VIII. Location map of chemically analyzed samples. Symbols and descriptions of locations are given in Table 6.


A
B
C
D
E
F
Z
I
H
G
Y
Q
L
hll
hm
hmk
1 mile
1 km

lavas. However, they are alkalic olivine basalts of the Pololu Formation based on Stearns' original Pololu Formation mapping in 1946 and the present mapping. Normative calculations were computed using the Graphic Normative Analysis Program (GNAP) by Roger W. Bowen of the U.S. Geological Survey (1971). Norms were calculated with this program for the previously published analyses as well as the six new analyses so that all analyses are comparable. There were no notable differences in the previously published norms and those recalculated using the GNAP program. In addition to the Kawaihae samples, the Hawaiian averages for the tholeiitic and alkalic suites from Macdonald (1968) are reported in Table 7 to serve as a basis of comparison for Kawaihae rocks in Figures 7-18.

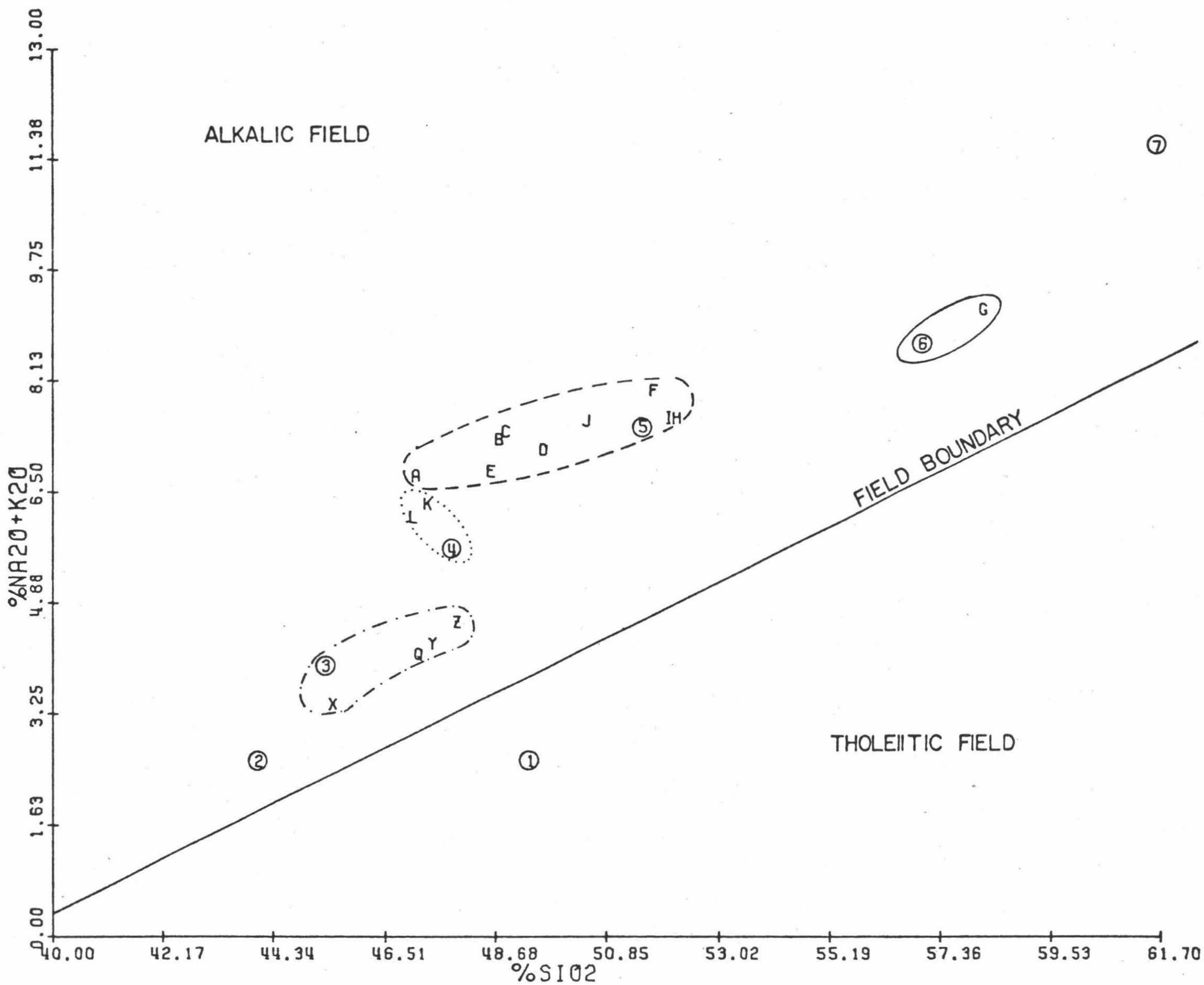
Petrologic Trends

Muir and Tilley (1961) suggest that hawaiite, mugearite and trachyte are derived from alkalic basalt parent magma at shallow depths. Macdonald (1968) demonstrates that it is possible to derive hawaiite from alkalic olivine basalt magma by crystal differentiation (1968, Table 9, p. 517). Similar calculations can be made for mugearite and trachyte. Chayes (1963) noted that oceanic basin lavas with compositions between mugearite and trachyte (benmoreite) are relatively rare and small in volume in comparison to the amount of trachyte. Therefore, crystal fractionation may not be the mechanism by which trachyte is derived from alkalic basalt, according to Chayes. However, mugearite and trachyte occur together and are of the same age (McDougall, 1964, Table 5, p. 122) on West Maui as well as on Kohala. Therefore, they are probably genetically related. The average Hawaiian fractionation trend from alkalic olivine basalts is from hawaiite to mugearite, benmoreite and trachyte (Macdonald and Katsura, 1964). The phases controlling fractionation and yielding these magmas from parental alkalic olivine basalts and basanites are probably olivine and clinopyroxene (Green and others, 1974, p. 42).

Figure 7 is an alkali:silica diagram showing the fractionation trend of Kawaihae lavas. All the lavas lie within the alkalic field. According to Macdonald (1968, p. 514), the Kawaihae fractionation corresponds to an alkalic trend found at low pressures (Fig. 7). The trend follows the olivine control line. Crystal differentiation appears to be the dominant process by which mugearite, benmoreite, and trachyte are derived from alkalic basalt magma. Volatile transfer and thermo-diffusion may also play a part (Macdonald and Katsura, 1962).

Although the Kawaihae lavas appear from Figure 7 to follow the Hawaiian fractionation trend exactly, the most alkalic lavas (i.e., the benmoreite) were not the last lavas

Figure 7. Alkali:silica diagram showing the range of Kawaihae lavas. Symbols are the same as those in Table 6. Solid line indicates benmoreite field; dashed line, mugearite field; dotted line, hawaiite field; dashed and dotted line, alkalic olivine basalt field. Field boundary is from Macdonald and Katsura (1964).

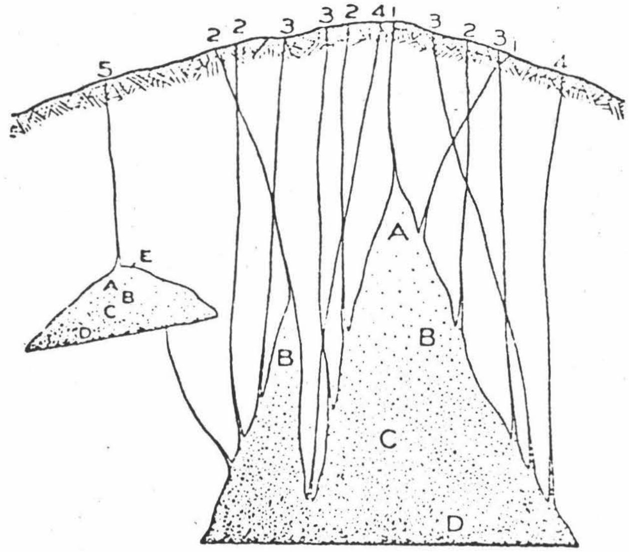

ALKALIC FIELD
THOLEIITIC FIELD
FIELD BOUNDARY
%NA2O+K2O
%SIO2
13.00
11.38
9.75
8.13
6.50
4.88
3.25
1.63
0.00
40.00
42.17
44.34
46.51
48.68
50.85
53.02
55.19
57.36
59.53
61.70
A
B
C
D
E
F
G
I
H
J
K
L
Q
X
Y
Z
①
②
③
④
⑤
⑥
⑦

to be erupted in time. The benmoreite dome of Puu Makela is stratigraphically older than at least the flow from Puu Loa and possibly others. The flow from Puu Aiea is shown in the correlation of map units to be younger in age than many of the units, yet in Figure 7 it plots very close to the hawaiite group. Because of these divergences from the normal fractionation trends, a scheme of eruptions similar to Figure 8 is strongly favored for the generation of hawaiite, mugearite and benromeite rock types. Magma is trapped in small shallow reservoirs where it differentiates and is later erupted.

A great amount of dunite nodules and olivine inclusions were noted at Puu Pili and Puu Makela. Lherzolite inclusions also were reported by Stearns and Macdonald (1946, p. 199). There are three possibilities for their origin: they are cumulates from the tholeiite phase of activity on Kohala Mountain; they are cumulates from the late alkaic (Hawi) phase of activity; or they originate from the mantle (M.O. Garcia, verbal communication, June, 1977). Based on Figure 8 and the fact that xenocrysts and inclusions observed in this section showed igneous textures rather than metamorphic, a crustal source is preferred for the origin of the inclusions.

