STRATIGRAPHY OF KILAUEA VOLCANO

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ABSTRACT

This paper reviews and revises the lithostratigraphic nomenclature of Kilauea Volcano. The major stratigraphic units of the volcano are redefined as the Hilina Basalt (oldest), Pahala Ash, and Puna Basalt (youngest) in accordance with the stratigraphic code. Four pyroclastic units within the Hilina Basalt can be used as stratigraphic markers; these are formally proposed and described here and given member rank. These new stratigraphic units are, from oldest to youngest, the Halape, Kahele, Pohakaa and Moo Ash Members. The Pohakaa has a similar distribution and lithology to the Pahala Ash and represents a major period of ash deposition on Kilauea at about 40–50 ka. Two pyroclastic units intercalated within the Puna Basalt are the circa 1.5-ka Uwekahuna Ash Member and the mostly A.D. 1790 Keanakakoi Ash Member. The origin and source of these pyroclastic units, particularly the Pahala Ash and the Pohakaa Ash Member, is briefly discussed, in light of new rare-earth-element and petrographic data from these units.

INTRODUCTION

A stratigraphic unit, whether it be a group, formation, member, or flow, becomes established through the repeated demonstration of its utility. Since the Hawaiian Volcano Observatory was established 75 years ago, a number of stratigraphic terms have been introduced to help geologists unravel the stratigraphy of Kilauea Volcano. Some of these terms have become well established through use; others, although widely used, do not meet all of the criteria required of formal stratigraphic units as outlined in Article 3 of the North American stratigraphic code (North American Commission on Stratigraphic Nomenclature, 1983).

The purpose of this paper is to review the stratigraphic nomenclature of Kilauea Volcano and to revise it so as to be consistent with the stratigraphic code and with current needs. Some new stratigraphic terms are herein formally proposed so that they will be available to the geologic community and their utility can be tested. Stratigraphy is an important tool in aiding our understanding of Kilauea Volcano, and I hope that this revision of stratigraphic nomenclature will make this tool even more effective.

ACKNOWLEDGMENTS

R.T. Holcomb was in large part responsible for this paper through his encouragement, and this paper has benefited from discussion over the years with M.O. Garcia, R.T. Holcomb, J.P. Lockwood, and G.A. Macdonald. As a historical note, it was G.A. Macdonald's intention to revise the stratigraphy of the Island of Hawaii and Kilauea Volcano in order to make the nomenclature consistent with the recommendations of the stratigraphic code, but this work was cut short by his untimely death. This paper was reviewed by R.L. Christiansen and R.T. Holcomb, and I thank them for their careful reading and helpful comments and suggestions.

PREVIOUS WORK

The various lithostratigraphic schemes that have been applied to Kilauea Volcano and correlations between them are summarized in figure 11.1. An essential element of all these schemes is the use of the Pahala Ash as a marker horizon to divide the lava of Kilauea Volcano into pre-Pahala and post-Pahala units. This usage arose because the Pahala Ash was considered to be the only stratigraphic unit found on several (four of the five) volcanoes on the Island of Hawaii (see Stearns and Macdonald, 1946). It has therefore been used as an important stratigraphic marker. As discussed in detail later, the Pahala Ash does not always meet the criteria required of a marker horizon, and this can present local correlation problems.

Stone (1926) divided Kilauea rocks into the pre-Kilauea Series, comprising all rocks below and including the unit he called the Pahala Ash, and the Kilauea Series, comprising prehistoric and historical lavas younger than the Pahala. L.F. Noble and W.O. Clark (unpub. data, 1920, in Washington, 1923) made a similar division, but used the terms Pahala Series and post-Pahala Series; this division was later revised in Stearns and Clark (1930). In both these works, the lavas of Kilauea and Mauna Loa were not differentiated stratigraphically. Stearns and Clark (1930) included lava and tuff of both volcanoes in the Pahala Basalt (which included the upper ash member now called the Pahala Ash) and the overlying Kamehame Basalt. The Kamehame Basalt was divided into a lower prehistoric part, which included all ash units above the Pahala Basalt, and an upper part composed essentially of historic flows (fig. 11.1).

Wentworth (1938), in his examination of Kilauea pyroclastic rocks, introduced the term Pahala Tuff for what has generally been called the Pahala Ash by workers both before and since. He also introduced the terms Uwekahuna Formation and Keanakakoi Formation for ash units of Kilauea stratigraphically above his Pahala Tuff.

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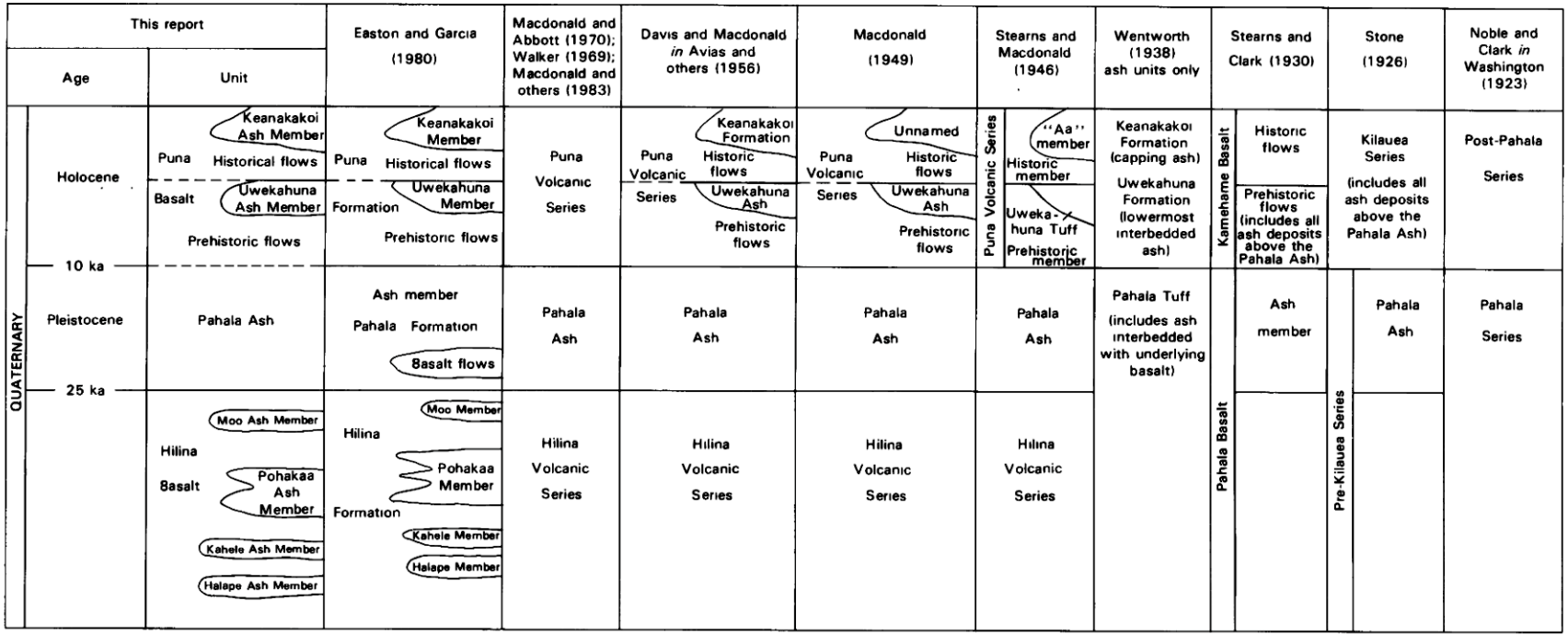

FIGURE 11.1.—Evolution of lithostratigraphic nomenclature for Kilauea Volcano. Stearns and Macdonald's (1946) "aa" member is probably erroneous for ash member. Dashed line between Puna Basalt and Pahala Ash of this report indicates that locally lowermost Puna flows are intercalated with Pahala Ash and are of Pleistocene age (see text).

Modern usage began when Stearns and Macdonald (1946) divided the rocks below the ash member of the Pahala Basalt (Stearns and Clark, 1930) into the Kahuku Volcanic Series for lava of Mauna Loa and the Hilina Volcanic Series for lava of Kilauea (fig. 11.1). In addition, they divided the rocks called the Kamehame Basalt by Stearns and Clark (1930), which overlie the Pahala on Mauna Loa and Kilauea and include the historical lava of the two volcanoes, into the Kau Volcanic Series on Mauna Loa and the Puna Volcanic Series on Kilauea (fig. 11.1), thus abandoning the term Kamehume Basalt. They included the Uwekahuna in the Puna and called it Uwekahuna Tuff, but treated rocks called the Keanakakoi Formation by Wentworth (1938) as an informal member. The Pahala Ash was used to separate these stratigraphic units. Macdonald (1949, p. 65, 67) also included the Uwekahuna in the Puna Volcanic Series but called it the Uwekahuna Ash. Davis and Macdonald (in Avias and others, 1956) included Wentworth's Keanakakoi Formation in the Puna. Walker (1969), Macdonald and Abbott (1970), and Macdonald and others (1983) essentially retained the nomenclature of Stearns and Macdonald (1946; fig. 11.1).

Easton and Garcia (1980) renamed the Hilina Volcanic Series and the Pahala Ash as the Hilina and Pahala Formations, respectively, and effectively reduced the rank of the Puna Volcanic Series (and its subdivisions) and renamed it the Puna Formation. Easton and Garcia (1980) also introduced new stratigraphic terms for several ash units within the Hilina Formation (fig. 11.1), but these terms were not formally proposed in the sense of Article 3 of the stratigraphic code.

STRATIGRAPHY OF KILAUEA VOLCANO

The revised stratigraphic nomenclature for Kilauea Volcano proposed in this paper is shown in figures 11.1 and 11.2. As the use of the term "Formation" does not indicate the predominant lithology or volcanic origin of each lithostratigraphic unit, the names Hilina Basalt, Pahala Ash, and Puna Basalt replace the names Hilina Formation, Pahala Formation, and Puna Formation of Easton and Garcia (1980), respectively. The name Pahala Ash is used in this report, although the ash is indurated and more properly could be called a tuff. However, the term ash is commonly applied to its indurated counterpart, and the name Pahala Ash is widely used.

Reference sections for each of the units are given in table 11.1; they are those of Stearns and Macdonald (1946) unless otherwise indicated. Short descriptions of the three major stratigraphic units are also given below.

In addition to the name changes of two main lithostratigraphic units of Kilauea Volcano, a number of subdivisions of these formations can be made (figs. 11.1, 11.2). These subdivisions are herein formally proposed as members and described in detail under the appropriate higher rank stratigraphic unit. Locations of reference sections for some of these units are given in table 11.1.

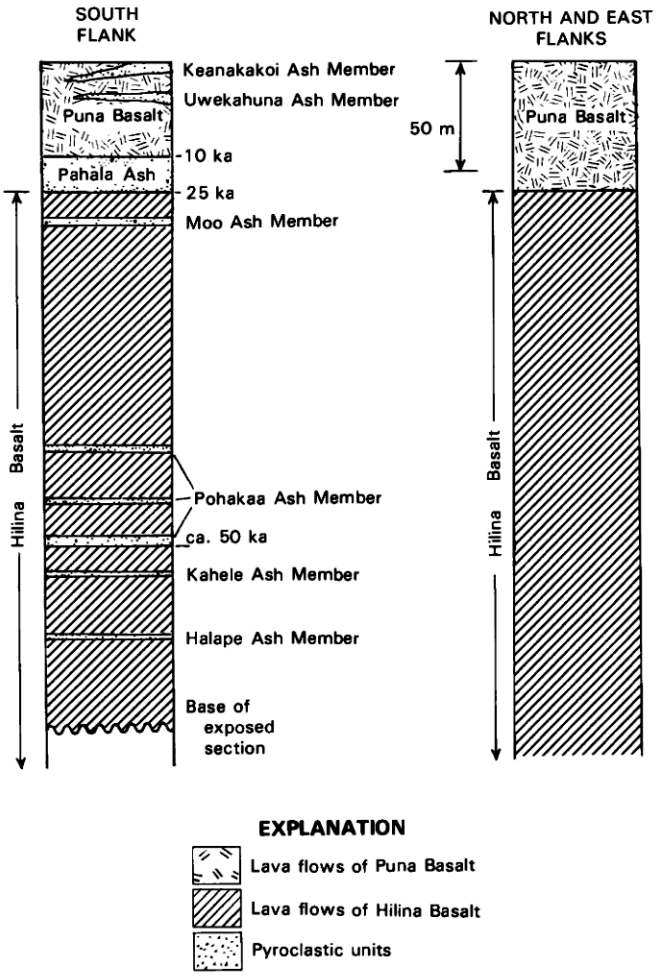

FIGURE 11.2.—Generalized stratigraphic column for south flank of Kilauea Volcano (left) based on sections measured along Hilina fault system (see fig. 11.4). Inferred stratigraphic column for north and east flanks of Kilauea Volcano shown on right. Absence of ash horizons on north flank indicated here reflects trade-wind patterns in Hawaiian region. Although Keanakakoi Ash Member of the Puna Basalt is present in Glenwood region on north flank of Kilauea, its distribution on east flank is unknown.