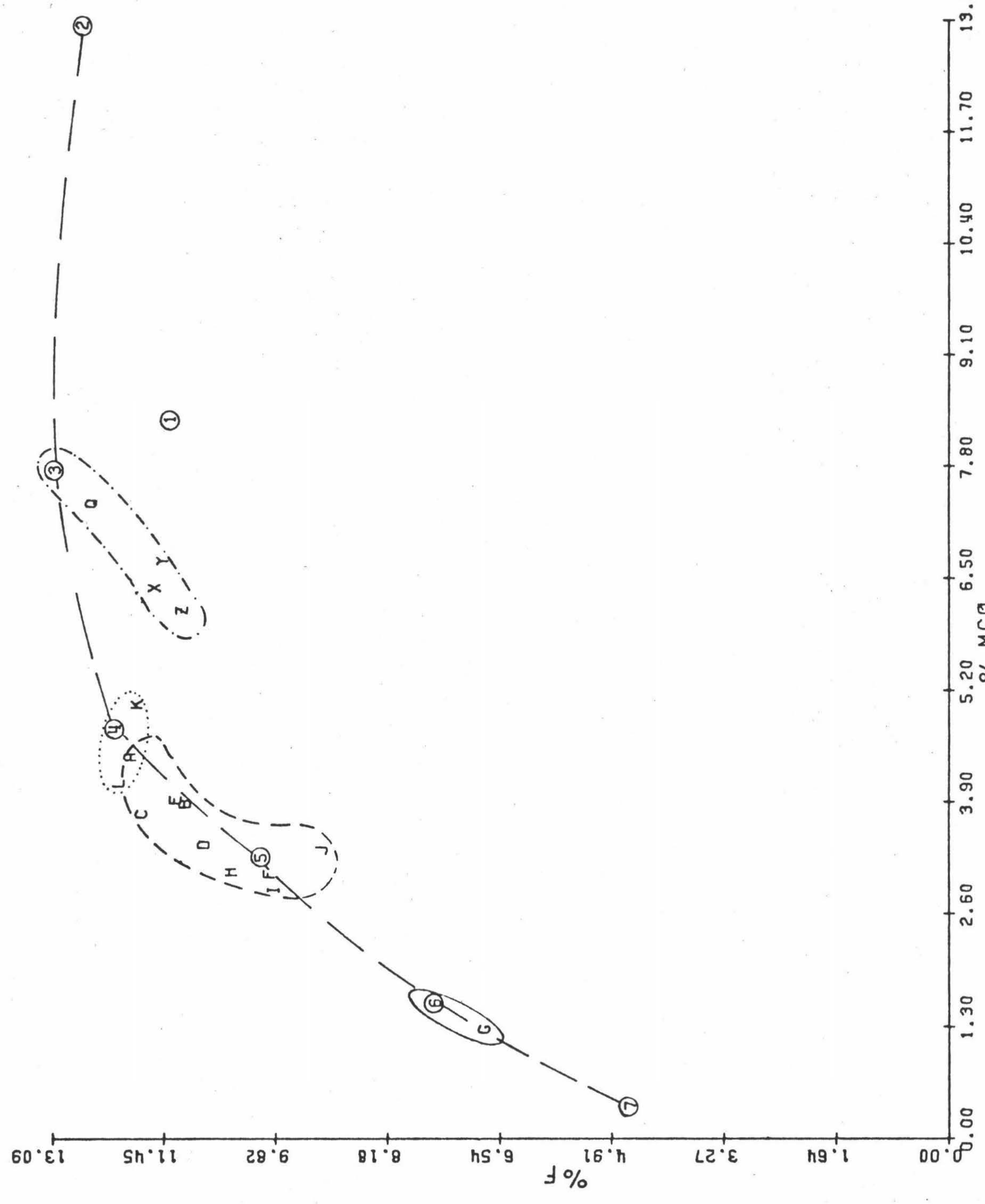
As noted from Figure 7, several of the rock samples from this study show a gradation between standard averages of the major Hawaiian rock types. Plot 'A' represents

Figure 8. Diagram showing the eruption of magmas of different composition from different levels in the same magma body. A, Hawaiite; B, basaltic hawaiite; C basalt; D, picritic basalt; E, trachyte. 1, Dike erupting hawaiite; 2, dike erupting basaltic hawaiite; 3, dike erupting basalt; 4, dike erupting picritic basalt; 5, dike erupting trachyte. The various types of lava may be erupted alternately, and may be interbedded in the volcano. (From Stearns and Macdonald, 1942.)


5
2 2
3
3 2 4 1
3
2
3 1
4
E
A B
C
D
A
B
B
C
D

the flow from Puu Aiea, which modally is a mugearite (oligoclase dominant over andesine). This sample, however, plots very close to the hawaiite field. 'A' is higher in Fe_2O_3 and MgO than in the other mugearites (Table 7). This is also shown in Figure 9, which shows total iron plotted against MgO. The hawaiite flow (L and K) from Puu Kawaiwai plots higher in alkalis and slightly lower in silica than the average hawaiite. Stearns and Macdonald (1946) suggested that Puu Kawaiwai might belong genetically to adjacent Mauna Kea, but topographically, the cone and flow belong to Kohala Mountain. The similarity of the rock in thin section to Kohala mugearite and the fact that it plots very close to the mugearites in Figure 7 suggest that chemically it is sufficiently similar to Kohala alkalic rocks to be genetically related to them. Sample J, which lies southeast of the map area, was described as a hawaiite on the basis of An/An+Ab (Macdonald and Katsura, 1964), but plots with the majority of the mugearites in Figure 7. Examination of the rock in thin section reveals that oligoclase is predominant over andesine and therefore, is a mugearite (Macdonald, verbal communication, May, 1977). Three of four of the alkali olivine basalts plotted in Figure 7 are higher in SiO_2 and slightly higher in alkali than the average Hawaiian alkali olivine basalt. Sample Z, a Pololu alkalic basalt, would be termed a hawaiite under a

Figure 9. Plot of F versus MgO. F is defined as FeO + 0.89981 x Fe_2O_3 + MnO. Symbols are the same as in Table 6. Rock type boundaries are the same as in Figure 7. Long dashes follow average Hawaiian trend.


% F
% MGO
0.00
1.64
3.27
4.91
6.54
8.18
9.82
11.45
13.09
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00
1
2
3
4
5
6
7
A
B
C
D
E
F
G
H
I
J
K
L
Q
X
Y
Z

classification (Upton and Wadsworth, 1972a) based on normative An/An+Ab, differentiation index, and Na_2O + K_2O. However, the plagioclase present is labradorite, not andesine.

These examples are mentioned for two reasons. The first is to call attention to classification of rock types. Classification should not be based on chemistry alone, but in combination with modal characteristics. The second is to point out the gradational character of the Hawi Formation lavas over a rather narrow range of composition.

MgO variation diagrams are presented in Figures 10 through 13. Except for CaO versus MgO, the slopes of the regression lines are negative. A negative slope for SiO_2 and K_2O is the expected trend if magma flowing from the source region is becoming more differentiated with time. In plotting CaO versus MgO, CaO is a good indicator of olivine versus clinopyroxene and feldspar crystallization. CaO increases with decreasing MgO during cyrstallization of olivine, and it decreases with decreasing MgO during the crystallization of clinopyroxene and feldspar. Removal of clinopyroxene is indicated by the overall trend and feldspar may dominate differentiation at the source region (Macdonald, 1968). Figure 11 represents the variation of the Or component of plagioclase; Figure 12, the variation of the Ab component of plagioclase; and Figure 13, the An

Figure 10. Plot of SiO_2 versus MgO. Symbols are the same as in Table 6. Rock type boundaries are the same as in Figure 7. Long dashes follow average Hawaiian trend.

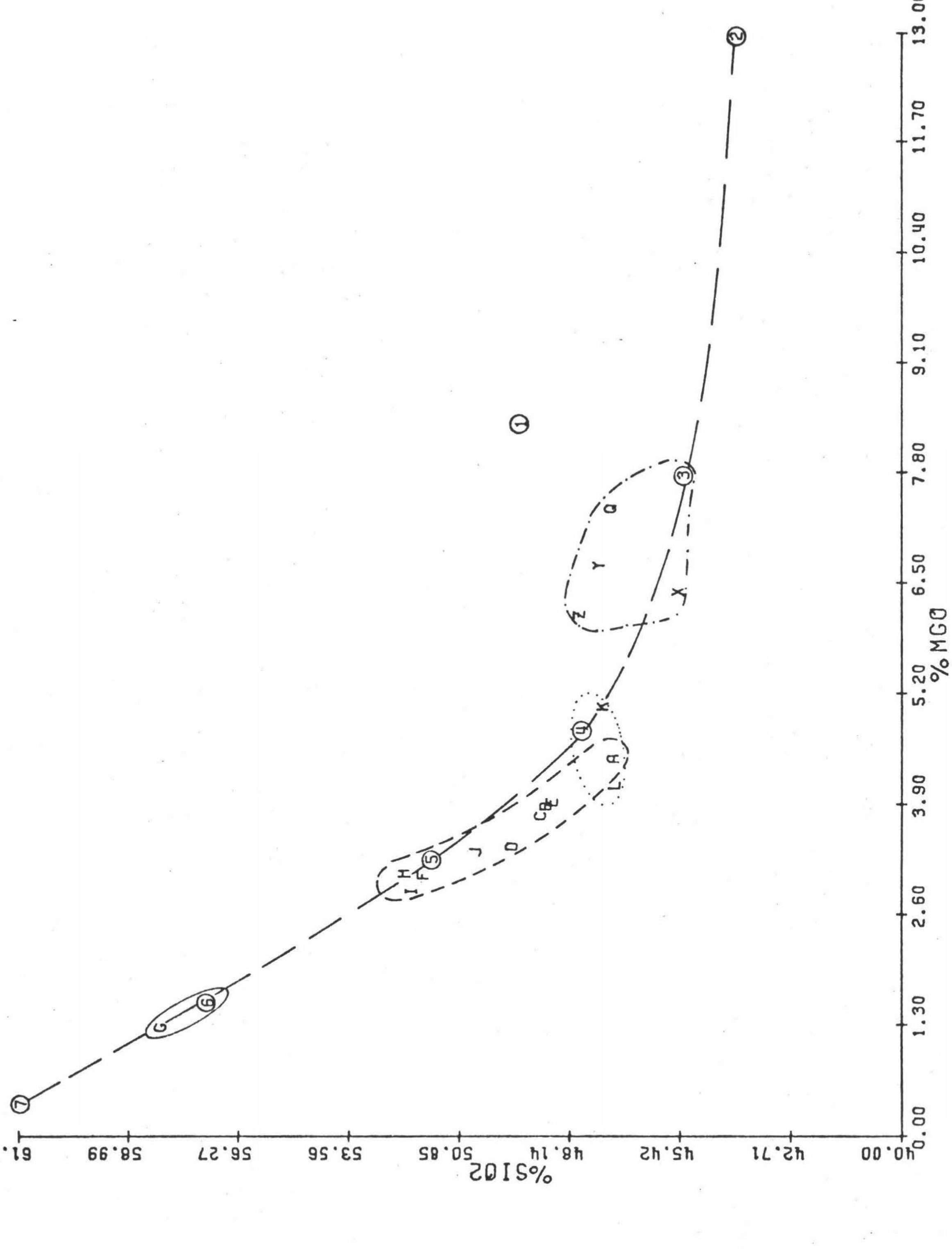

%MGO
%SIO2
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00
40.00
42.71
45.42
48.14
50.85
53.56
56.27
58.99
61.70

Figure 11. Plot of K_2O versus MgO. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.