HILINA BASALT

The Hilina Basalt is exposed only in valleys along the Hilina fault system on the south flank of Kilauea Volcano (fig. 11.3). Exposures are limited to Puu Kapukapu, Puu Kaone, Puueo Pali, Hilina Pali, and a fault scarp north of Kalaeapuki (fig. 11.3). The Hilina Basalt consists predominantly (95 percent) of lava flows, but several major ash horizons are present.

Stone (1926) and Stearns and Clark (1930) examined the formation but gave only general descriptions. Macdonald described a section of the formation 1.6 km southwest of the end of Hilina Road (Stearns and Macdonald, 1946, appendix) and also gave brief petrographic descriptions of the lava (Macdonald, 1949).

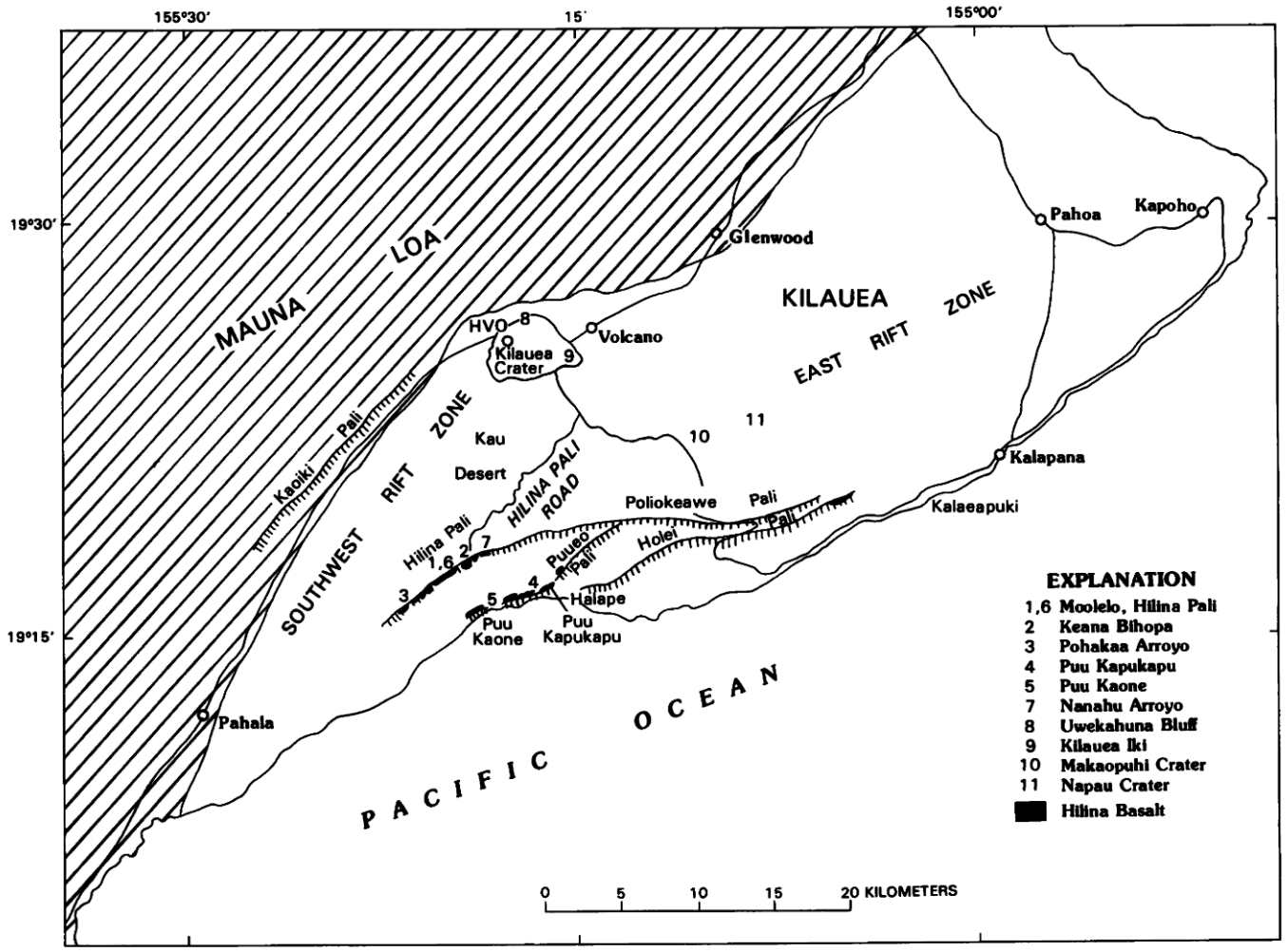

FIGURE 11.3.—Location of type and reference sections for stratigraphic units of Kilauea Volcano (see table 11.1).

PYROCLASTIC AND SEDIMENTARY DEPOSITS

The Hilina Basalt contains several altered and reworked ash horizons (fig. 11.4). The number of ash horizons varies between sections, reflecting intercalation of lava flows with the ash beds. More distal sections such as Puu Kapukapu contain fewer ash horizons because in these areas ash from occasional explosive eruptions could accumulate for longer periods without flow activity occurring. The overall thickness of the ash horizons is relatively constant in any area, but it decreases with distance from Kilauea's summit. The above features make bed-to-bed correlation difficult. Nevertheless, it is still possible to define at least three major ash events and one minor one, widely separated in space and time within the Hilina Basalt which can be correlated between sections over distances of tens of kilometers (figs. 11.2, 11.4).

HALAPE ASH MEMBER (NEW TERM)

This member is found at Puu Kapukapu and at Keana Bihopa near the base of the exposed Hilina section (figs. 11.3, 11.4). The name is derived from the Halape area at the base of Puu Kapukapu (Pukui and others, 1974). The type section is at Keana Bihopa (tables 11.1, 11.3). The unit is found at roughly the same stratigraphic level in both localities, but at each locality it varies laterally in thickness from 10 cm to 50 cm. At Puu Kapukapu, the unit grades downward into a deeply weathered aa clinker zone; at both localities it is overlain by aa flows.

The member is composed of red-weathering, poorly bedded, clayey soil and palagonite. Soil predominates at Puu Kapukapu, but at Keana Bihopa, brown beds of palagonite 0.5–1 cm thick are present. A section from Keana Bihopa is described in table 11.3.

TABLE 11.1.—*Type localities and reference localities of lithostratigraphic units, Kilauea Volcano*

[See figure 11.3 for localities]

Locality	Description
1	Type section of the Hilina Basalt (Stearns and Macdonald, 1946). 1.6 km southwest of end of Hilina Pali Road (approx. lat 19°17'00" N., long 155°18'45" W., Kau Desert 7.5-min quadrangle).
2a	Reference section of Hilina Basalt, Keana Bihopa, from base of pali (370 m elev) to top (640 m elev) (19°17'19" N., 155°18'25" W., Kau Desert 7.5-min quadrangle). 250 m south-southwest of end of Hilina Pali Road.
2b	Type section of Halape Ash Member, Hilina Basalt, Keana Bihopa, (395 m elev) (19°17'19" N., 155°18'25" W., Kau Desert 7.5-min quadrangle).
2c	Type section of Moo Ash Member, Hilina Basalt, Keana Bihopa (570 m elev) (19°17'19" N., 155°18'25" W., Kau Desert 7.5-min quadrangle).
2d	Reference section of Puna Basalt, Keana Bihopa (600–640 m elev) (19°17'19" N., 155°18'25" W., Kau Desert 7.5-min quadrangle).
3a	Type section of Kahele Ash member, Hilina Basalt, Pohakaa Arroyo (approx. 470 m elev) (19°16'40" N., 155°20'00" W., Kau Desert 7.5-min quadrangle).
3b	Type section of Pohakaa Ash Member, Hilina Basalt, Pohakaa Arroyo (approx. 425–450 m elev) (19°16'40" N., 155°20'00" W., Kau Desert 7.5-min quadrangle).
4a	Reference section of Hilina Basalt and Halape, Kahele, Pohakaa and Moo Ash Members, Puu Kapukapu, from base of pali (100 m elev) to top (300 m elev) (19°16'45" N., 155°15'35" W., Kau Desert 7.5-min quadrangle).
4b	Reference section of Pahala Ash, Puu Kapukapu (19°16'15" N., 155°17'15" W., Kau Desert 7.5-min quadrangle).
5	Reference section of Pahala Ash, Puu Kaone (19°16'15" N., 155°17'15" W., Kau Desert 7.5-min quadrangle).
6	Principal reference section of Pahala Ash, Moolelo, Hilina Pali (19°17'00" N., 155°19'00" W., Kau Desert 7.5-min quadrangle).
7	Reference section of Puna Basalt and Uwekahuna Ash Member, Nanahu Arroyo, Hilina Pali, 0.5 km northeast of end of Hilina Pali Road (19°18'15" N., 155°18'34" W., Kau Desert 7.5-min quadrangle).
8	Type sections of Puna Basalt and of Uwekahuna Ash Member, Uwekahuna Bluff, Kilauea caldera (Kilauea Crater 7.5-min quadrangle).
9	Reference section of Puna Basalt, Kilauea Iki Crater, summit lava (Volcano 7.5-min quadrangle).
10	Reference section of Puna Basalt, east-rift-zone lava, Makaopuhi Crater (Makaopuhi Crater 7.5-min quadrangle).
11	Reference section of Puna Basalt, east-rift-zone lava, Napau Crater (Volcano 7.5-min quadrangle).

Walker (1969) examined the Hilina while mapping the Kau Desert quadrangle. Easton and Garcia (1980) described the petrography and geochemistry of the Hilina lava in detail. Easton (1978) examined the Hilina in detail and measured sections through the formation at most exposures (Easton, 1978, fig. 3, appendix). The two most extensive and best exposed sections are at Keana Bihopa (Hilina Pali) and Puu Kapukapu (figs. 11.3, 11.4).

LAVA FLOWS

The exposed Hilina Basalt consists of a sequence of aa and pahoehoe flows. Individual pahoehoe flows are 0.5–3 m thick, averaging 2 m. Upper surfaces are commonly ropy and reddish to purplish, and surface crusts are rarely preserved, indicating minor erosion (1–10 cm of material removed) between flows. Pahoehoe sequences of mineralogically similar rocks 8–16 m thick are common, and it is difficult to distinguish individual flows in these sequences. These flow sequences, more abundant in the upper part of the Hilina Basalt, could represent different phases of the same eruption (much like the 1969–74 flows erupted from Mauna Ulu).

The aa flows are 1–6 m thick, averaging 4 m including the clinker zones; the core zone accounts for 20–80 percent of the flow thickness. The clinker zones are partially to totally weathered to reddish-brown clay and commonly contain soil or yellow palagonite horizons in their upper parts. The palagonite layers are probably remnants of ash pockets or lenses. Otherwise, all flow rocks are fresh, mainly because of the low rainfall in the area.