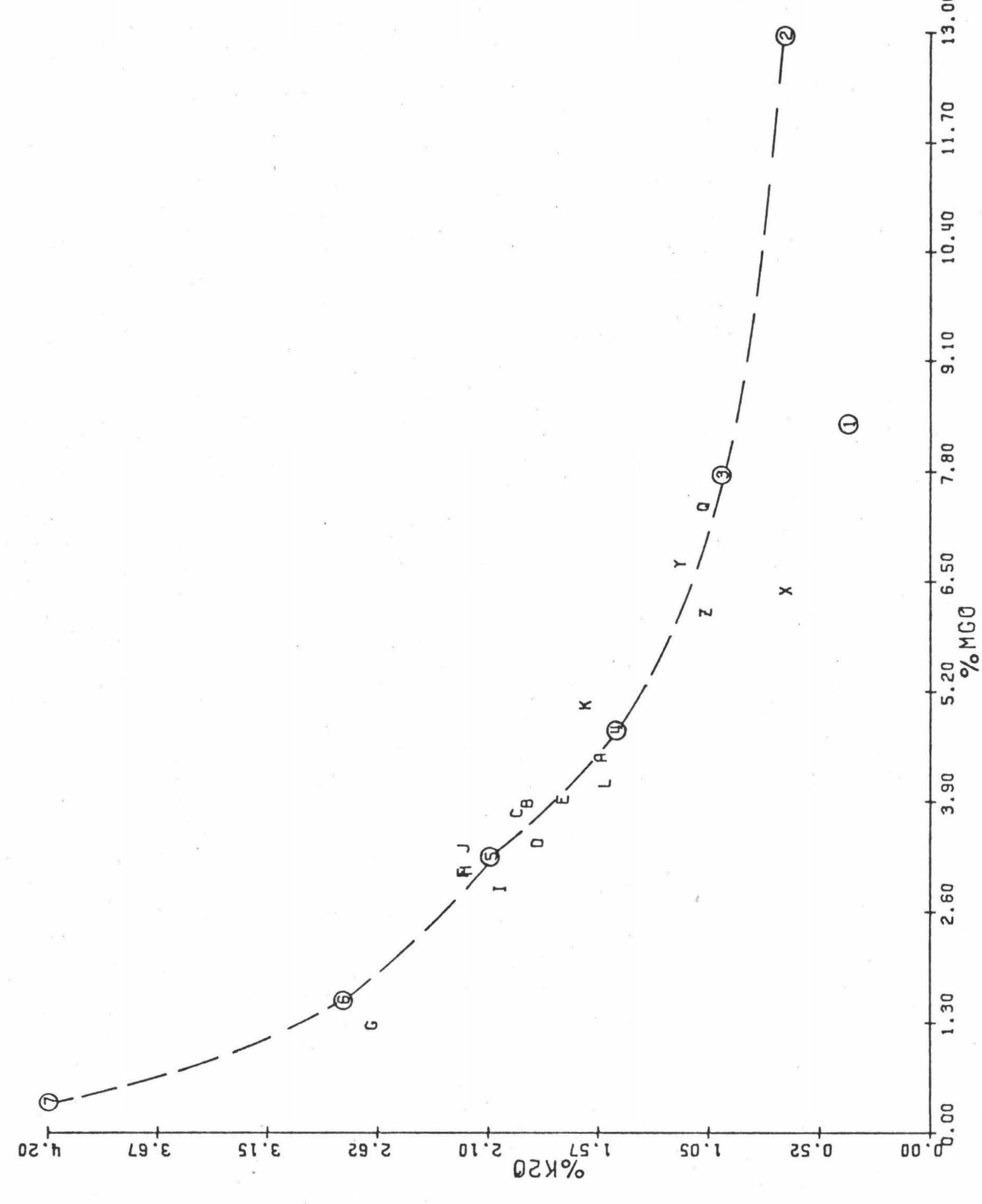

%K2O
4.20
3.67
3.15
2.62
2.10
1.57
1.05
0.52
0.00
%MGO
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00
1
2
3
4
5
6
7
G
I
J
D
C
B
E
L
A
K
Z
Y
X
Q

Figure 12. Plot of Na_2O versus MgO. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.

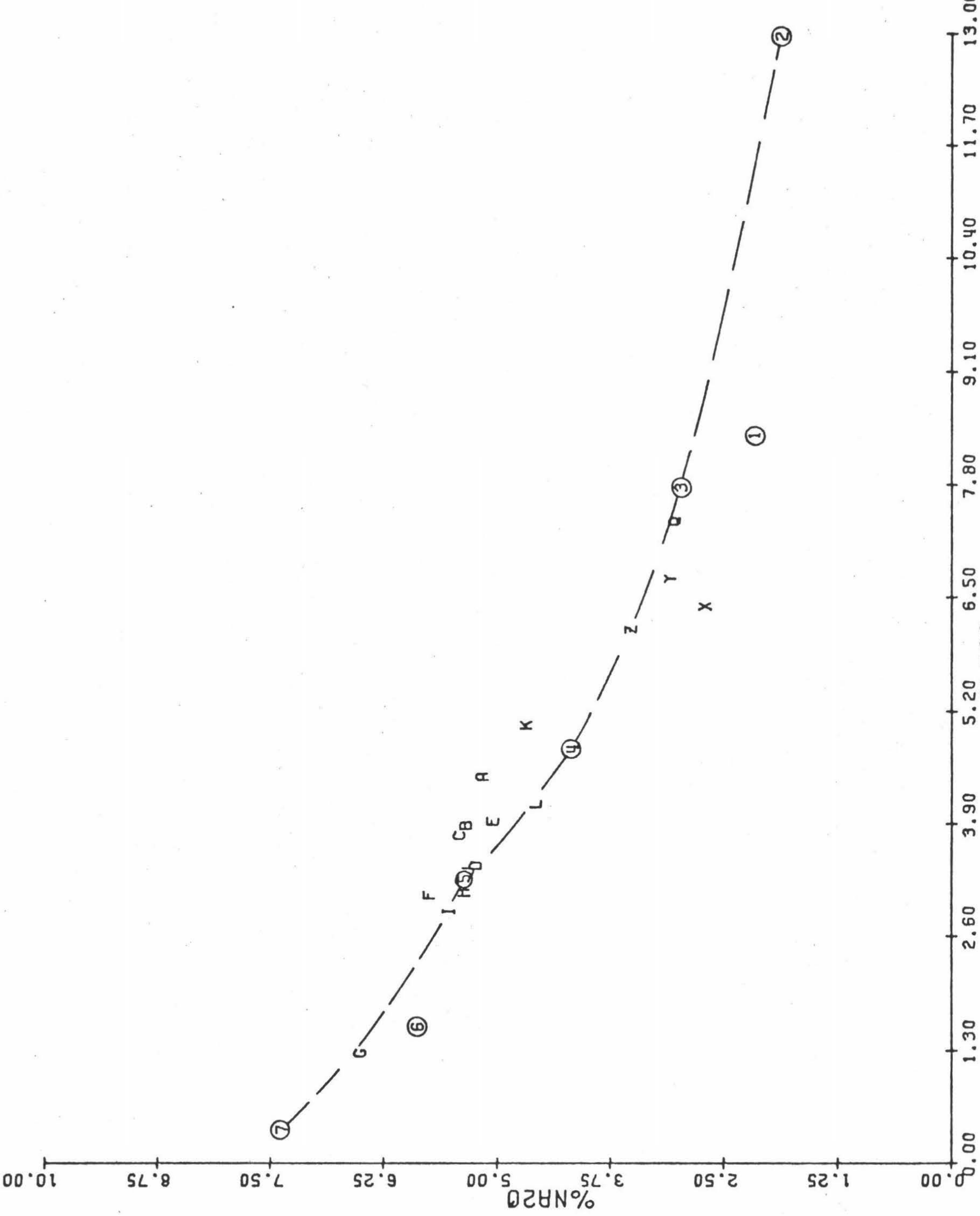
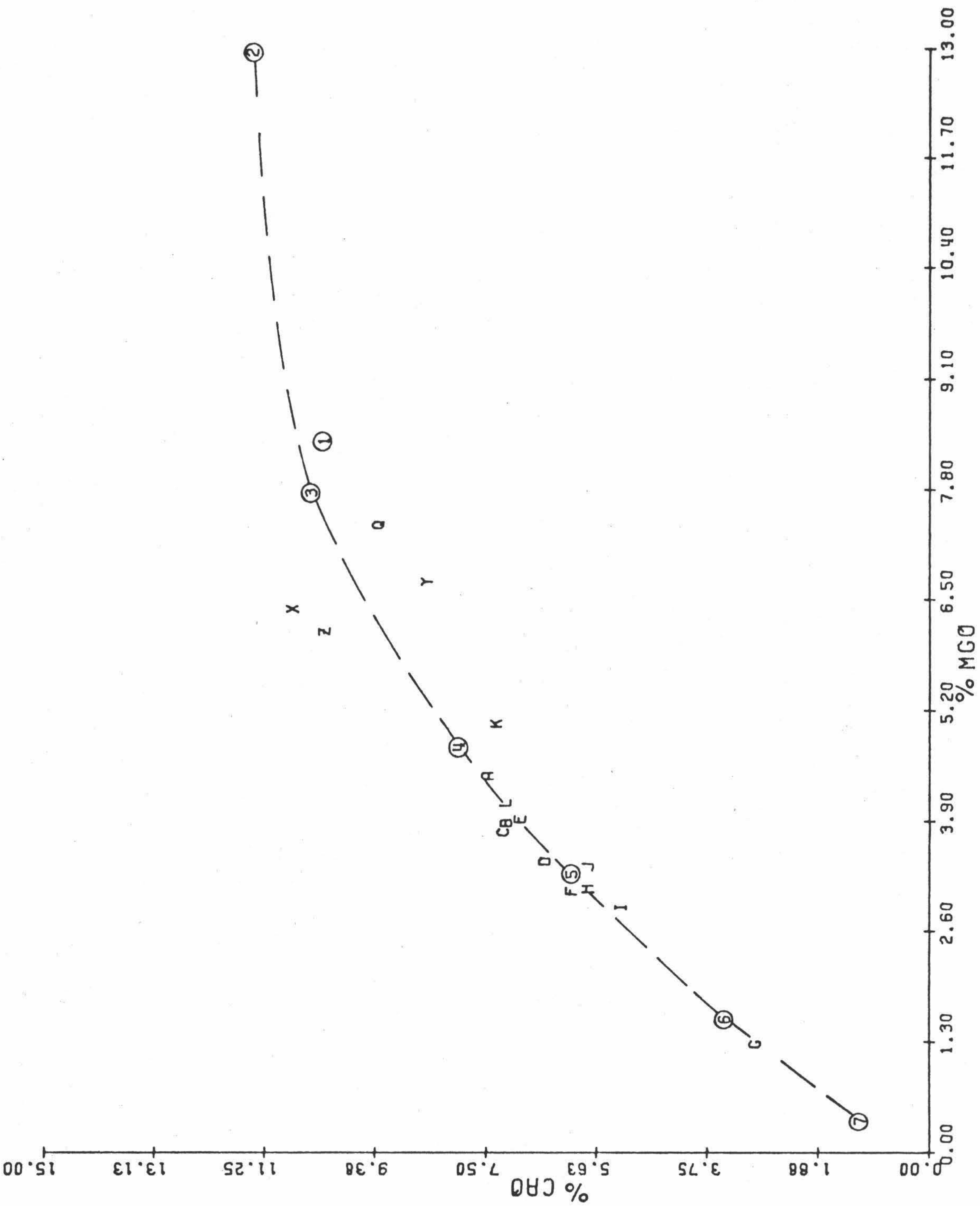

%MGO
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00
%NA2O
0.00
1.25
2.50
3.75
5.00
6.25
7.50
8.75
10.00

Figure 13. Plot of CaO versus MgO. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.


% MGO
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00
% CAO
0.00
1.88
3.75
5.63
7.50
9.38
11.25
13.13
15.00

component of plagioclase. A ternary plot of K_2O versus Na_2O versus CaO is shown in Figure 14. The trend is away from CaO and towards Na_2O and K_2O. Figure 15 is an AFM diagram of Kawaihae lavas. Plotting symbols are as shown in Table 6. Again, the lavas are shown to follow the normal Hawaiian trend.

Figure 16 shows that phosphorous increases from the alkalic olivine basalts to the hawaiites and mugearites, but then decreases in the benmoreite group. Maximum abundance of phosphorous is in the mugearite group at about 5% soda. The crystallization and separation in the mugearites of the large brown apatites mentioned earlier may be the reason for the decrease of phosphorous in the benmoreite (Macdonald, 1968, p. 504-505), if benmoreite results from fractionation of mugearite. Kawaihae mugearites and the Puu Kawaiwai hawaiite as well, show a much higher content of P_2O_5 than the average Hawaiian mugearite and hawaiite. The very common occurrence of large brown apatites in the Kawaihae rocks coincides with the greater amount of P_2O_5.

Figure 17 is a plot of TiO_2 versus Na_2O. Titanium increases with the alkalis from alkalic olivine basalt to hawaiite, but then decreases greatly in the mugearites and trachytes according to Macdonald (1968, p. 504). Kawaihae rocks follow this trend except that the Puu Kawaiwai

Figure 14. Ternary diagram of K_2O versus Na_2O versus CaO. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.

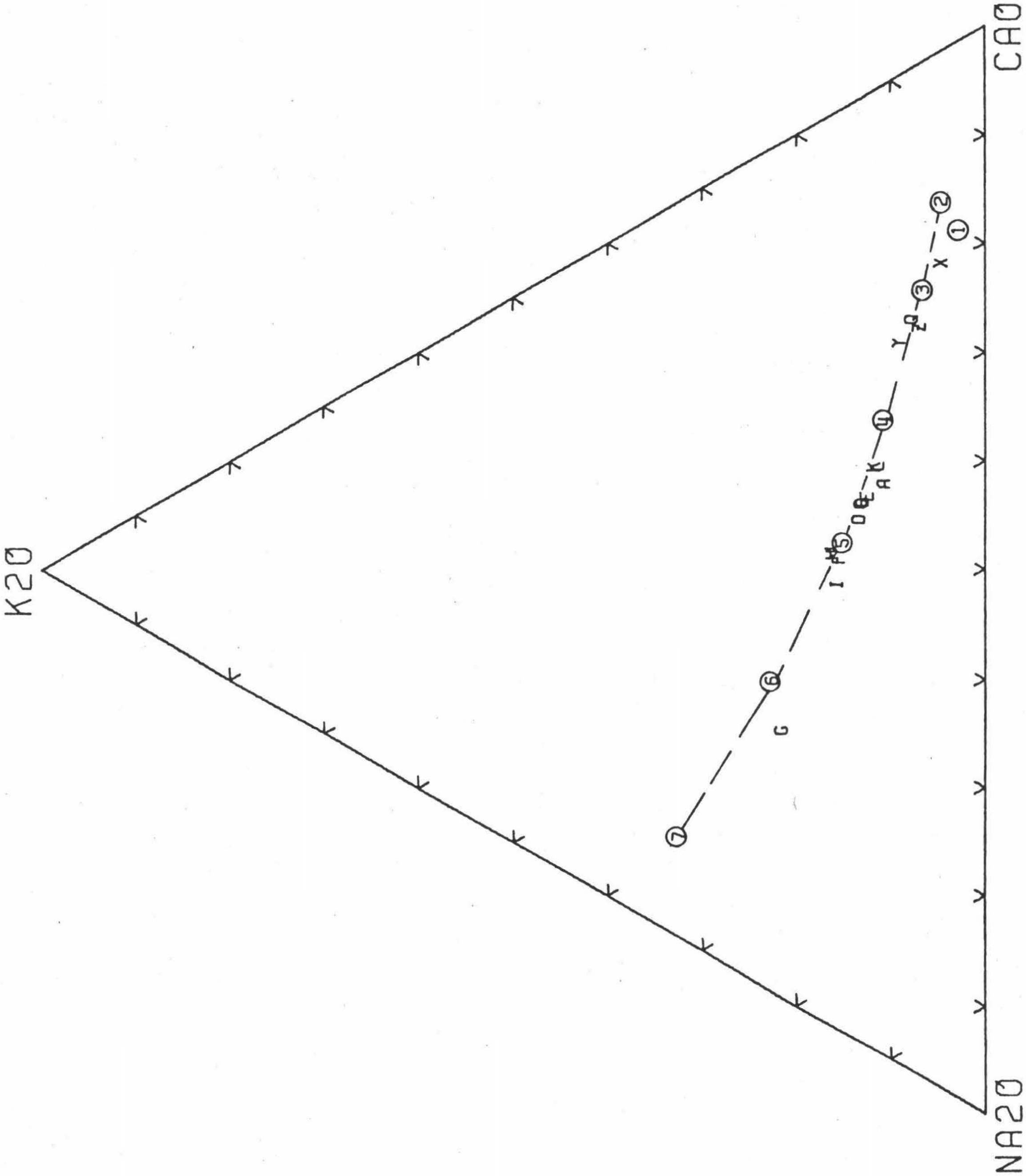

K2O
CAO
NA2O

Figure 15. FAM diagram. F is FeO + 0.89981 x Fe_2O_3 + MnO; A is Na_2O + K_2O; M is MgO. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.

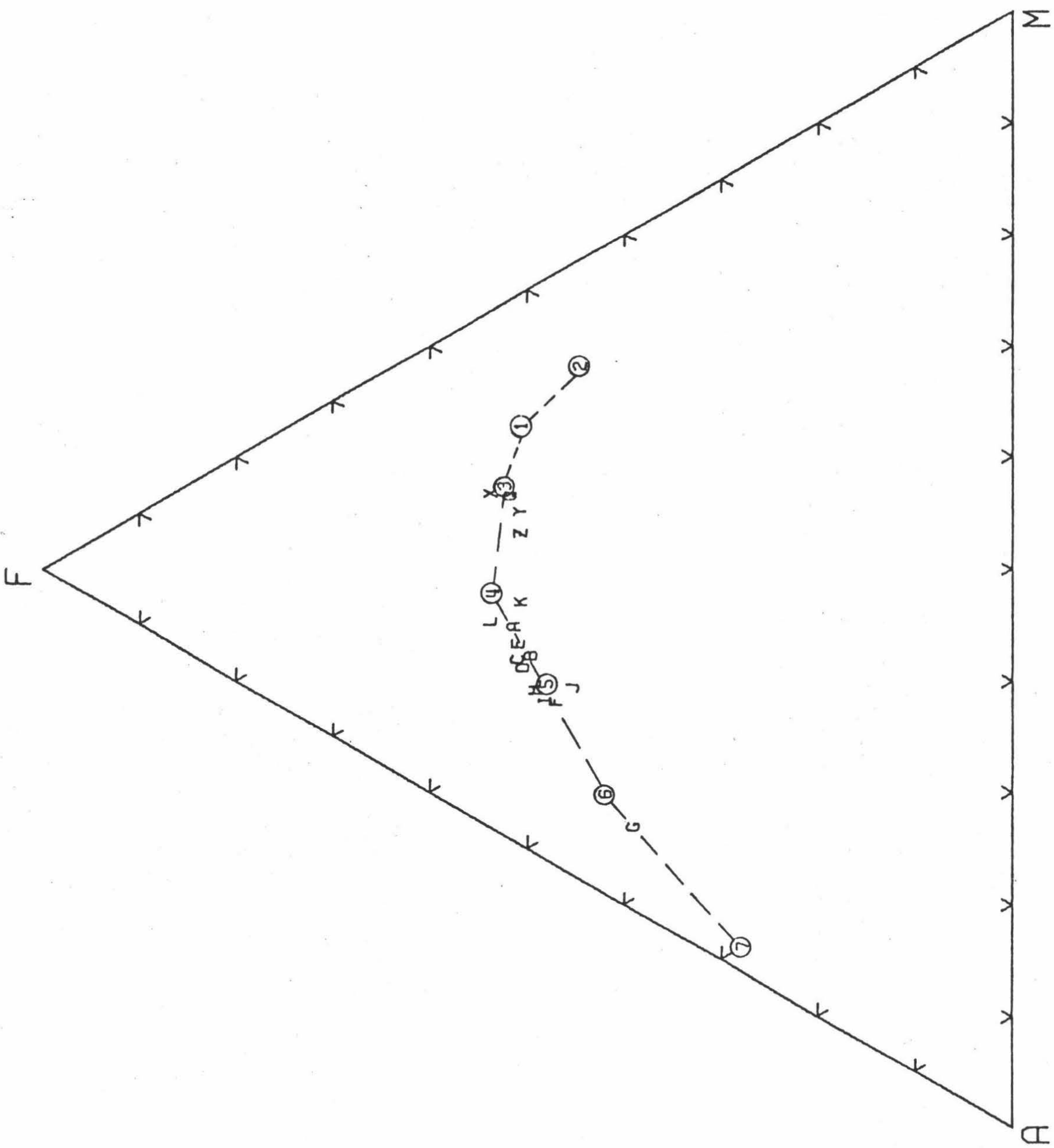

F
M
A
1
2
3
4
5
6
7
G
J
K
L
X
Y
Z

Figure 16. Plot of P_2O_5 versus Na_2O. Symbols are the same as in Table 6. Rock type boundaries are the same as in Figure 7 and long dashes follow average Hawaiian trend.