The relative amounts of aa and pahoehoe in the measured sections vary (fig. 11.4, table 11.2). In general, pahoehoe flows predominate in sections farthest away from the caldera (for example, Puueo Pali), supporting the suggestion of Swanson (1973) that only large volume, tube-fed pahoehoe eruptions are able to reach and flood large areas of Kilauea's south flank.

The relative abundances of rock types in the Hilina Basalt are also shown in table 11.2. Olivine basalt contains more than 5 percent olivine phenocrysts (Macdonald, 1949). Picrite basalt contains less than 35 percent modal plagioclase and more than 15 percent modal olivine (Macdonald, 1949; Wright, 1971). Olivine basalt is more abundant than other kinds of basalt in the sections examined (table 11.2). Hypersthene was only rarely observed in lava of the Hilina Basalt, and then only in small amounts. Picrite basalt and plagioclase porphyritic basalt are present only at Puueo Pali and Puu Kapukapu and may be derived from the nearby east rift zone (Macdonald, 1944). Further details on the petrography of Hilina Basalt lava are found in Easton and Garcia (1980).

The Hilina Basalt flows are chemically distinct from the overlying Puna Basalt flows, the former having higher FeO^t content for the same MgO content and lower K_2O/P_2O_5 ratio than the latter (Easton and Garcia, 1980). This distinction may aid in mapping the Hilina and Puna Basalts in areas where the intervening Pahala Ash is thin or absent. Easton (1978) and Easton and Garcia (1980) concluded on the basis of mapping and geochemistry that the Hilina Basalt exposed on the south flank of Kilauea was an intricately stacked sequence of flows derived from the summit caldera and from the east and southwest rift zones of Kilauea. Further details on the chemistry of Hilina Basalt lava are given in Easton and Garcia (1980).

The lower contact of the Hilina Basalt is not exposed, but at least 300 m of lava is exposed along the Hilina Pali. The upper contact of the Hilina Basalt has been defined as the base of the Pahala Ash (Stearns and Macdonald, 1946). The age of the Hilina Basalt is not well defined, but it is older than the radiocarbon age of 31 ± 0.9 ka obtained from the base of the Pahala Ash on Mauna Loa (Kelley and others, 1979). The base of the exposed Hilina Basalt lava at Puu Kapukapu may be estimated to be on the order of 100 ka from average eruption rates determined at Nanahu Arroyo[2] along the Hilina Pali (Easton, 1978).

[2]Name does not appear on current topographic map, but has recently been approved by the U.S. Board on Geographic Names (Donald J. Orth, written commun., 1986).

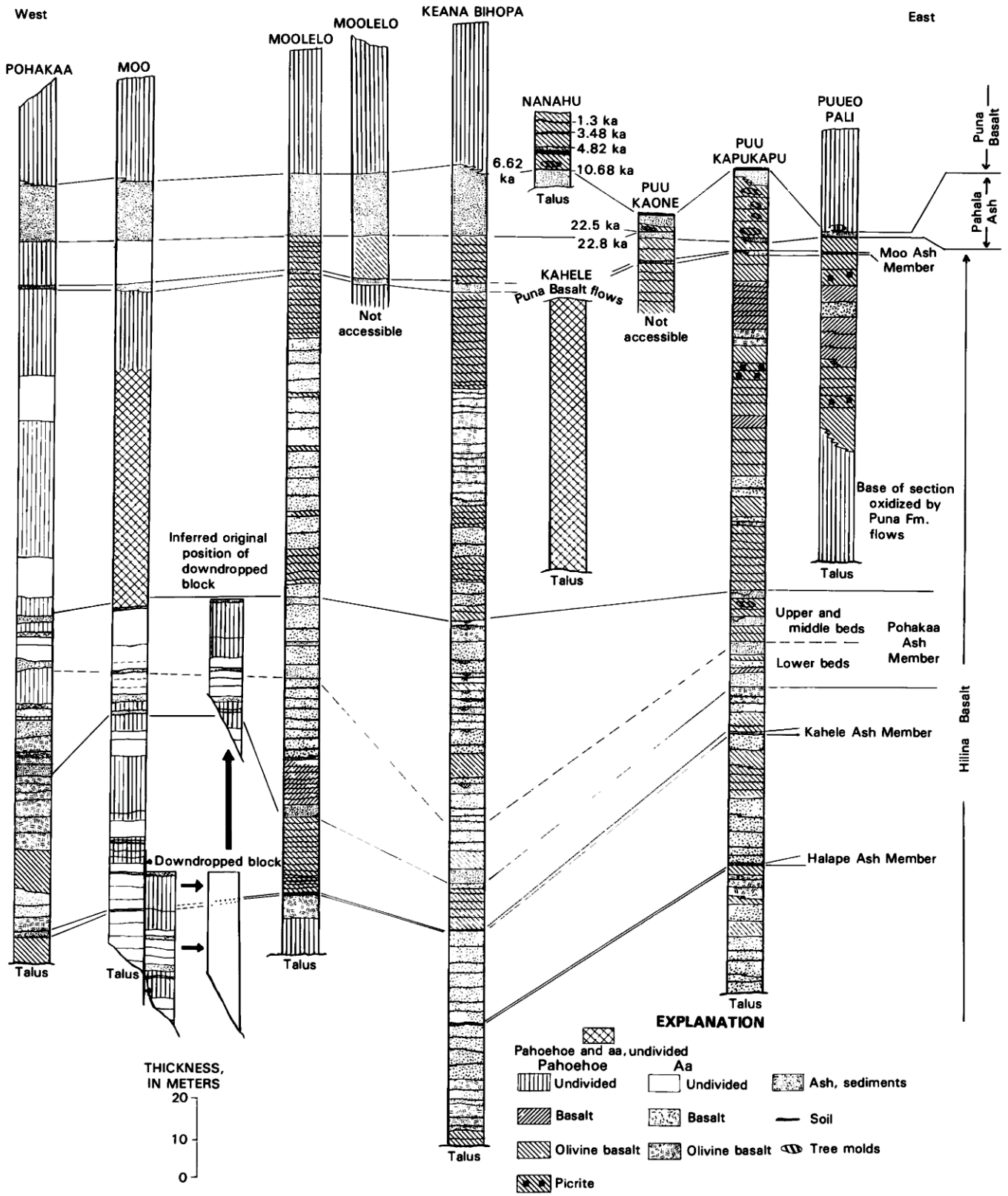

FIGURE 11.4.—Measured stratigraphic sections of Hilina Basalt along Hilina fault system, south flank of Kilauea Volcano. Data adapted from Easton (1978). Base of Hilina Basalt is nowhere exposed. Intercalated lava flows shown in sections of Pahala Ash and Pohakaa Ash Member are Puna Basalt flows and Hilina Basalt flows, respectively (see text).

TABLE 11.2.—*Abundance of rock and flow types exposed on Kilauea Volcano, in part modified from Easton and Garcia (1980)*

[All figures in percent; n.d., not determined]

Area or subdivision	Relative abundance of rock type exposed				Relative abundance of flow types exposed		Relative abundance of flow type in each rock type			
	Olivine basalt	Picrite basalt	Basalt	Hypersthene-bearing basalt	Aa	Pahoehoe	Basalt		Olivine basalt	
							Aa	Pahoehoe	Aa	Pahoehoe
Puna Basalt										
Historical flows	78	7	13	2	n.d.	[1]100	n.d.	n.d.	n.d.	n.d.
Prehistoric flows	71	5	22	2	n.d.	[1]100	n.d.	n.d.	n.d.	n.d.
Moolelo[2]	67	3	30	0	50	50	n.d.	n.d.	n.d.	n.d.
Hilina Basalt										
Keana Bihopa[3]	56	0	44	0	60	40	90	10	38	62
Pohakaa[4]	68	n.d.	32	n.d.	57	43	n.d.	n.d.	n.d.	n.d.
Kapukapu[5]	62	4	34	0	36	64	60	40	24	76
Puueo Pali[6]	67	8	25	n.d.	5	95	5	95	0	100

[1]Cliff sections, Hilina Pali and Kapukapu only.
[2]Difficult to estimate number of flows; pahoehoe, aa figures approximate. From Macdonald (1946).
[3]50 flows of olivine basalt: 20 aa, 30 pahoehoe; 40 flows of basalt: 35 aa, 5 pahoehoe.
[4]Lower half of section, top of Pohakaa Ash Member to base of section.
[5]50 flows of olivine basalt and picrite basalt: 12 aa, 30 pahoehoe, transition pahoehoe; 25 flows of basalt: 15 aa, 10 pahoehoe.
[6]Upper section, above top of the Pohakaa Ash Member: 16 flows of olivine basalt, 2 flows of picrite basalt, all pahoehoe; 6 flows of basalt, 5 pahoehoe, 1 aa.

The Halape Ash Member is lithologically similar to the better exposed Kahele Ash Member. Although the unit is thin, it can be correlated between palis (fig. 11.2). The age of the member is not known, but it is probably between 100 ka and 30 ka on the basis of the estimated age of the base of the Hilina Basalt (Easton, 1978).

KAHELE ASH MEMBER (NEW TERM)

This pyroclastic unit crops out all along the Hilina Pali and at Puu Kapukapu (fig. 11.4). The name is derived from Kahele Arroyo[2], a valley at approximately 19°18′00″ N. latitude and 155°17′10″ W. longitude located 1 km east-southeast of the Hilina Shelter. The type section is at Pohakaa Arroyo[2] (table 11.3). Thickness is variable, being only 10-50 cm at Keana Bihopa and Puu Kapukapu, but increasing along the Hilina Pali to 125 cm at Pohakaa Arroyo. Except at Pohakaa Arroyo, the unit is crudely bedded; bedding is better developed than in the Halape Ash Member. The Kahele Ash Member contains some brown and red-brown palagonite but consists mostly of a red clay; 10 to 25 percent more ash material is present than in the Halape Ash Member. At Pohakaa Arroyo the unit also includes a bed, 10–15 cm thick, of gray, coarse, crossbedded sand composed of rounded olivine and lava fragments (table 11.3; fig. 11.5). In addition, a bed of glassy, vesicular scoria and glass fragments only 2–5 cm thick is present; these materials are interpreted to be cinder-cone eruptive debris derived from the southwest rift zone of Kilauea. Eastward thinning of the Kahele Ash Member indicates a possible source in the southwest rift zone for much of this unit. A representative section of this unit is described in table 11.3. The age of this member is not known, but it is presumed to be between 100 ka and 30 ka. Both the Halape and Kahele Ash Members differ from ash units higher in the section in being more deeply weathered (possibly a result of greater age) and in consisting of red clay rather than yellow-brown palagonite. It is possible that the Halape and Kahele Ash Members may represent a period of soil development as well as ash deposition.

POHAKAA ASH MEMBER (NEW TERM)

The Pohakaa Ash Member represents a major period of ash production comparable in scale to that of the Pahala Ash. The name is derived from Pohakaa Arroyo[2] on the Hilina Pali. Pohakaa was a Hawaiian god who lived in precipitous places and who rolled down stones, frightening and injuring passersby (Kalakaua, 1888). The name is appropriate both to the exposure and to the lithology of the unit.

The Pohakaa Ash Member contains intercalated flows, but it is underlain and overlain by about 100 m of lava containing no ash units. The intercalated flows have no distinctive features and are not considered to be part of the Pohakaa Ash Member. At Pohakaa Arroyo, the member consists of six individual ash layers, each 1–4 m thick (total thickness 10–12 m), at Moolelo of five horizons (total 6.5 m), at Keana Bihopa three to five layers (total 7 m), and at Puu Kapukapu four layers (total 10 m). The Pohakaa Member is not exposed at Puueo Pali, probably because the section there is incomplete. The type section of the Pohakaa Member is at Pohakaa Arroyo (tables 11.1, 11.3), where it shows the greatest number, thickness, and lithologic variation of the ash layers; however, the member is more accessible at Keana Bihopa and Puu Kapukapu.