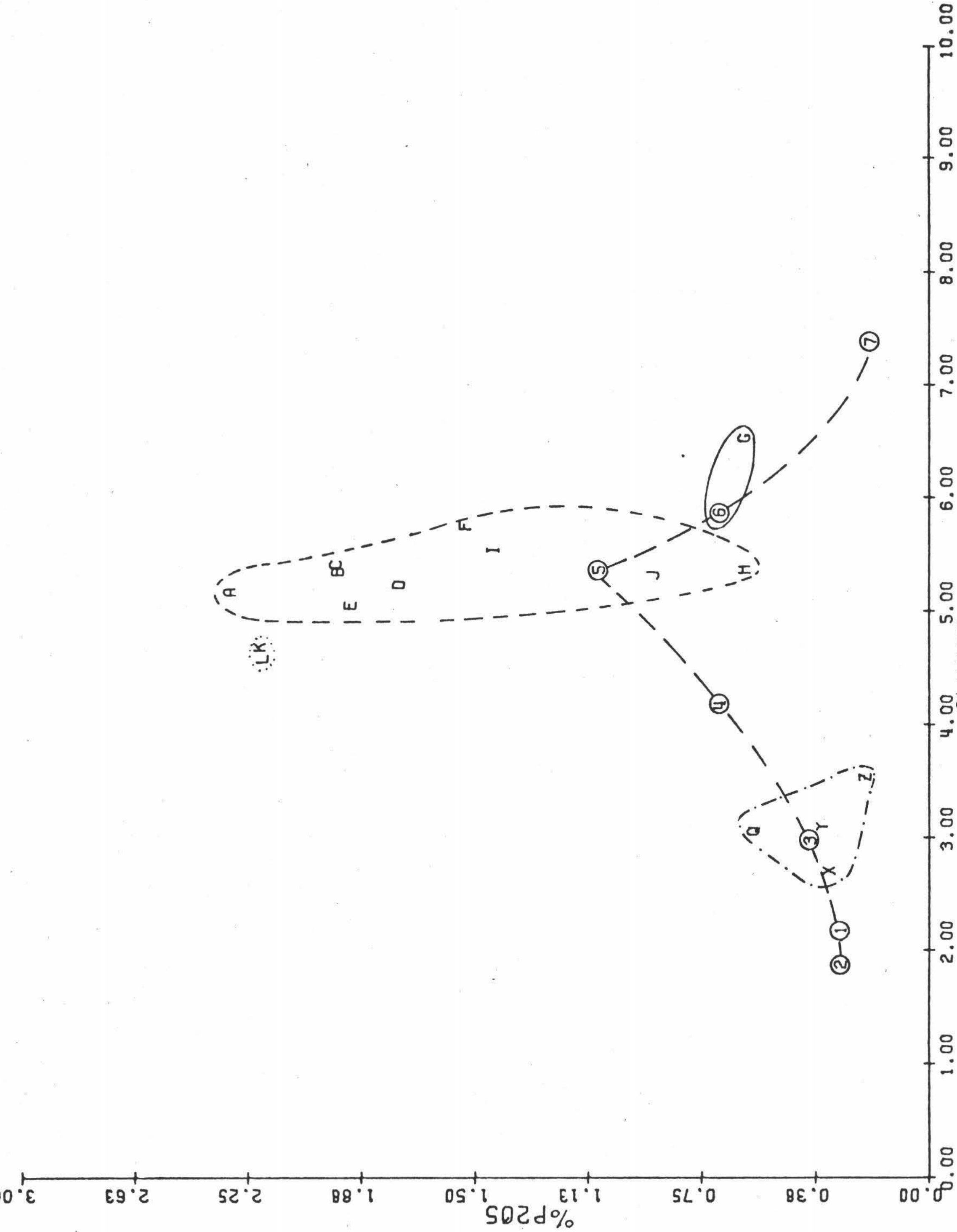
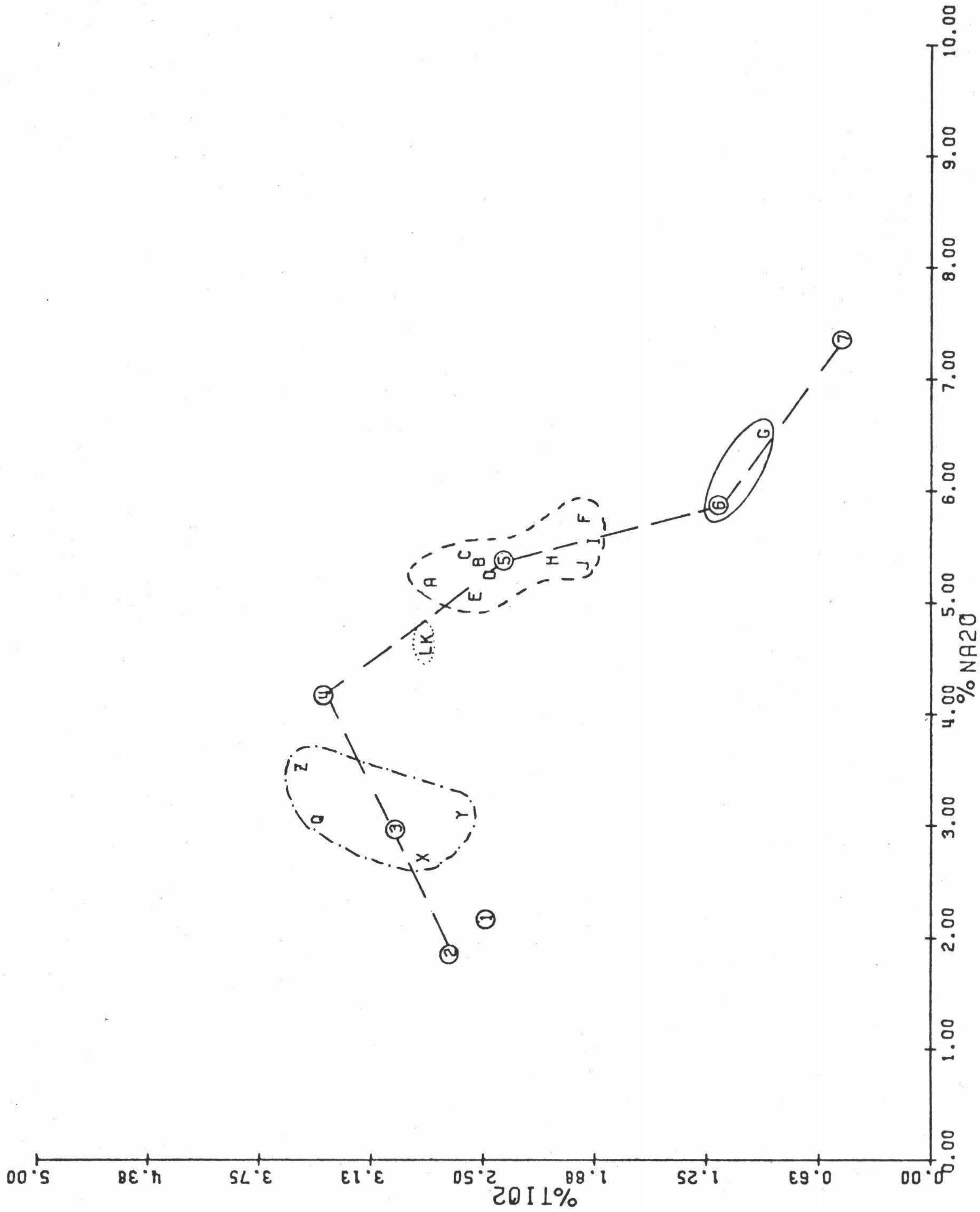

%P2O5
0.00
0.38
0.75
1.13
1.50
1.88
2.25
2.63
3.00
%NA2O
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
A
BC
D
E
F
G
H
I
J
LK
Q
X
Y
Z

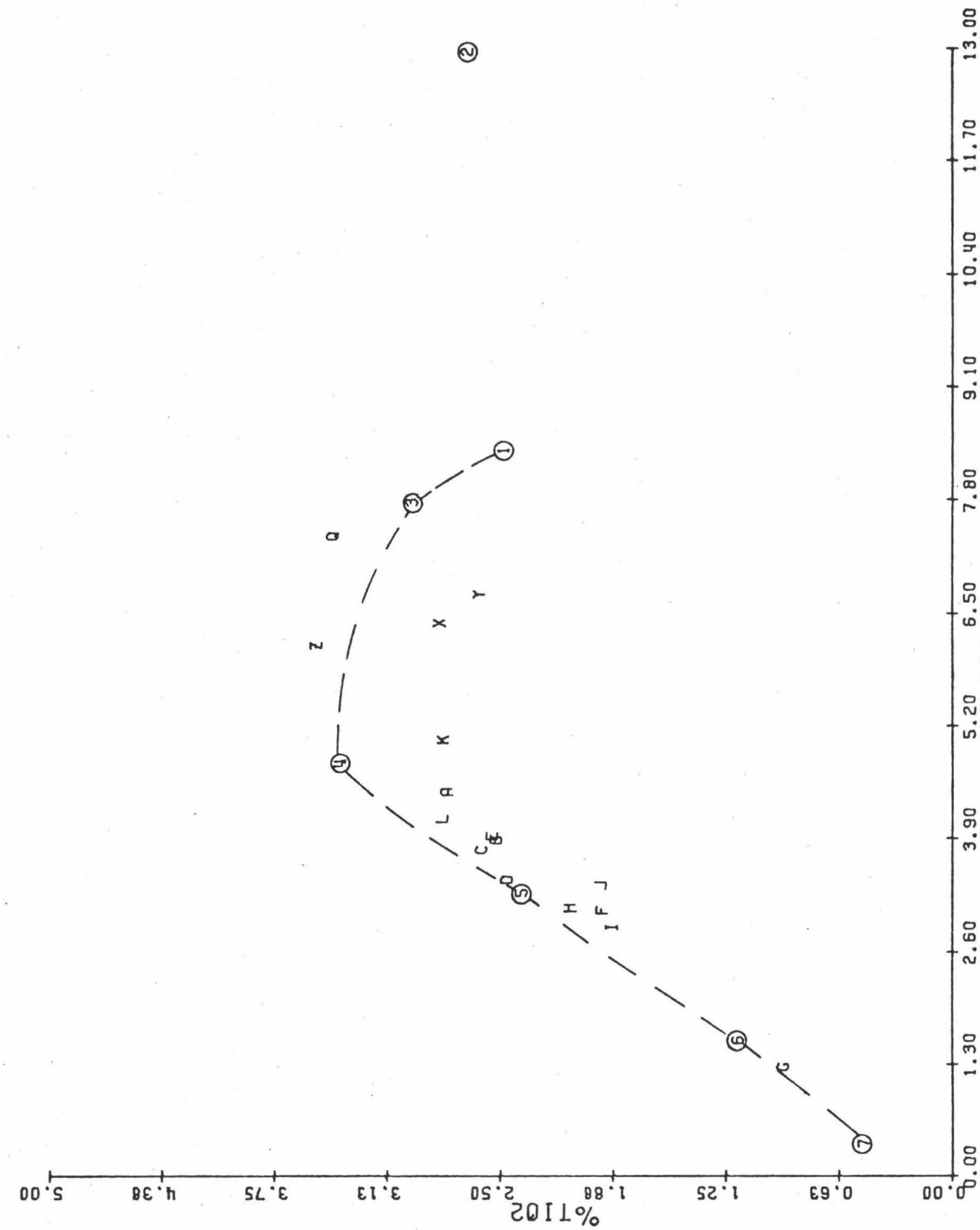
Figure 17. Plot of TiO_2 versus Na_2O. Symbols are the same as in Table 6. Long dashes follow average Hawaiian trend.


%NA2O
%TIO2
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
0.63
1.25
1.88
2.50
3.13
3.75
4.38
5.00
1
2
3
4
5
6
7
A
B
C
D
E
F
G
H
I
J
LK
Q
X
Y
Z

hawaiite (L, K) plots well below the average Hawaiian hawaiite. Figure 18, a plot of TiO_2 versus MgO, shows a similar trend. Except in the benmoreite (G), TiO_2 always is present in excess of 1.75%

Available chemical data are insufficient for further delineation of the differentiation history of Kohala and Mauna Kea lavas. Although stratigraphic control is established for adjacent Hawi flows, many nonadjacent flows may have been erupted simultaneously. In summary, the lavas in the Kawaihae Quadrangle of Kohala Mountain follow the normal Hawaiian fractionation trend of the alkalic suite.

Figure 18. Plot of TiO_2 versus MgO. Symbols are the same as in Table 6. Long dashes follow the average Hawaiian trend.


%TIO2
0.00
0.63
1.25
1.88
2.50
3.13
3.75
4.38
5.00
% MGO
0.00
1.30
2.60
3.90
5.20
6.50
7.80
9.10
10.40
11.70
13.00

SUMMARY AND CONCLUSIONS

The rocks of the Kawaihae Quadrangle are alkalic lavas of the Hawi Formation capping the Pololu Formation of the shield-building stage of Kohala Mountain. A soil horizon separates the two formations. The southern flank of Kohala Mountain was buried by lavas of Mauna Kea's Hamakua Formation. Hawi activity was previously thought to have ended before the final burial of Kohala's southern flank. One Hawi flow, however, the mugearite flow from Puu Loa, overlies a late Hamakua flow in the Kawaihae quarry. The youngness of the Puu Loa flow is demonstrated stratigraphically: in addition to the Hamakua flow, it overlies the Puu Ahia flow and diverges around the dome of Puu Makela. Potassium-argon age determinations of the Puu Loa flow are 0.077, 0.087, and 0.082 m.y., which are within the age range of 0.06 to 0.25 m.y. for Hawi lavas determined by McDougall (1972). Pahala Ash occurs over the entire map area with the exception of the young Puu Loa flow.

Puu Makela is a volcanic dome, as demonstrated by its massive character and steeply dipping concentric joints. Although it is the most differentiated member (benmoreite) of the alkalic suite in this area, the dome is not the youngest Hawi event.

The southwestern slope of Kohala has been changed very little by erosion. No marine deposits to suggest deep submergence were found on the slope of the volcano in this area, although they were reported in the Mahukona area by Stearns (1973). The presence on the coast of Puu Ulaula, a Pololu cinder cone, suggests that sea level since the cone was formed has not been higher than present sea level.

All rock types mapped are members of the alkalic suite. Within the mapped area, the Pololu and Hamakua Formations consist of alkalic olivine basalts. The Hawi Formation consists of mugearite, hawaiite and benmoreite; mugearite is the most abundant. Six new chemical analyses are reported for Kawaihae rocks. The analyses, in addition to previously reported analyses, show that Kawaihae lavas follow the average Hawaiian fractionation trend for alkalic rocks. Petrographic, microprobe, and chemical analyses show that Hawi lavas are intergradational; mugearite and hawaiite fields overlap. The Puu Kawaiwai hawaiite, topographically a part of Kohala Mountain, is considered to have a Kohala source rather than a Mauna Kea source, because of its similarity to Hawi mugearites.

Available chemical data are insufficient to delineate in detail the differentiation history of Kohala lavas. Furthermore, stratigraphic control for Hawi events has not been absolutely established beyond the stratigraphic relationships determined between adjacent map units. More whole rock chemical analyses and detailed microprobe analyses are recommended for further work to establish detailed chemical trends for Kohala lavas. More extensive potassium-argon age dating might provide better stratigraphic control for Hawi events, establish the hiatus between the Pololu and Hawi Formations, determine the age relationship between Kohala and Mauna Kea, and better define the range of ages for Hawi and Pololu lavas.

APPENDIX

SUMMARY OF PETROGRAPHY AND SAMPLE LOCATIONS

A-12-1 Mugearite; Puu Pili flow, Waimea-Kohala roadcut 0.5 km (0.3 mi) N of North Kohala/South Kohala District Boundary; intergranular, lack of strong flow texture, 8% vesicularity; average groundmass grain size 0.06 mm; oligoclase (2V-83°, Michel-Levy average 0°, An20-28) predominant over andesine (Michel-Levy 21°, An38), traces of alkali feldspar in vesicles; pale green groundmass clinopyroxene; euhedral to anhedral olivine altered to iddingsite; apatite, colorless needles and large brown crystal, 2%; opaques:hematite, magnetite and possible ilmenite; magnetite present as groundmass and microphenocryst up to 0.36 mm.

A-15-1 Mugearite; Puu Lapalapa flow, Waimea-Kohala roadcut 0.7 km (0.45 mi) SE of North Kohala/South Kohala Boundary; intergranular, very fine grained (0.02 mm), small vesicles, 4%; oligoclase (Michel-Levy average 0°, An20-28), 4% alkali feldspar; anhedral olivine altered to iddingsite; clinopyroxene, pale green needles; biotite, 0.08 to 0.18 mm in size, pleochroic from pale yellow to reddish brown, 2V(-) less than 10°; magnetite, gives dusty appearance, some microphenocrysts up to 0.28 mm; minor hematite; apatite, large brown pleochroic longitudinal and basal sections, 0.30 mm.

A-18-2 Mugearite; Puu Mala flow, Waimea-Kohala roadcut 0.3 km (0.1 mi) NW of Kilohana Gulch at 3564 foot elevation marker; intergranular, poor flow texture, 5% vesicularity, average groundmass grain size 0.03 mm; oligoclase (An20-28), minor andesine microphenocrysts (Michel-Levy 26°, An47), 5% alkali feldspar; olivine, euhedral to anhedral, some altered to iddingsite, most very fresh (2V-85 Fo78); clinopyroxene, short green needles; magnetite, dusty appearance, several microphenocrysts as large as 0.43 mm; minor biotite, many grains in or near vesicles or magnetite microphenocrysts; 2% large brown apatites, some pleochroic.

APPENDIX (continued)

A-20-3 Mugearite; Puu Ahia flow, Waimea-Kohala roadcut 1.3 km (0.8 mi) NW of the Puu Makela overlook; intergranular, 1% vesicularity average grain size 0.03; oligoclase, medium composition, minor alkali feldspar, ragged oligoclase phenocrysts with more sodic oligoclase rims, some albite rims; olivine altered to iddingsite; 4% aegirin-augite, needles or stubby prisms, pleochroic from pale yellow to brownish green, birefringence up to 0.039, 2V-60°; augite, pale green, 2V+55°, anhedral grains or needles; magnetite up to 0.34 mm in size; minor hematite and ilmenitite; 2% large brown apatites up to 0.8 mm long, pleochroic purple centers, basal sections and longitudinal sections showing (0001) basal cleavage.

A-33-1 Mugearite; Puu Loa flow, sample from flow ridge between Puu Loa and Puu Makela; intergranular, 7% vesicularity, average groundmass grain size 0.06 mm; medium oligoclase, 5% andesine (Michel-Levy 25°, An45), 3% alkali feldspar; olivine, euhedral to anhedral, 2V 90°, some alteration to iddingsite, several larger microphenocrysts up to 0.5 mm; clinopyroxene, pale green needles; magnetite, dusty appearance; traces of hematite and ilmenite; 3% apatite, colorless needles and large brown grains.

M^2-4

A-33-2 Same as above except vesicularity is 12%; 5% andesine (Michel-Levy combined albite and Carlsbad twins, 11° and 24°, 6° and 14°, 5° and 18°, 4° and 15°, An33-45); olivine is very fresh.

A-34-1 Benmoreite; very top of ridge of Puu Makela dome; mostly intergranular, but locally intersertal with 1% yellow to pale brown glass, double fabric; microphenocrysts of feldspar average 0.43 mm, very fibrous groundmass feldspar average 0.03 mm; major constituent, calcic to sodic oligoclase (2V 90°) and calcic albite (2V+75°), groundmass alkali feldspar; olivine, average 0.07 mm in size, total alteration to iddingsite, clinopyroxene, pale green needles; magnetite, subhedral to anhedral, ragged aggregates associated with olivine grains; 1% hematite, apatite, colorless needles and larger grains up to 0.2 mm.