Although the Pohakaa Ash Member has an areal distribution on Kilauea and is lithologically similar to the Pahala Ash, it has been given member instead of formation rank for the following reasons: (1) The Pohakaa Ash Member is limited in present-day exposure and, unlike the Pahala Ash, has only been found on Kilauea Volcano; thus the unit is not as widespread as the Pahala Ash. (2) If the Pohakaa Ash Member were upgraded to formation rank, then the Hilina Basalt would need to be raised to group rank or split into an upper and lower formation separated by the Pohakaa ash layers. Such a division would cause confusion and would be unsuitable for areas where the Pohakaa Ash Member is thin or absent. As there is no compelling need to give the Pohakaa formational rank, the designation of the rank of member seems most adequate at present.

The Pohakaa Ash Member can be subdivided into lower, middle, and upper beds; however, it is not always possible locally to separate the middle and upper beds. These smaller units are not sufficiently characteristic to warrant formal designation as beds or members.

The total thickness of the member is 6–10 m at Puu Kapukapu, 7–15 m at Keana Bihopa, and 8–15 m at Pohakaa; it thus shows an eastward and southward thinning. This thinning is best defined when only the thickness of primary ash beds is included. It has been possible to distinguish reworked beds from primary ash beds within the Pohakaa Ash Member, the Pahala Ash, and younger ash horizons on Kilauea by means of the following criteria:

(1) Primary beds are regularly layered beds of palagonite, 1–30 cm thick, containing remnant small glass shards, distinct grains of pumice or accretionary lapilli, usually yellow-brown in color, and few olivine crystals or rock fragments.

TABLE 11.3.—*Descriptions of Hilina Basalt ash units, Kilauea Volcano*

[Descriptions from type sections; listed in order from oldest to youngest. Location of sections shown in figure 11.3.]

Thickness (cm)	Description
	Halape Ash Member—Keana Bihopa section
	Overlying aa flow
10–20	Red palagonite, grades downward into red-weathered clinker of underlying aa flow.
	Underlying aa flow.
	Kahele Ash Member—Pohakaa Arroyo
	Overlying lava flow.
20	Coarse, red-brown to black, glassy scoria, clinker and pumice, refractive index of glass 1.602±0.002, fragments as large as 20 mm.
40	Red-brown indurated palagonite, rare plagioclase grains, subhedral olivine phenocrysts, some glass shards with refractive index of 1.604.
5–10	Rippled, coarse-bedded, pink to white-gray pebble gravel; 40–50 percent olivine sand, rounded grains; also vesicular lava sand and gravel-size grains.
30	Yellow-red palagonite.
	Underlying lava flow.
	Pohakaa Ash Member—Keana Bihopa
	Overlying lava flow.
	Upper beds (may include parts of middle beds) (45–50 percent ash material; 1.25–1.5 m total thickness).
20	Brown palagonite, fining upward; minor clinker and pumice, mostly altered glass, refractive index of palagonite 1.548±0.002.
5–8	Gray, friable, sand-size lava fragments.
5–8	Pale red palagonite with black glassy cinders 0.5–1 mm large.
30	Gray, laminated, friable beds of fragments 2–4 mm large of rounded, red, gray, and black lava, minor rounded olivine.
35	Pale brown to yellow palagonite, cinders as large as 1 mm, some glass with refractive index 1.606±0.002.
50–100	Weathered aa clinker and red soil.
	Interstratified lava: 16 m of aa and transition pahoehoe olivine basalt and basalt flows (6 flows).
	Middle beds (30 percent ash material; 1.75 m total thickness). Unit cut by stream channels with many local unconformities.
10–20	Red-brown palagonite, with or without soil.
5	Gray, rounded, red and black lava fragments, beds of friable sand.
10	Yellow-brown palagonite.
30	Brown indurated palagonite in beds 1–2 cm thick, locally eroded and unconformably in contact with overlying flow.
8	Finely laminated, gray, friable sand-size rounded lava and olivine fragments, mantles underlying unit.
10 (locally 30–50)	Finely bedded and crossbedded; gray, rounded lava grains; fills channels cut in underlying beds.
10	Brown to red-brown palagonite, vitric cinders 1–2 mm large.
5	Coarse rounded sand-size lava fragments.
20	Brown to red-brown clay, palagonite, or soil.
20	Brown soil containing aa blocks and clinker.
	Interstratified lava: 18 m of aa and pahoehoe basalt and olivine basalt flows (6 flows).
	Lower beds (50 percent ash material; 2.75–3 m total thickness).
30	Brown to red-brown soil and palagonite.
10	Yellow-gray palagonite with black cinders as large as 3 mm.
25	Brown to red-brown palagonite with local beds of glassy cinders.
60	Beds 1–10 cm thick of gray, rounded olivine and lava fragments 2–3 mm large, locally beds 1–2 cm thick of yellow-brown palagonite.
25	Yellow-brown palagonite in beds 1–3 cm thick, brown beds contain glassy cinders 1–2 mm large.
10	Rounded lava and rock fragments, as large as 5 cm.
5	Gray to yellow-brown palagonite.
1–3	Red, black, and gray rounded lava fragments as large as 3 cm.
7	Gray-brown palagonite, bedding on 5-mm scale, vitric cinders as large as 1 mm.
12	Yellow-brown palagonite.
15	Red, black, and gray, vesicular, rounded basalt fragments.
3–7	Brown palagonite, vitric cinders 0.5–1 mm large.
20–50	Gray, finely laminated beds of olivine and lava sand and gravel.
20	Yellow-brown palagonite with rounded red and black lava fragments as large as 1 cm, weakly bedded.
5	Brown palagonite with vitric, angular cinders as large as 4 mm.
25	Brown palagonite.
30	Reddish to purplish-gray aa clinker, brown to pale yellow-brown ash and soil matrix.
	Underlying aa and pahoehoe flows.
	Moo Ash Member—Keana Bihopa (50 percent ash material, 2.5 m total thickness)
	Overlying pahoehoe flows.
10–15	Fine black sand, soil, brown palagonite.
6	Pale brown, accretionary lapilli 1–2 mm in diameter.
1	Purple-brown palagonite, vitric cinders 1–2 mm large.
5	Pink-brown palagonite, vitric cinders 1 mm large.
5	Purple-brown to brown palagonite, with red and black cinders 1 mm large, local carbonized roots.
2–3	Red-brown palagonite, pumice fragments 5–7 mm large.
5–7	Gray, rounded lava and olivine sand.
2	Purple-brown palagonite, vitric cinders 1 mm large.
2	Gray lava sand.
10	Accretionary lapilli 2–3 mm in diameter, local charcoal at base.
1–2	Reddish clay or soil.
5	Finely laminated beds (1–2 mm thick) of gray lava and olivine sand.
5	Brown accretionary lapilli.
1	Reddish soil.
25–30	Brown to purple-gray, red, and black altered flow fragments 10–25 mm large.
1–2	Reddish clay (soil?).
5	Brown, coarse, rounded lava fragments.
5	Brown, glassy, angular pahoehoe crusts 2–3 mm across.
10	Finely laminated gray lava and olivine sand.
5	Vitric black cinders 2–3 mm large.
5	Red-brown clay (soil?).
40–50	Gray, finely laminated beds of rounded flow and clinker material.
10–40	Yellow to red-brown palagonite, soil near base.
	Underlying aa flows.

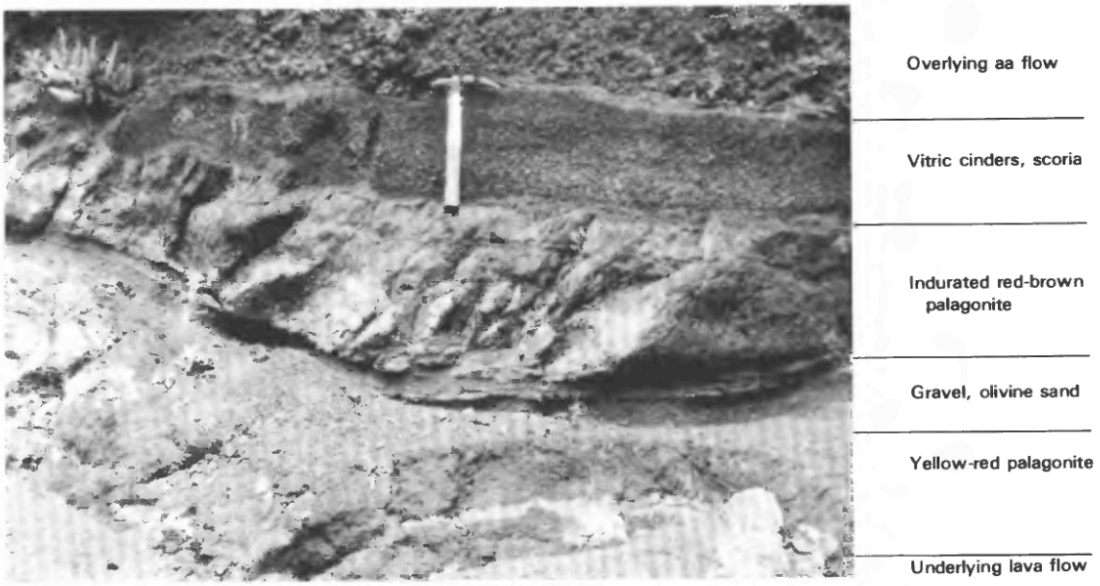

FIGURE 11.5.—Kahele Ash Member of Hilina Basalt at Pohakaa Arroyo, Hilina Pali. Entire thickness of member is shown.

(2) Reworked beds contain sedimentary and pyroclastic material, including: distinct rounded to angular fragments of flow rocks; broken pahoehoe crusts, scoria, and clinker; abundant subrounded olivine fragments (10 percent or more), commonly attached to rock; and minor plagioclase crystal fragments. The bedding layers are thin (1 mm to 5 cm), and crossbedding, undulatory bedding, truncated bedding, and local soil horizons are often present in local channels cut into palagonite. These reworked units are commonly found as friable, gray-weathering, fine-sand to granule-gravel beds.

(3) Surge deposits, which are present mainly in some of the younger ash units contain both primary and reworked layers. The characteristics of these deposits have been described by Swanson and Christiansen (1973) and Decker and Christiansen (1984). Primary and reworked material are intercalated on a fine scale, and it must be realized that most ash layers on Kilauea are a mixture of both types. Sedimentary material similar to that present in the older ash units is found on the surface throughout the Kau Desert region of Kilauea.

The lower beds of the Pohakaa Ash Member form the thickest part of the member (3–4 m) and constitute the first two ash horizons at Pohakaa, Moo, Moolelo, and Puu Kapukapu. At Keana Bihopa, these lower beds are thicker than at other localities. The lower beds consist of alternating beds (5–30 cm) of primary ash (table 11.3; fig. 11.6) and local interbeds of reworked ash and sediment. The lower beds of the Pohakaa Ash Member mark the first appearance of thick palagonitized ash horizons in the exposed Hilina Basalt; they are characterized by a greater proportion of yellow-brown palagonite than the middle and upper beds, by a greater proportion of primary ash beds (50 percent and more along the Hilina Pali, 25 percent and more at Puu Kapukapu), and by the absence of local unconformities, crossbedding, truncated beds, and large- and small-scale channels.

The middle beds of the Pohakaa Ash Member are characterized by a greater abundance of reworked ash beds and sediment (75 percent along the Hilina Pali, 90–95 percent at Puu Kapukapu), a greater abundance of brown and red-brown palagonite, more soil horizons, extensive development of small stream channels 5–50 cm deep, and the presence of crossbedding, truncated beds, channel filling by later ash beds, and filling of channels by lava flows and later primary ash beds (fig. 11.7). Local unconformities are also common in the middle beds.

The upper beds of the Pohakaa Ash Member are present only locally and are restricted almost entirely to large-scale stream channels as much as 10 m deep. These channels grade laterally into a yellow-brown palagonite matrix found in aa clinker layers (usually a red-brown soil matrix is present), indicating that eruption of ash and lava occurred concurrently, in contrast to the situation during formation of the Pahala Ash and the lower parts of the Pohakaa Ash Member. There is also more primary ash material in the upper beds than in the middle beds. Yellow-brown palagonite is more abundant in the upper beds, and small-scale channeling (less than 2 m across), crossbedding, and other sedimentary structures common to the middle beds are less pronounced in the upper beds. A section through the Pohakaa Ash Member at Pohakaa Arroyo is described in table 11.3.

The thickness of the middle and upper beds is difficult to establish. At Keana Bihopa and Pohakaa Arroyo, the middle and upper beds are thickest where located in the deepest parts of the valley chutes, central to the incised valleys. Aa flows are present locally in these channels, but they do not fill them. Along Moolelo and at Puu Kapukapu, the beds of the Pohakaa Ash Member are much more uniform in thickness, and they can be traced laterally with little variation in thickness. These latter two areas lack present-day stream channels. The presence of the thickest, best developed

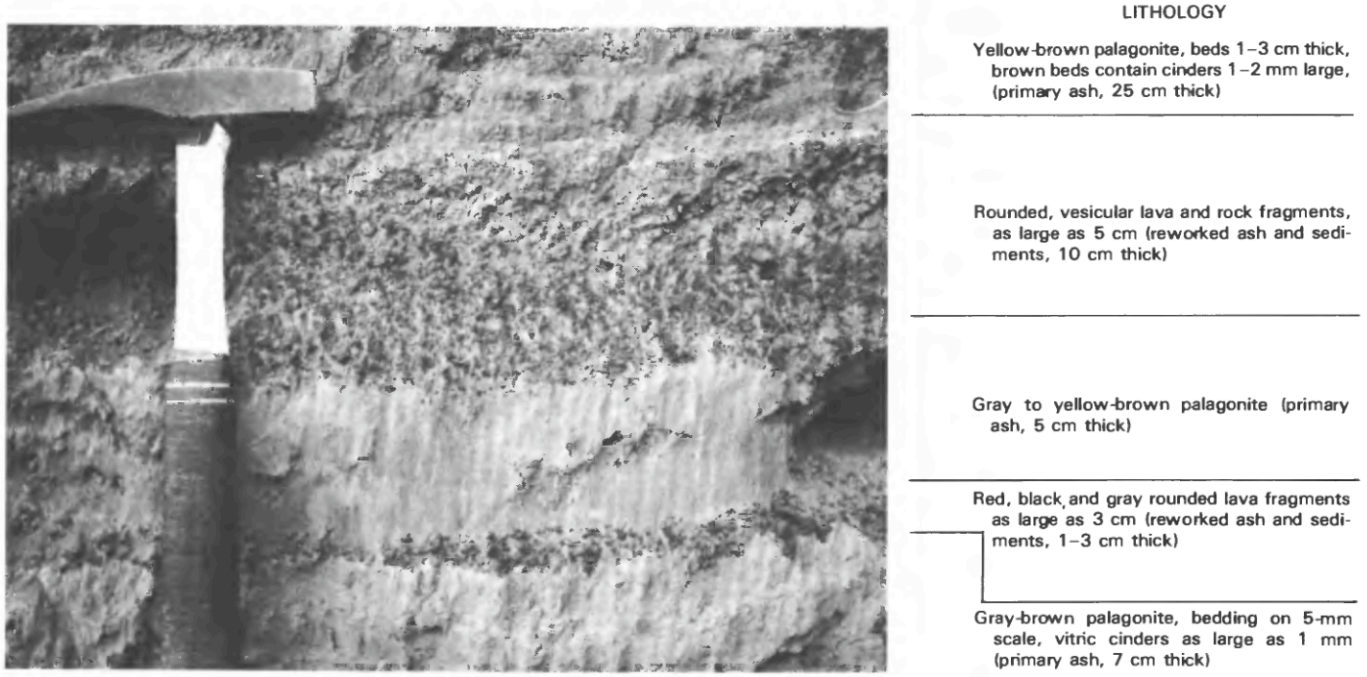

FIGURE 11.6.—Closeup view of lower beds of Pohakaa Ash Member, Keana Bihopa, showing typical bedding and lithology. Pahala Ash beds are similar to those shown here.

FIGURE 11.7.—Middle beds of Pohakaa Ash Member of Hilina Basalt, Keana Bihopa. Stream channel and minor crossbeds to left of hammer (30 cm long) are mantled by later ash and stream deposits. Overlying aa flow (upper right) fills later channel developed within upper beds in photograph.

sections in current valley cuts and the absence of channels elsewhere along the palis indicate that the drainage system on the south flank of Kilauea has changed very little for several thousand years.

At Pohakaa Arroyo, in the middle beds of the Pohakaa Ash Member, a crossbedded, rippled, pale-gray unit of finely laminated beds containing lithic and crystal fragments forms a horizon 10–15 cm thick that is interbedded with the typical red and yellow-brown palagonite beds (fig. 11.8). This unit closely resembles an outcrop at the Lanai Lookout on Oahu described by Fisher (1977) and attributed to base-surge deposition. Unfortunately, there are no diagnostic textures present at the Pohakaa exposure that would confirm a base-surge origin for the deposit. The proximity of this outcrop to the southwest rift zone does indicate that a base-surge deposit could be present. No similar unit was found in any of the other Hilina sections.

Abundant soils, red-brown palagonite, and extensive stream development imply a more humid climate during the deposition of the Pohakaa Ash Member than at present. This is supported by the presence of *Metrosiderus* sp. (Ohia lehua) tree molds in flows overlying the middle beds of the Pohakaa Ash Member at Puu Kapukapu and at Pohakaa Arroyo. These are the only tree molds found in the Hilina section, other than those present in flows within and overlying the Pahala Ash.

The age of the Pohakaa Ash Member is not known. The member is older than 30 ka because it underlies the Pahala Ash (Kelley and others, 1979), and it may be on the order of 40–50 ka. This age is based on lava and ash accumulation rates obtained from Nanahu Arroyo[2] by Easton (1978): 1 cm/yr for 100 m lava; 1 cm/yr for 10 m of ash and soil. No chemical data are available on ash from the Pohakaa Ash Member. Refractive-index measurements of basaltic glass from the member are similar to those of other Kilauea glass samples (fig. 11.9). A Kilauea source is thus very likely for the primary ash units in the Pohakaa Ash Member, and

FIGURE 11.8.—Middle beds of Pohakaa Ash Member of Hilina Basalt, Pohakaa Arroyo. Undulating beds near hammer may be base-surge deposit. See text for additional details.

the distribution of ash material in the member is consistent with such a source. As discussed in further detail below in the section "Pahala Ash," a Mauna Loa source for both the Pahala and the Pohakaa cannot be ruled out.

MOO ASH MEMBER (NEW TERM)

The Moo Ash Member is well exposed along the Hilina Pali and is also present at Puu Kapukapu and Puueo Pali. The name is derived from Moo Arroyo[2], where the unit is exposed; Moo is the Hawaiian word for dragon. The type section is at Keana Bihopa and is described in tables 11.1 and 11.3.

At Keana Bihopa, the Moo Ash Member underlies a sequence of olivine basalt pahoehoe flows 10–12 m thick, which are capped by Pahala Ash. At this locality, the Moo Ash Member ranges in thickness from 2.5 m on the inward (north) side of the arroyo to 1.5 m near the face of the pali. The overlying flows thicken where the ash thins. It appears that the ash has been eroded away from the lip of the pali and later covered by flows that draped the pali. The Moo Ash Member is lithologically similar to the Pohakaa Ash Member and the Pahala Ash, being composed of a mixture of palagonite and vitric ash (primary ash beds) and reworked ash and sediment.

Criteria for distinguishing the Moo Ash Member from the Pahala Ash include the following: (1) The Pahala Ash is overlain by and intercalated with flows bearing tree molds of *Cibotium* sp. (tree ferns). No tree molds are found below the base of the Pahala Ash down to the middle beds of the Pohakaa Ash Member. (2) The Moo Ash Member is a tuff and sediment horizon 1–2 m thick located 10–15 m below the Pahala and separated from it by a series of mineralogically uniform basalt flows. (3) The Moo Ash Member contains several beds of accretionary lapilli, which are absent from the Pahala Ash on Kilauea.

The Moo Ash Member may be present at Puu Kapukapu and Puueo Pali (fig. 11.4) as a bed of yellow-brown palagonite and

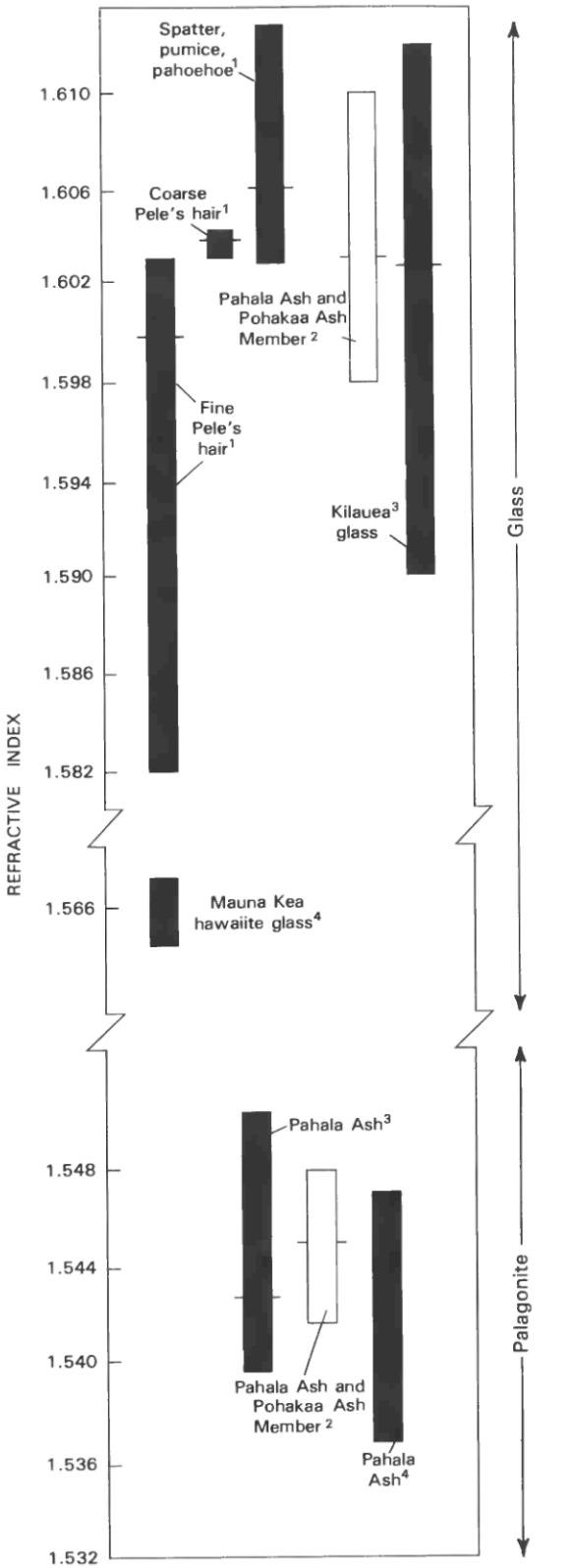

FIGURE 11.9.—Refractive-index measurements of Kilauea glass and palagonite and Mauna Kea glass showing basaltic nature of preserved glass in Pahala Ash and Pohakaa Ash Member. Sources identified by number: 1, Duffield and others (1977); 2, Easton (1978); 3, Wentworth (1938); 4, Macdonald (1949).

sediment 50–100 cm thick and located 3 m below the base of the Pahala Ash. At both these localities, and at Puu Kaone, this ash layer lacks accretionary lapilli, and its assignment to the Moo Ash Member is tentative.

In some areas the Moo Ash Member may be conformable with the lower part of the Pahala Ash, and in such instances it would be difficult to distinguish the two units without radiocarbon ages. At present, the Moo Ash Member is considered part of the Hilina Basalt, because the overlying lavas are similar chemically to those of the Hilina Basalt and distinct from Puna Basalt flows, and wherever the Moo Ash Member is exposed, it is separate from the Pahala Ash.