M^2-3

APPENDIX (continued)

A-35-1 Mugearite; Puu Ahia flow, Waimea-Kohala roadcut 0.2 km (0.1 mi) SE of Kilohana Gulch; intergranular, locally intersertal, poor flow texture, 15% vesicularity, average groundmass grain size 0.08 mm; oligoclase predominates as microlites and microphenocrysts and rims ragged phenocrysts of medium andesine up to 0.7 mm in size; minor alkali feldspar, some anorthoclase (2V-45 to 50°, square to rectangular, lack of twinning, but very faint gridiron twinning, irregular extinction); olivine altered to iddingsite, microphenocrysts 0.7 mm maximum size; clinopyroxene, pale green needles and anhedral grains; magnetite, groundmass euhedral grains and microphenocrysts up to 0.5 mm; 2% hematite, traces of ilmenite; apatite, colorless needles and large brown grains; biotite, anhedral xenocrysts up to 0.8 mm long, heavily rimmed by opaques.

A-42-2 Mugearite; Puu Mala flow, 1.2 km (0.7 mi) NE of Waimea-Kohala road along NE bank of Waipahoehoe Gulch; intergranular, flow texture, 5% vesicularity, average groundmass feldspar 0.03 mm; medium oligoclase (2V-70°), 6% andesine (Michel-Levy 27°, 2V+55°, An49), minor alkali feldspar; olivine, subhedral to anhedral, alteration to iddingsite nearly complete; clinopyroxene, pale green needles and anhedral grains; magnetite, clumps of subhedral to anhedral grains, microphenocryst up to 0.32 mm; 2% hematite; apatite, colorless needles and large brown grains up to 0.4 mm long.

A-60-1 Benmoreite; deep roadcut on Waimea-Kohala road through dome of Puu Makela; intergranular, porphyritic, double fabric: microphenocrysts of feldspar average 0.23 mm, very fibrous groundmass feldspar average 0.03 mm; oligoclase (2V 90°) and albite (2V-50°), An20 to An5; 8% alkali feldspar includes anorthoclase (2V-50°, $\beta \wedge c = 20°$); two large rounded phenocrysts: one is andesine, 3.0 mm long, Michel-Levy 19°, An37; the other, calcic oligoclase with thin shell of albite, 6.0 mm long, 2V+50°; augite, greenish-yellow, 2V+50°; 2% brown hornblende (2V-70°, $\gamma \wedge c = 28°$), surrounds core of augite in some cases; magnetite, 0.45 mm maximum size; anhedral hematite; ilmenite; apatite, colorless needles; olivine, euhedral to subhedral grains altered to iddingsite, average 0.12 mm in size.

APPENDIX (continued)

B-1-1 Mugearite; Puu Lapalapa flow, Waimea-Kohala roadcut just N of Honokoa Gulch; intergranular, equigranular, very strong trachytic texture, extremely fine grain size, 0.01 mm; medium oligoclase, minor alkali feldspar which microprobe analyses indicate is anorthoclase; one very large ragged feldspar, 0.9 mm in length, xenocrystic, appreciable zoning, undulatory extinction, sodic andesine core (2V 90°, slightly negative), rim of oligoclase of same composition as the groundmass; olivine, anhedral, stained by iddingsite; clinopyroxene, green needles and anhedral grains; magnetite, clumps of euhedral and subhedral grains, a few larger microphenocrysts; apatite, large brown grains up to 0.2 mm, some colorless needles; biotite, trace amounts.

C-12-1 Hawaiite; Puu Kawaiwai flow, northern side of Makeahua Gulch at E boundary of map area, 0.2 km N of Waimea-Kawaihae road; intergranular, trachytic texture, grain size 0.07 mm; andesine (An37-41), oligoclase, 1% alkali feldspar; one ragged 1.0 mm grain of feldspar (2V+ about 80°), birefringence 0.010, undulatory extinction, shows reaction with groundmass; olivine, some altered to iddingsite, some very fresh; pale green needles of clinopyroxene; magnetite, euhedral to anhedral, some microphenocrysts up to 0.68 mm; 2% hematite and traces of ilmenite; apatite, large brown grains up to 0.12 mm, colorless needles.

F-1-1 Mugearite; Puu Ahia flow, Kawaihae-Hawi roadcut at W boundary of map area, 1.2 km (0.75 mi) NW of Kapole Gulch; intergranular, trachytic texture, 8% vesicularity, average grain size 0.08 mm; oligoclase dominant over andesine (Michel-Levy 17°, An45), 2% alkali feldspar; olivine, altered to iddingsite; augite (2V+55°), anhedral to subhedral, colorless to pale green-yellow, birefringence 0.015; magnetite, euhedral to anhedral, a few microphenocrysts as large as 0.43 mm; apatite, colorless needles and large brown grains, vesicles are partially filled with calcite.

APPENDIX (continued)

F-4-1 Mugearite; Puu Lapalapa flow, Kawaihae-Hawi roadcut 0.2 km (0.1 mi) NW of the North Kohala/ South Kohala District Boundary; intergranular, strong trachytic texture, 5% vesicularity, average groundmass grain size 0.07 mm; one plagioclase phenocryst 0.8 mm in size, undulatory extinction, 2V+75°, core probably sodic andesine, rim same composition as groundmass feldspar; augite, pale green, anhedral, 2V+50°, birefringence 0.022; biotite not present; remainder of description similar to B-1-1.

<u>POLOLU FORMATION</u>

A-27-1 Alkalic olivine basalt; 0.2 km NE of the Waimea-Kohala road in gulch that forms NE boundary of the Puu Loa flow; average groundmass grain size 0.03 mm, porphyritic intergranular, 4% vesicularity. Phenocrysts: sodic labradorite, An56, 2.2 mm maximum, very ragged and fractured; olivine F078-88 (2V90° to -85°), 2.0 mm maximum, euhedral to subhedral, rimmed by iddingsite and more olivine with higher birefringence, some embayed, some magnetite in iddingsite rims; augite, 2V+49°, subhedral, 2.0 mm maximum. Groundmass: sodic labradorite microlites, An50-52; olivine, very fresh; augite, pale green, 2V+55°; magnetite, euhedral to anhedral; alkali feldspar 2V-50°, interstitial; biotite; apatite, colorless needles.

A-100 Alkalic olivine basalt; 2.4 km (1.5 mi) NW of Puu Kawaiwai access road; porphyritic, intergranular texture, 4% vesicularity, average groundmass grain size 0.08 mm. Phenocrysts: sodic labradorite, many ragged, undulatory extinction, some show reversed zoning--core extinguishes at 31°, An56 (Michel-Levy), rim at 36° An64, maximum size 3.0 mm; olivine Fo78-88 (2V 90° to -85°), maximum size 1.5 mm, euhedral to subhedral, embayed, fractured, iddingsite alteration is within grains rather than as rims; augite, buff colored, 2V+50 to 55°, 1.3 mm maximum size. Groundmass: similar to mineralogy in A-37-1; sodic labradorite, An55; olivine, clinopyroxene, magnetite, biotite.

APPENDIX (continued)

B-4-2 Alkalic olivine basalt; sample from plunge pool in Keawewai Stream 0.3 km south of the Waimea-Kohala road; porphyritic intergranular texture, 40% vesicularity, average groundmass grain size 0.3 mm. Phenocrysts: sodic labradorite An55 (Michel-Levy combined, 17° and 19°), calcic labradorite An62 (Michel-Levy 34°), maximum size 6.0 mm; olivine, rimmed by iddingsite and completely altered, Fo88, 2V90° slightly negative, euhedral to subhedral; augite, buff colored, 2V+60°, 2.2 mm maximum size. Groundmass: sodic labradorite An53 (microlite method, 30°); olivine, fresh or iddingsite cores rimmed with fresh olivine, 2V 90° slightly negative; clinopyroxene, pale green-yellow; magnetite, euhedral to anhedral; interstitial alkali feldspar; apatite, colorless needles.

C-2-1 Alkalic olivine basalt; Makeahua Gulch 0.9 km SE of Kemole Falls, 0.6 km due N of Kawaihae-Waimea road. Porphyritic intergranular texture, locally intersertal, 30% vesicularity, 3% brown glass, average groundmass grain size 0.2 mm. Phenocrysts: labradorite, Michel-Levy, 30°, glomerocrysts, laths, maximum size 7.0 mm, ragged, zoned; olivine, subhedral, embayed, fractured, nearly completely altered to iddingsite, maximum size 2.0 mm; augite, 2V+55°, buff colored, subhedral, glomerocrysts, 2.0 maximum size, twinned. Groundmass: sodic labradorite An55, Michel-Levy combined 19° and 27°; olivine, euhedral to anhedral, groundmass generation olivine in shells around iddingsitized olivine microphenocrysts; augite, buff colored, anhedral, 2V+55°; opaques include magnetite, ilmenite, and hematite.

C-18-1 Alkalic olivine basalt; sampled in quarry soil horizon below Puu Loa flow at mouth of Makeahua Gulch. Porphyritic intergranular texture, locally subophitic, 17% vesicularity, average groundmass grain size 0.1 mm. Phenocrysts: calcic labradorite An66, ragged laths and glomerocrysts, maximum length 3.0 mm; olivine, Fo88, 2V 90°, subhedral, very minor alteration to iddingsite along fractures and grain boundaries; augite, pale yellow to pale brown, 2V+50 to 55°, twinned grains, maximum size 0.34 mm. Groundmass: sodic labradorite, An58, Michel-Levy combined 13° and 31°; olivine, fresh,

APPENDIX (continued)

anhedral; augite, 2V+50°, pale brown; magnetite; ilmenite, interstitial alkali feldspar; apatite, colorless needles.

HAMAKUA FORMATION

C-5-1 Alkalic olivine basalt; lip of Kemole Falls, Makeahua Gulch; porphyritic, intergranular texture, average groundmass grain size 0.1 mm. Phenocrysts: calcic labradorite An62, Michel-Levy 35°, 2V+80°, normal zoning, maximum length 6.0 mm; olivine Fo78, 2V 86°, euhedral to subhedral, embayed, fractured, iddingsite rims, maximum size 2.0 mm; augite, buff, greenish-yellow in color, 2V+55° to 60°, subhedral, maximum size 3.0 mm; biotite microphenocrysts, anhedral, maximum size 0.3 mm. Groundmass: sodic labradorite An55, microlites--28° extinction; olivine, subhedral to anhedral, some alteration to iddingsite; magnetite, euhedral to anhedral, dusty appearance, apatite, colorless needles.