The age of the Moo Ash Member is not precisely known. It is older than the 24 ka age for the base of the Pahala Ash at Puu Kaone and the 30 ka age for the base of the Pahala Ash on Mauna Loa (Kelley and others, 1979). A reasonable estimate for the age of the Moo Ash Member is between 30–35 ka. Charcoal is present in the Moo Ash Member, but sufficient quantities have not yet been recovered for dating purposes. The Moo Ash Member is lithologically similar to the Pohakaa Ash Member and the Pahala Ash and probably had a similar origin and source.

PAHALA ASH

The Pahala Ash on Kilauea Volcano is only exposed atop fault scarps at Hilina Pali, Puueo Pali, Holei Pali, Puu Kapukapu, and Puu Kaone, and in the Glenwood District (figs. 11.3, 11.10). The distribution of the Pahala Ash on the Island of Hawaii is shown in figure 11.10. The Pahala Ash on Kilauea has been described by Stone (1926), Stearns and Clark (1930), Wentworth (1938), Stearns and Macdonald (1946), Fraser (1960), Walker (1969), and Easton (1978). Stearns and Macdonald (1946) review the older literature on the Pahala Ash on the Island of Hawaii, much of which is concerned with the origin and source of the ash. Wentworth (1938), Hay and Iijima (1968), and Hay and Jones (1972) present chemical analyses of the Pahala from Kilauea, although many of these samples were highly altered. Hay and Iijima (1968), Hay and Jones (1972), and Easton and Easton (1983) have examined the alteration of the Pahala Ash.

The formation was named for the town of Pahala on Mauna Loa Volcano, where the ash is exposed on the surface, but not in section (Wentworth, 1938). Stearns and Macdonald (1946) do not specify a type or reference locality but do present a section through the Pahala Ash at the base of Kaoiki Pali, 5 km southwest of Kilauea caldera. Wentworth (1938) describes a number of sections through the Pahala Ash. The Pahala Ash at Puu Kapukapu and Puu Kaone on Kilauea (fig. 11.3) is well exposed, and it is proposed that sections at these two localities be designated as reference sections for the Pahala Ash on Kilauea. A section through the Pahala Ash at Moolelo (fig. 11.11) is typical of the character of the formation on the south flank of Kilauea and is here designated as the principal reference section. It consists of a mixture of yellow-brown palagonite derived from weathered ash, and beds of reworked ash and sediment. The section at Puu Kaone (fig. 11.12) shows the presence of intercalated flows, which are present locally throughout the Pahala Ash.

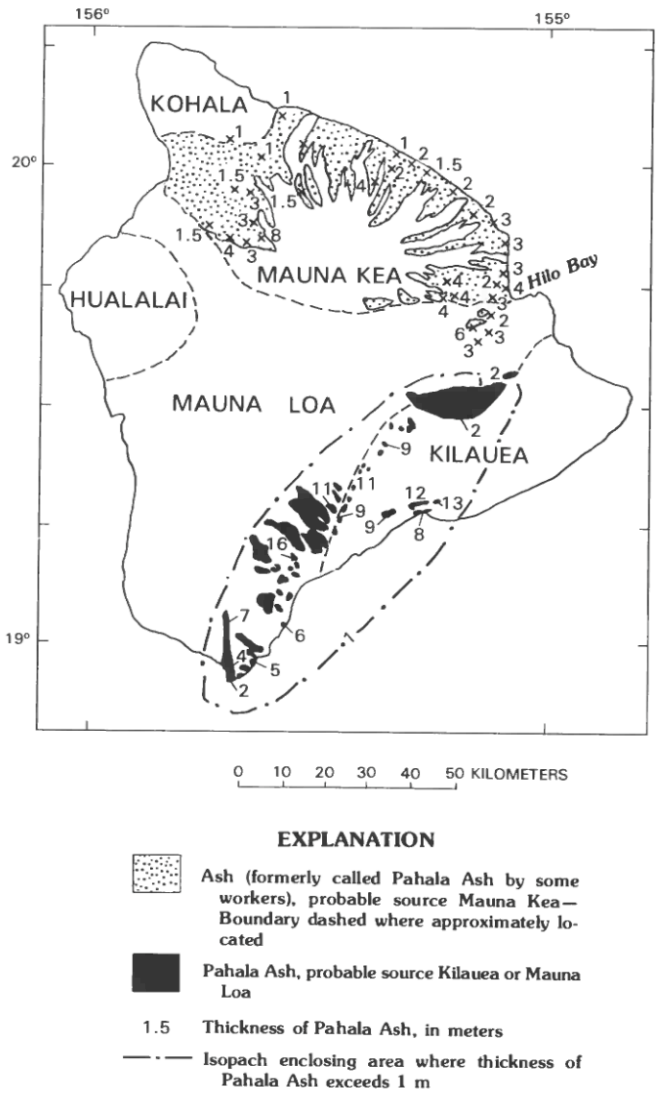

FIGURE 11.10.—Distribution of Pahala Ash on Island of Hawaii. Data from Stearns and Macdonald (1946) and Fraser (1960). The main period of Pahala Ash deposition on Kilauea and Mauna Loa was between 24 ka and 10 ka (Kelley and others, 1979). Distribution of Pahala Ash is also consistent with a Mauna Loa source instead of Kilauea source indicated here.

Flows are interbedded with or overlie the Pahala Ash at Puu Kaone, Puu Kapukapu, and in places along the Hilina Pali. Flows within the Pahala Ash are more abundant south and east of the summit area and are characterized by the presence of *Cibotium* sp. (tree fern) tree molds 15–25 cm in diameter. In addition, some flows contain hypersthene, a mineral rarely observed in the Hilina Basalt. Chemically, these lava flows are similar to Puna Basalt lava flows, and they are here considered to be part of the Puna Basalt. They are also mineralogically similar to the Puna Basalt flows, and they

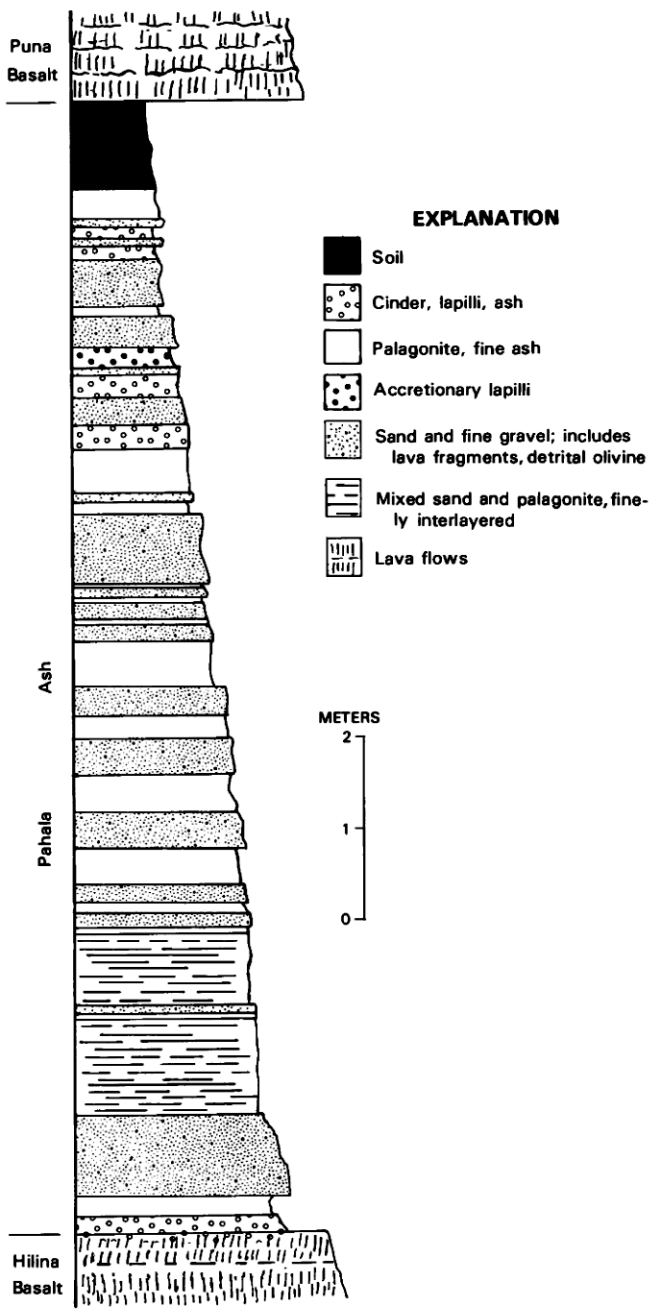

FIGURE 11.11.—Measured section of Pahala Ash exposure 14.25 m thick at Moolelo, Hilina Pali, 20 km south of Kilauea caldera (lat 19°17′ N., long 155°19′ W.), showing proportion of ash and reworked material (sand and gravel) in typical section.

differ only in the presence of tree molds. In areas where the Pahala Ash is absent, it is unlikely that these flows could be distinguished from other Puna Basalt flows. This supports the historical designation of the Pahala Ash as essentially a pyroclastic unit.

Pahala Ash beds at Puu Kapukapu are 1–2 m thick and are underlain by 6–8 m of basalt flows with *Cibotium* sp. tree molds. Farther east, the beds are 0–2 m thick and are overlain by 10–12 m of olivine basalt flows and capped by an additional 2–4 m of ash. The section at Puu Kaone (fig. 11.12) is similar in that it also contains interbedded Puna flows. At Puueo Pali, farther to the east, three 1-m-thick ash beds are interstratified with lava flows 30 m below the top of the pali. These beds contain coarser vitric fragments than are common to the west, and they may be related to fire-fountaining along the east rift zone. If this is the case, these ash beds may not be correlative with the Pahala Ash.

Widely varying thicknesses for the Pahala Ash at Puu Kaone (10–14 m) and Puu Kapukapu (6–12 m) have been reported in the literature (Stone, 1926; Stearns and Clark, 1930; Wentworth, 1938; Stearns and Macdonald, 1946), but these figures include the lava flows. Ground slumping in the area has moved blocks of ash downslope, burying underlying flows and coating flows with a thin veneer of ash. Both effects make the Pahala Ash appear thicker than it truly is.

The Pahala Ash exposed along the Hilina Pali averages 15 m in thickness. In addition, the amount of primary ash versus reworked ash and sediment is greater along the Hilina Pali (50 percent primary) than at Kapukapu (25–40 percent primary). Both effects are consistent with a source for the Pahala on Kilauea or Mauna Loa (see later discussion).

On Mauna Loa, the Pahala Ash contains fewer reworked or sedimentary beds than on Kilauea, and lapilli-size material is more common (Stearns and Macdonald, 1946). The thickness of the Pahala Ash on Mauna Loa varies (fig. 11.10), but locally it is as thick as on Kilauea. On parts of Mauna Loa, the ash resembles loess and may have been transported by wind either during or after deposition.

A charcoal sample collected by G. Fraser from the lower part of the Pahala Ash at Puu Kaone was dated at 17.36±0.65 ka (Rubin and Berthold, 1961). Resampling near this site in 1977 at the base of an olivine basalt flow (Puna Basalt) interbedded with the ash (fig. 11.12) yielded charcoal that was dated at 22.5±0.5 ka and 22.8±0.5 ka (Kelley and others, 1979). These ages are preferred over the previous age of 17.36 ka because three counters were used instead of one, and the earlier sample was diluted because of insufficient carbon (M. Rubin, written commun., 1978). The data indicate that the base of the Pahala Ash on Kilauea has an age of about 23–25 ka. An age of 31.1±0.9 ka has been reported from the base of Pahala Ash on Mauna Loa (Kelley and others, 1979). This is older than the age at Puu Kaone, and it is possible that these lowermost dated ash beds on Mauna Loa may be correlative with the Moo Ash Member of the Hilina Basalt on Kilauea.

The upper part of the Pahala Ash has been dated at several localities on Mauna Loa and Kilauea (see Kelley and others, 1979). The ages range from about 12 ka to 0.2 ka; such a range would be expected because these ages date the time the formation was first buried by lava. The oldest of these overlying flows have ages of 10–12 ka, indicating that the bulk of the ash was deposited between 24 ka and 10 ka on the two volcanoes. Little flow activity occurred on the south flank of Kilauea during this interval. The upper part of

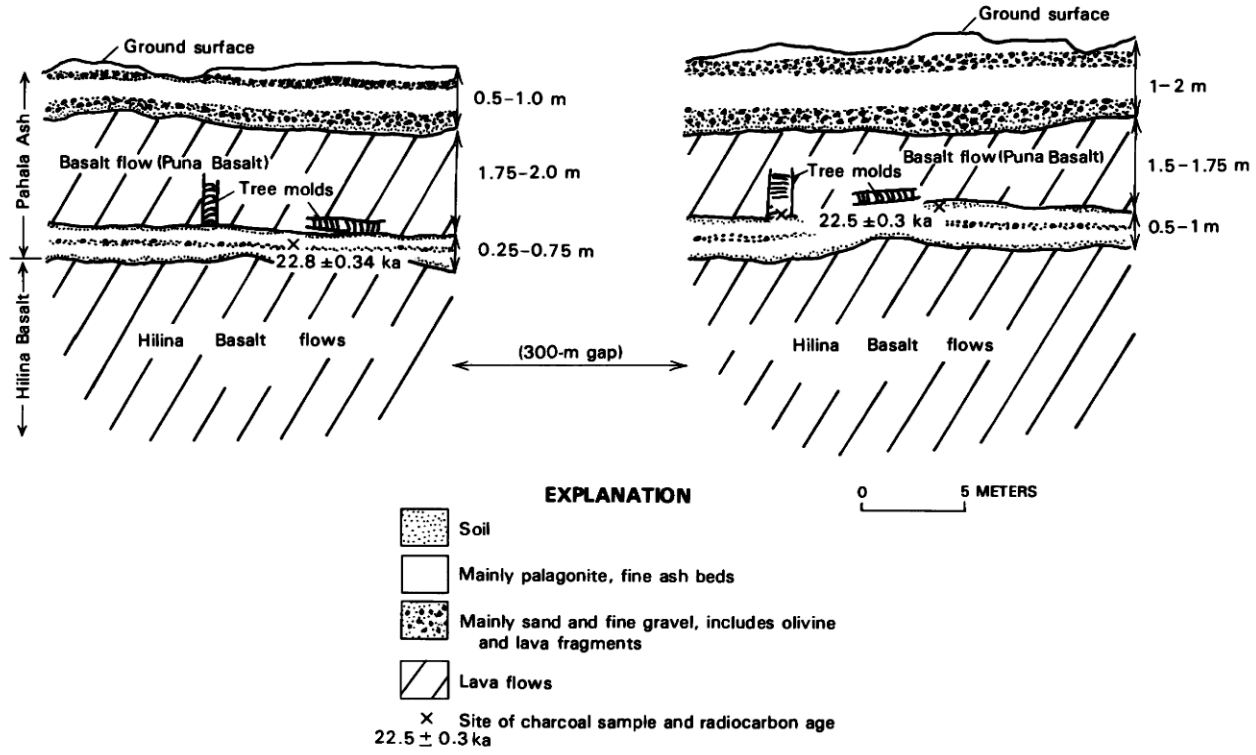

FIGURE 11.12.—Stratigraphic sections of Pahala Ash at Puu Kaone, Kilauea Volcano. Radiocarbon ages from Kelley and others (1979).

the Pahala Ash is obviously not useful as a time-stratigraphic horizon because of the long interval between deposition and burial of the ash. The base of the ash may mark a time-stratigraphic horizon, but additional ages are needed to confirm this. The origin of the ash is discussed later in the paper.

PUNA BASALT

The Puna Basalt covers most of Kilauea and was mostly erupted within the last 10,000 years following Pahala Ash deposition. Historical lava flows are included within the formation. The name is derived from the Puna District of Kilauea, where these flows are abundant (Stearns and Macdonald, 1946). Although Stearns and Macdonald defined the Puna as overlying the Pahala Ash, lava flows here considered to be part of the Puna are locally intercalated with the Pahala Ash (see section "Pahala Ash"). Thus, the base of the Puna Basalt generally overlies the Pahala, but locally may be present within the Pahala and may be as old as about 23 ka. No good sections of the prehistoric lava flows are present in the type locality designated by Stearns and Macdonald (1946, p. 193–194), in the walls of Kilauea caldera, although many surface exposures of flows are present.

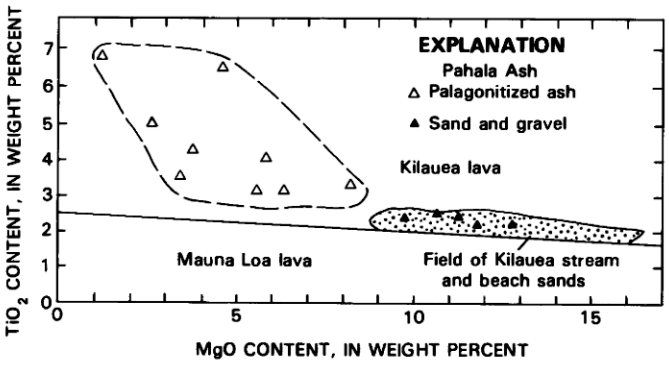

FIGURE 11.13.—TiO_2 content plotted against MgO content for two main lithologies in Pahala Ash. Palagonite beds show a wide range, in part because of in-place alteration (Hay and Jones, 1972; Easton and Easton, 1983). Detrital beds in Pahala Ash fall in field of recent Kilauea stream and beach sands and show less evidence of alteration (Easton and Easton, 1983). Straight line separates field of Kilauea and Mauna Loa lava flows (Wright, 1971; Easton and Garcia, 1980).

LAVA FLOWS

There are some slight chemical and mineralogical differences between Hilina Basalt and Puna Basalt lavas (see section above on Hilina Basalt; Easton and Garcia, 1980). Descriptions of Puna Basalt lava, particularly the historical flows, can be found in Stearns and Clark (1930), Stearns and Macdonald (1946), Easton and Garcia (1980), and Holcomb (1981). Chemical analyses of prehistoric flows of the Puna Basalt are given in Wright (1971). Sections through the prehistoric flows of the formation are present in the walls of Kilauea caldera, notably at Uwekahuna Bluff. Other sections through prehistoric flows are in pit craters along the east rift zone, including Kilauea Iki, Makaopuhi Crater, and Napau Crater; and along the Hilina Pali at the same locations as the Hilina Basalt exposures; these sections can be regarded as reference sections (table 11.1) for the Puna Basalt because they typify groups of flows originating from the summit, the east rift zone, or both areas of Kilauea.

PYROCLASTIC AND SEDIMENTARY DEPOSITS

Several prehistoric ash units are interbedded with lava flows of the Puna Basalt. Only two of these units have been given formal status as members of the Puna Basalt—the Keanakakoi Ash Member and the Uwekahuna Ash Member (renamed to indicate their dominant lithology; formerly the Keanakakoi and Uwekahuna Members of Easton and Garcia, 1980). These members are generally restricted to the summit region of Kilauea. Apart from these and several unnamed older ash layers, the products of the 1924 phreatic eruption in Kilauea crater are also present overlying the Keanakakoi Ash Member on the southwest flank of Kilauea (Decker and Christiansen, 1984). These very young deposits are considered to be part of the Puna Basalt.

OLDER ASH UNITS

At Nanahu Arroyo along the Hilina fault system (figs. 11.3, 11.14) several flow and ash units overlie the Pahala Ash. The uppermost of these units has a radiocarbon age of 1.13 ± 0.25 ka (Kelley and others, 1979) and may be correlative with the Uwekahuna Ash Member. The next lowest soil layer was overlain by lava at about 3.48 ± 0.25 ka (Kelley and others, 1979). A third unit consists of 65 cm of ash that overlies a 69-cm-thick soil horizon developed on a lava flow overlying the Pahala Ash. This ash unit was covered by lava at 4.82 ± 0.2 ka (Kelley and others, 1979).

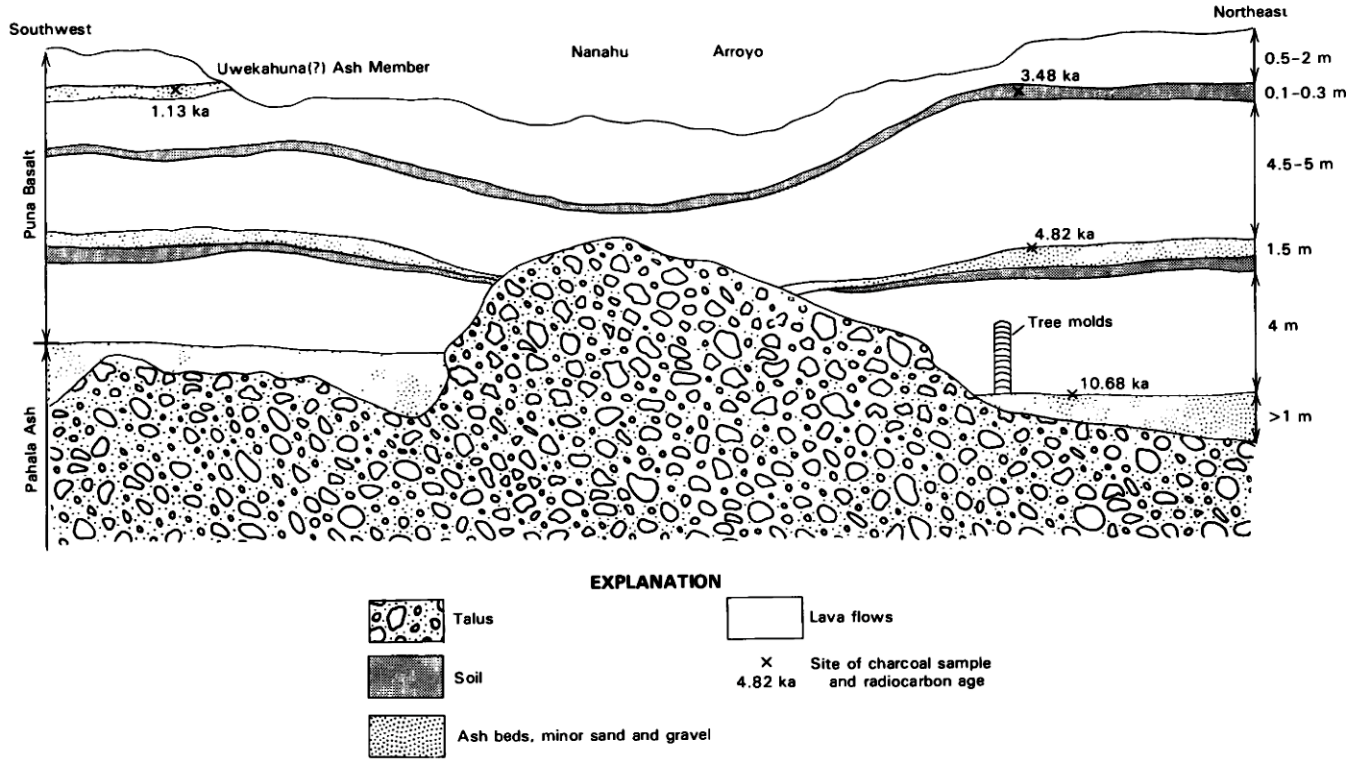

FIGURE 11.14.—Stratigraphic section through Puna Basalt at Nanahu Arroyo. Location of dated charcoal samples (Kelley and others, 1979) and Puna Basalt soil and ash units are shown. Only part of exposed Pahala Ash at this locality is shown.

Given the thick accumulation of soil beneath the ash and the minimal evidence of soil formation in the ash itself, this age may be close to the time of ash deposition. None of these older ash units is widespread enough to be given formal stratigraphic status at present, but they do indicate older explosive activity of Kilauea Volcano between the times the Pahala Ash and Uwekahuna Ash Member were deposited.