C-11-1 Alkalic olivine basalt; Kawaihae quarry; porphyritic intergranular texture, locally intersertal, 10% vesicularity, average groundmass grain size 0.02 mm. Phenocrysts: calcic labradorite An68, Michel-Levy combined 19° and 38°, normal zoning, 2V+75°, maximum length 4.0 mm; olivine, Fo78, 2V 86°, euhedral to subhedral, some embayed, iddingsite alteration along fractures and grain boundaries, maximum size 2.0 mm; augite, 2V+55° to 60°, twinned grains, pale greenish yellow to buff in color, euhedral to subhedral, maximum size 3.0 mm. Groundmass: sodic labradorite, An54, Michel-Levy 30°; olivine, subhedral to anhedral; clinopyroxene, pale green, euhedral to anhedral; magnetite, euhedral to subhedral, dusty appearance; apatite, colorless elongate grains; glass, trace amounts, dark brown.

C-14-1a Alkalic olivine basalt; Kawaihae quarry below Puu Loa flow; porphyritic intergranular texture, average groundmass grain size 0.05 mm. Phenocrysts: calcic labradorite An67, Michel-Levy combined, 19° and 36°, 2V+86°, normal zoning, maximum length 3.0 mm; olivine, Fo88, 2V 90°, slightly

APPENDIX (continued)

negative, cores of olivine rimmed by iddingsite, then by more olivine of higher birefringence, maximum size 1.0 mm; augite, 2V+50° to 55°, Z Λ c 51°, R > V, euhedral to subhedral, pale greenish-yellow to pinkish, maximum size 2.0 mm. Groundmass: sodic labradorite An55, 28° microlite extinction; olivine, Fo78, 2V 85°, anhedral; clinopyroxene, pale green to buff colored, 2V+45°, some probably smaller, R > V, anhedral grains and needles; magnetite, anhedral to subhedral, dusty appearance; ilmenite; hematite, apatite, colorless needles.

C-14-1b Similar to C-14-1a except olivine phenocrysts and microphenocrysts show no alteration to iddingsite.

D-1-1 Alkalic olivine basalt, Kawaihae-Kona roadcut 0.2 km (0.1 mi) N of southern map boundary; porphyritic intergranular texture, 9% vesicularity, average groundmass grain size 0.03 mm. Phenocrysts: calcic labradorite, An67, Michel-Levy 38°, 2V+85°, subhedral, ragged laths, some glomerocrysts, maximum length 3.0 mm, normal zoning; olivine, Fo78 2V-85°, euhedral to subhedral, maximum size 1.0 mm; augite, 2V+50°, greenish-yellow to buff in color, euhedral to subhedral, maximum size 1.0 mm. Groundmass: sodic labradorite An54, microlites 28° extinction; olivine Fo78, 2V-85°, subhedral to anhedral; clinopyroxene, pale green, 2V+45° to 50°, subhedral to anhedral; magnetite, subhedral to anhedral; apatite, colorless needles.

D-3-3 Alkalic olivine basalt, Kawaihae-Kona roadcut 0.6 km (0.35 mi) north of southern map boundary. Similar to D-1-1.

D-7-1 Alkalic olivine basalt, 0.2 km (0.1 mi) south of the intersection of the Kawaihae-Kona and Kawaihae-Waimea roads; porphyritic intergranular, 8% vesicularity, average groundmass grain size 0.05 mm. Phenocrysts: medium labradorite An60, Michel-Levy 33°, 2V+80°, euhedral to subhedral, "moth-eaten" laths, normal zoning, maximum length 2.0 mm; olivine Fo88, 2V 90°, slightly negative, subhedral, embayed, iddingsite alteration rims, rimmed by fresh olivine, some iddingsite alteration irregular, along fractures, maximum size 2.0 mm; Groundmass: sodic labradorite An56, microlite extinction 31°; olivine; clinopyroxene, pale green, anhedral; magnetite, dusty appearance; hematite, colorless grains.

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Plate I. Geologic map of the Kawaihae Quadrangle, Kohala Mountain, Island of Hawaii.

PLATE I. GEOLOGIC MAP OF THE KAWAIHAE QUADRANGLE, KOHALA MOUNTAIN, ISLAND OF HAWAII

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Geology mapped by Marion J. Malinowski, 1975, 1976

Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography from aerial photographs by multiplex methods
Aerial photographs taken 1954. Field check 1956
Hydrography compiled from USC&GS charts 4140 (1953) and 4167 (1952)
Polyconic projection. Old Hawaiian datum
10,000-foot grid based on Hawaiian coordinate system, zone 1
1000-meter Universal Transverse Mercator grid ticks, zone 5, shown in blue

DESCRIPTION OF MAP UNITS

SEDIMENTARY ROCKS (Holocene)

bs Beach sand - Fine grained sand along the western coast derived from offshore coralline material.

cf Coralline fill - Man-made deposits for harbor fill and Kawaihae Quarry access roads.

IGNEOUS ROCKS

MAUNA KEA

HAMAKUA FORMATION (Holocene and Pleistocene)

hmk Alkalic olivine basalt - buries the southern flank of Kohala Mountain; units vary locally from feldspar-phyric to massive lava with few olivine and augite phenocrysts to ankaramite with abundant olivine and augite phenocrysts; is overlain in the Kawaihae Quarry by the flow from Puu Loa; maximum thickness is 14 meters.

KOHALA MOUNTAIN

HAWI FORMATION (Holocene and Pleistocene)

hcc Cinder cones formed at vents by explosive eruption of Hawi lavas; cones composed largely of unconsolidated scoria from 1 to 2.5 cm in diameter, finer lapilli and ash, and larger fragments of scoria up to 30 cm in diameter; very little spatter; large dunite xenoliths up to 15 cm diameter found at Puu Pili; cones are little eroded.

hlo Lava flow from Puu Loa - Mugearite; block lava, dark bluish grey to light grey, vesicular near Puu Loa, has platy cleavage near terminal flow margins, not covered by Pahala Ash.

ha Lava flow from Puu Aiea - Mugearite; dark grey, fine grained, massive a'a flows transitional to block lava, covered by Pahala Ash.

hkw Lava flow from Puu Kawaiwai - Hawaiite; fine grained, medium grey, occasional feldspar phenocrysts, sparkly sheen, massive a'a flows transitional to block lava.

hpi Lava flow from Puu Pili - Mugearite; medium to light grey, sparkly sheen, occasional olivine and feldspar phenocrysts, massive a'a flows transitional to block lava, covered by Pahala Ash.

hm Lava flow from Puu Mala - Mugearite; dark bluish grey, sparkly sheen, occasional olivine phenocrysts, varies from vesicular to massive, a'a flows trending towards block lava, covered by Pahala Ash.

hw Lava flow from Puu Waiakanonula - Mugearite; medium grey, massive, surrounds small cone of Kaipuolelo.

hll Lava flow from Puu Lapalapa - Mugearite; extremely fine grained, dark grey, xenocrysts of olivine and dunite inclusions from 3 mm to 8 cm in diameter, occasional phenocrysts of feldspar, platy cleavage especially prominent at terminal margins of flows, massive a'a flows transitional to block lava, covered by Pahala Ash.

hpa Lava flow from Puu Pala - Mugearite; medium grey, occasional olivine phenocrysts, massive a'a flows trending toward block lava, covered by Pahala Ash.

hah Lava flow from Puu Ahia - Mugearite; light grey, contains numerous feldspar phenocrysts up to 4 mm in length, prominent platy cleavage seen in flows along Kamuela-Hawi road, varies form very vesicular to very massive a'a flows trending toward block lava, covered by Pahala Ash.

hmd Dome of Puu Makela - Benmoreite; coarse grained, massive lava approximately 60 meters thick, numerous feldspar phenocrysts up to 8 mm long and dunite inclusions up to 6 cm in length, covered by Pahala Ash.

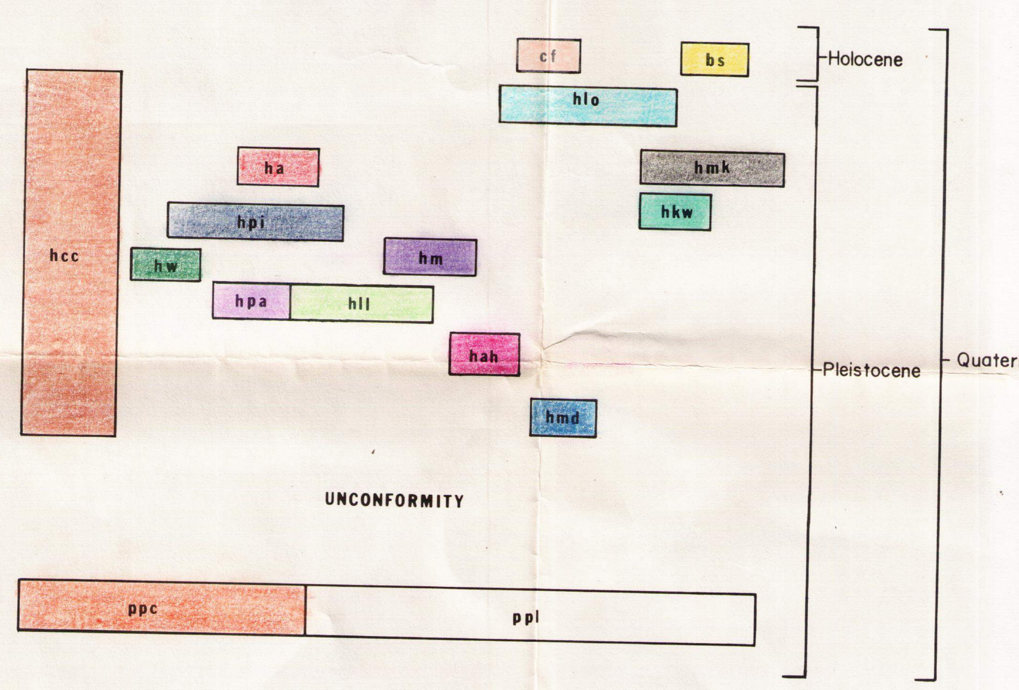
EROSIONAL UNCONFORMITY

POLOLU FORMATION (Upper Pleistocene)

ppc Cinder cones formed at vents by explosive eruption of Pololu lavas, cones are gullied by erosion and covered with a thick red lateritic soil.

ppl Alkalic olivine basalt lava flows; generally vesicular, contain abundant feldspar phenocrysts, augite phenocrysts are abundant in some flows; both a'a and pahoehoe type flows are present, with thin intercalated ash units; flows covered by a red soil approximately 30 cm thick which separates it from the overlying Hawi Formation.

CORRELATION OF MAP UNITS



CONTACTS

Definite

Approximate

Inferred

Hachures point towards younger unit within the Hawi Formation

Quarry boundary