Uwekahuna Ash Member

The Uwekahuna Ash Member is a hydromagmatic deposit exposed near the base of the present caldera cliffs at Kilauea and on or near the surface of some areas on the southeast flank of Mauna Loa. The unit was named by Stone (1926) for Uwekahuna Bluff, where about 5 m was previously well exposed (see Powers, 1916). It was subsequently covered by lava and has been partly exposed (about 2 m) more recently (Casadevall and Dzurisin, chapter 13). The member has a distribution similar to that of the Keanakakoi Ash Member, and it probably had a similar origin (Decker and Christiansen, 1984). Radiocarbon ages on charcoal from overlying and underlying flows indicate an approximate age of 1.1–1.5 ka for this unit (Kelley and others, 1979). Descriptions of the unit are found in Casadevall and Dzurisin (chapter 13), and also in Powers (1916), Wentworth (1938), Stearns and Macdonald (1946), and Decker and Christiansen (1984). A reference section is here designated as shown in table 11.1.

Keanakakoi Ash Member

This unit was originally called the Keanakakoi Formation by Wentworth (1938), who considered it to comprise the whole series of ash layers southwest of Kilauea caldera, including ash of the 1790 and 1924 eruptions. The name is derived from Keanakakoi Crater near Kilauea caldera, and the unit is well exposed at its type locality along scarps southwest of Keanakakoi Crater. Powers (1948) also considered the unit to include all fragmental eruptive deposits southwest of Kilauea caldera, and he recognized that these deposits included a number of unconformities. Only the uppermost layer of the member was considered by Powers (1948) to be related to the 1790 eruption. Recent work by Swanson and Christiansen (1973), Christiansen (1979), and Decker and Christiansen (1984) indicate that the member consists of fallout, pyroclastic-surge, and reworked deposits, and were mostly deposited during the 1790 eruption. Recent radiocarbon dating has confirmed this interpretation (Kelley and others, 1979). Decker and Christiansen (1984) showed an idealized section of the member, Malin and others (1983) briefly described the member, and Stearns and Clark (1930) produced a map of its distribution.

Decker and Christiansen (1984) noted the following six major units within the Keanakakoi Ash Member, each unit separated from its neighbors by truncated surfaces: (1) Basal wind-redeposited Pele's hair and reticulite pumice. (2) Predominantly well sorted vitric ash with planar mantle bedding. (3) Less well sorted lithic-vitric ash, commonly with wavy and lenticular bedding, cross-stratification, and bedding sags beneath lithic blocks. (4) A local lava flow. (5) Lithic ash and blocks, with abundant accretionary lapilli and cross-stratification. (6) An uppermost deposit of fallout and wind-resorted pumice and Pele's hair. Units 1 and 2 correspond roughly to the "lower mixed unit" of Malin and others (1982); unit 3 is their "intermediate vitric unit"; and unit 5 is their "upper lithic unit." Malin and others (1982) suggested that the upper layer of fallout and wind-resorted pumice and Pele's hair was deposited between 1790 and 1823, but do not include it in their Keanakakoi.

The definition of the Keanakakoi in this report is that of Decker and Christiansen (1984), including both the lower and upper pumices. The Keanakakoi was mainly deposited during the 1790 eruption, but the basal pumice is slightly older (R.L. Christiansen, oral commun., 1986), and the overlying fallout and the unconformably overlying fallout and resorted pumice layer—the "golden pumice" of Sharp and others (chapter 15)— is circa A.D. 1820.

PALEOCLIMATE AND PALEOGEOGRAPHY

During the 10,000 to 15,000 years of Pahala Ash deposition on Kilauea, very few lava flows reached its south flank. This in part accounts for the thickness of the formation and is probably a result of diversion of lava away from the south flank by an incipient Kaoe fault zone, by entrapment of lava within a deep caldera, or by a prolonged period of mainly ash production at Kilauea caldera. This long period of deposition also allowed reworking of the ash and development of sheetwash plains consisting of reworked ash and broken flow material, much as is occurring today southwest of Kilauea caldera. Similar conditions probably also existed during deposition of the Pohakaa Ash Member of the Hilina Basalt.

In addition, lava flows intercalated with and immediately overlying the Pahala Ash and Pohakaa Ash Member contain abundant tree molds. The presence of *Cibotium* sp. (tree fern) molds as much as 25 cm in diameter within Pahala flows at Puu Kaone and Puu Kapukapu indicate that sufficient time elapsed between deposition of the ashes and the flows to produce forest growth (about 400 years; see Atkinson, 1971). Annual rainfall of about 200 cm is needed for the development of fern forests. The area of these molds now receives less than 50 cm of rain annually; hence a wetter climate probably existed during these periods of ash deposition. Tree molds are absent elsewhere in the Hilina Basalt. This paleoclimatic regime may also have been important in establishing conditions favorable for ash production (for example, by producing a higher ground-water table).

DISCUSSION

In the following discussion on the origin and source of the Pohakaa, Moo, and Pahala pyroclastic deposits, emphasis is placed on the better studied Pahala Ash. However, all of these units are similar in lithology and distribution, and the comments with regard to the Pahala Ash are probably applicable to the Pohakaa and Moo ashes as well.

The source of the Pahala Ash is controversial. Stearns and Clark (1930) and Wentworth (1938) attributed the ash to explosive eruptions of vents on Mauna Loa Volcano and elsewhere outside Kilauea. Stone (1926), Stearns and Macdonald (1946), Fraser

(1960), and Easton (1978) regarded the Pahala deposits southwest of Kilauea caldera as originating from Kilauea (fig. 11.10). Refractive-index measurements of Pahala Ash glass (fig. 11.9) and chemical analyses of the glass (Fraser, 1960; Hay and Iijima, 1968; Hay and Jones, 1972; Easton and Easton, 1983) confirm that the bulk of the ash is basaltic in composition; hence it is probably not derived from Mauna Kea, which would likely have glass erupted of hawaiite composition at that time (Porter, 1979). Isopach patterns of the Pahala Ash (fig. 11.10; Fraser, 1960) are also consistent with a Kilauea source, as is the greater proportion of ash versus detrital material closer to the summit of Kilauea caldera. However, the isopach data is also consistent with a Mauna Loa source for the Pahala Ash (R.T. Holcomb, written commun., 1983, 1984). Rare-earth-element data on the Pahala Ash (fig. 11.15; Easton and Easton, 1983) are inconclusive regarding the origin of the primary ash material. It is definitely basaltic in composition, but alteration makes it difficult to distinguish between a Kilauea and a Mauna Loa source (fig. 11.15). The detrital component of the Pahala Ash on Kilauea (fig. 11.13) is derived from the weathering of Kilauea lavas and is not as altered as the ash component of the formation (fig. 11.13; Easton and Easton, 1983).

Since the original nature of the Pahala Ash is difficult to decipher because of alteration, the origin of the ash has also remained controversial. Two suggested origins are as follows: (1) The ash may consist of magmatic fire-fountain debris (Stearns and Clark, 1930; Wentworth, 1938; Stearns and Macdonald, 1946); Stearns and Macdonald (1946) considered that most of the Pahala Ash was of fire-fountain origin, but allowed for the possibility of a phreatic or phreatomagmatic origin. (2) The ash may be the product of phreatic or phreatomagmatic eruptions of Kilauea that were similar to but of larger scale and duration than the 1790 and May 1924 eruptions of Kilauea's summit (Stone, 1926; Fraser, 1960).

Physical evidence for a phreatic or phreatomagmatic origin include the presence of accretionary lapilli and lithic and crystal fragments in the Pahala, Pohakaa, and Moo ashes in addition to the predominant vitric ash. Judging from the 1790 and 1924 eruptions, hydromagmatic activity at Kilauea's summit is an effective means of producing large quantities of ash; this process of origin is also consistent with a wetter climate during these periods of ash deposition. If the ash is from eruptions at Mauna Loa, then snow and ice in the summit area could also have been a significant factor in ash production (R.T Holcomb, written commun., 1983, 1984). Alternatively, G.A. Macdonald (written commun., 1978) reported that the fire-fountain debris for the 1959 Kilauea Iki eruption could be found as far south as Ka Lae (the southernmost point on the Island of Hawaii) on Mauna Loa, hence the extensive distribution of the Pahala Ash on Kilauea and Mauna Loa does not preclude a magmatic origin. However, this fire-fountain debris consists only of pumiceous shards and Pele's hair and does not include blocky shard fragments such as are common in the Pahala Ash. Possibly both origins are correct: the ash may be predominantly hydromagmatic in origin, but magmatic deposits may also be present locally within the formation.

Decker and Christiansen (1984) have discussed the significance of the number of pyroclastic deposits within the exposed Kilauea section with respect to future volcanic hazards. Holcomb (chapter 12) discusses how some of these ash deposits may be related to caldera collapse at Kilauea. The ash horizons are therefore important markers of Kilauea volcanic activity.

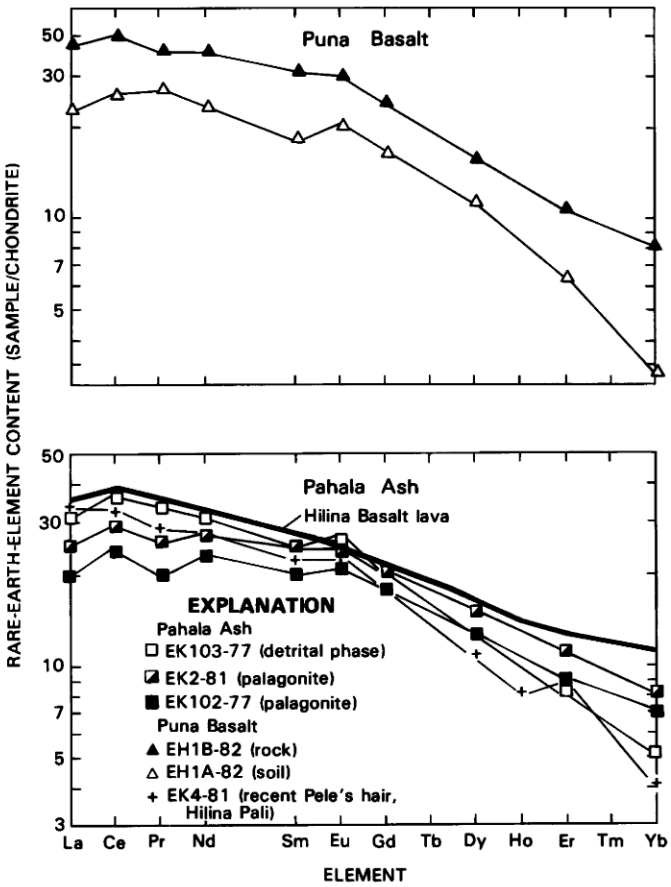

FIGURE 11.15.—Chondrite-normalized rare-earth-element (REE) data for Pahala Ash samples. Sample EK103-77 is a gray-weathering sand bed from Pahala Ash at Keana Bihopa, Hilina Pali. Its REE pattern is similar to typical Kilauea lava (for instance, Hilina Basalt lava shown) and modern Kilauea stream and sheetwash sands (not shown; Easton and Easton, 1983); low content of heavy REE in sample may be a result of presence of detrital olivine in the sample. Sample EK102-77 is palgonitized ash from Pahala Ash overlying EK103-77. Although the REE pattern is similar to that for Hilina Basalt lava, REE abundances are about 20–25 percent lower than in lava. The same is true of sample EK2-81, a Pahala Ash sample from Mauna Loa near town of Waiohinu. The REE loss in Pahala Ash palagonite is similar to that observed for soils developed over Puna Basalt lava flows from east rift zone of Kilauea (EH1A-82, EH1B-82) and is probably related to weathering and alteration. The REE data indicate a basaltic composition for Pahala Ash, but alteration, particularly with respect to light REE, prevents discrimination between Mauna Loa and Kilauea sources.

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